16SM

Key Risks across Sectors and Regions
Supplementary Material

Coordinating Lead Authors: Brian O'Neill (USA), Maarten van Aalst (the Netherlands), Zelina Zaiton Ibrahim (Malaysia)

Lead Authors: Lea Berrang Ford (UK/Canada), Suruchi Bhadwal (India), Halvard Buhaug (Norway), Delavane Diaz (USA), Katja Frieler (Germany), Matthias Garschagen (Germany), Alexandre Magnan (France), Guy Midgley (South Africa), Alisher Mirzabaev (Uzbekistan/Germany), Adelle Thomas (Bahamas), Rachel Warren (UK)

Contributing Authors: Sharina Abdul Halim (Malaysia), Idowu Ajibade (Nigeria/Canada/USA), Philip Antwi-Agyei (Ghana), Laura Astigarraga (Uruguay), Govindasamy Bala (India), Birgit Bednar-Friedl (Austria), Magnus Benzie (Sweden/UK), Richard Betts (UK), Rachel Bezner Kerr (USA), Joern Birkmann (Germany), Martina Angela Caretta (USA), Tamma Carleton (USA), Connor Cavanagh (Ireland/Norway), Winston Chow (Singapore), Guéladio Cissé (Mauritania/Switzerland/France), Andrew Constable (Australia), Mark John Costello (New Zealand/Norway/Ireland), Jackie Dawson (Canada), Richard Dawson (UK), Heleen de Coninck (the Netherlands), Simon Donner (Canada), Sybren Drijfhout (the Netherlands), Laurent Drouet (Italy), Virginie K.E. Duvat (France), Kristie Ebi (USA), Tamsin Edwards (UK), Francois Engelbrecht (South Africa), Alexandra Paige Fischer (USA), Isabel Fletcher (UK), James Ford (UK), Eranga Galappaththi (Sri Lanka/Canada), Oliver Geden (Germany), Francois Gemenne (Belgium), Veronika Ginzburg (Russia), Patrick Gonzalez (USA), Neal Haddaway (Sweden/Germany/UK), Isabel Hagen (Switzerland), Stephane Hallegatte (France/USA), Toshihiro Hasegawa (Japan), Masahiro Hashizume (Japan), Stefanie Heinicke (Germany), Cullen Hendrix (USA), Kevin Hennessy (Australia), Tom Hertel (USA), Jeremy Hess (USA), Helene Hewitt (UK), Kirstin Holsman (USA), Veronika Huber (Germany/Spain), Christian Huggel (Switzerland), Bramka Jafino (Indonesia/the Netherlands), Kripa Jagannathan (Canada/India/USA), Rhosanna Jenkins (UK), Chris Jones (UK), Vhalinavho Khavhagali (South Africa), Elco Koks (the Netherlands), Gerhard Krinner (France), Judy Lawrence (New Zealand), Gonéri Le Cozannet (France), Alexandra Lesnikowski (Canada), Karen Levy (USA), Tabea Lissner (Germany), Rachel Lowe (UK), Simone Lucatello (Mexico), Yong Luo (China), Brendan Mackey (Australia), Katherine Mach (USA), Shobha Maharaj (Germany/Trinidad and Tobago), Custodio Matavel (Mozambique/Germany), Timon McPhearson (USA), Aurélie Méjean (France), Veruska Muccione (Switzerland/Italy), Aditi Mukherji (India), Didacus Namanya (Uganda), Gerald Nelson (USA), David Obura (Kenya), Jean Ometto (Brazil), Friederike Otto (UK/Germany), Camille Parmesan (UK/USA), Anthony Patt (Switzerland), Patricia Pinho (Brazil/UK), Franziska Piontek (Germany), Prajal Pradhan (Nepal/Germany), Jeff Price (UK), Joacim Rocklov (Sweden), Steven Rose (USA), Alexander Ruane (USA), Inga Sauer (Germany), Daniela Schmidt (Germany/UK), Alcade Segnon (Republic of Benin), Sonia Seneviratne (Switzerland), Olivia Serdeczny (Poland/Germany), Mohammad Aminur Rahman Shah (Bangladesh/UK), Yuanyuan Shang (China/Australia), Roopam Shukla (India/Germany), AR Siders (USA), Nicholas P. Simpson (Zimbabwe/South Africa), Chandi Singh (India), Asha Sitati (Kenya), Tom Spencer (UK), Nicola Stevens (South Africa), Masahiro Sugiyama (Japan), Emily Theokritoff (Germany), Maria Cristina Tirado-von der Pahlen (Spain/USA), Christopher Trisos (South Africa), Nicola Ulibarri (USA), Mariana Vale (Brazil), Krispa Vasant (India), Ana Vicedo-Carbrera (Spain/Switzerland), Thomas Vogt (Germany), Colette Wabnitz (Canada), Anita Wreford (New Zealand), Gary Yohe (USA), Carol Zavaleta (Peru), Xuebin Zhang (Canada), Zhibin Zhang (China)

Review Editors: Tong Jiang (China), Michael Oppenheimer (USA)

Chapter Scientist: Rhosanna Jenkins (UK)

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SM16.1 Section 16.3.1: Methodology for Systematic Assessment of Adaptation Responses in Human Systems

The purpose of this section (SM16.1) is to outline the methods used to systematically assess adaptation responses in human systems for Section 16.3.1. Research questions guiding this assessment include:

- What hazards are motivating adaptation responses?
- Who is responding?
- What types of responses are documented?
- What is the evidence base on effectiveness, adequacy and risk reduction associated with responses?
- What maladaptations and co-benefits are reported?
- What is the evidence of transformational adaptation?

Summary of assessment

We leveraged an external initiative, the Global Adaptation Mapping Initiative (GAMI) to develop a database of scientific literature reporting on adaptation-related responses to climate change in human systems. GAMI was initiated by AR6 authors in collaboration with a large network of adaptation researchers around the world (*n* = 126 team members) to synthesise the scientific literature on human adaptation, providing an evidence base within the peer-reviewed literature to support AR6 assessment of adaptation responses. Since GAMI is thus external to the AR6 process, with results published in peer-reviewed journals and participation from a wide range of researchers, the initiative was designed to provide a foundation for AR6 assessment on adaptation responses. The adaptation assessment in Section 16.3.1 extends the analyses that are published in Berrang-Ford (2021).

GAMI conducted a systematic review of literature from 2013–2019 using machine learning and a global team of adaptation researchers (*n* = 126 researchers) to screen and code information. In total, 48,816 documents were screened, and 1682 articles were deemed eligible for inclusion in the database and coded to extract adaptation information. The review focused on a narrow subset of adaptation literature: articles reporting on documented and implemented adaptation actions with the potential to directly reduce risk. This excludes a large literature focusing on the processes of adaptation decision-making and governance, such as adaptation planning and vulnerability assessment. GAMI excluded this large literature base, including only reports of implemented adaptations. In doing so, GAMI, and our Section 16.3.1 assessment focused primarily on adaptation within the scope of Chapter 16 to encompass adaptation actions that can directly affect risk. Broader adaptation processes are captured in Chapter 17 and were not included within the scope of this Chapter 16 assessment.

A database of 1682 articles was developed, including data extracted for each article as per an adaptation typology developed by GAMI. For assessment within Section 16.3.1, the GAMI database was extended to include additional eligible citations from all regional and sectoral chapters (Chapters 2–15) from the AR6 WGII Second Order Draft (SOD). All analyses presented in Section 16.3.1 thus present analyses and results using this updated data set.

Here, we summarise the methods used by GAMI to develop the database that we draw on for our AR6 assessment, as well as updates and additional analyses developed within the Section 16.3.1 assessment.

Global Adaptation Mapping Initiative (GAMI)—Methodology

GAMI methods and emerging results are available at:

Detailed protocols are published via the *Nature Protocol Exchange*, including:

- Part 1: Introduction and overview of methods (DOI: 10.21203/rs.3.pex-1240/v1)
- Part 2: Screening protocol (DOI: 10.21203/rs.3.pex-1241/v1)
- Part 3: Coding protocol (DOI: 10.21203/rs.3.pex-1242/v1).

Publications:

- Berrang-Ford et al. (2021) A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change.* doi: 10.21203/rs.3.rs-100873/v1.
- Thomas et al. (2021) Global evidence of constraints and limits to human adaptation. *Regional Environmental Change* 21:85 https://doi.org/10.1007/s10113-021-01808-9.
- Williams et al. (2021) Feasibility assessment of climate change adaptation options across Africa: an evidence-based review. *Environmental Research Letters* **16:**073004.
- Turek-Hankins et al. (2021) Climate change adaptation to extreme heat: a global systematic review of implemented action. *Oxford Open Climate Change* **1:**kgab005.
- Scheelbeek et al. (2021) The effects on public health of climate change adaptation responses: a systematic review of evidence from low- and middle-income countries. *Environmental Research Letters* **16:**073001.

Scope and objectives of GAMI systematic review

The GAMI review protocol followed guidance for systematic review mapping and general guidelines for evidence synthesis (e.g., Cochrane, Campbell, CEE). GAMI follows the RepOrting standards for Systematic Evidence Syntheses (ROSES) established reporting standards (Haddaway et al. 2018). Review of scientific literature was framed using standards for formulating research questions and searches in systematic reviews, using a PICoST approach: population/problem (P), interest (I), context (Co), and time (T) and scope (S) (Table SM16.1).

The activity of interest (I) was adaptation-related responses. Consistent with the WGII Chapter 16 approved outline, and due to the lack of scientifically robust literature assessing the potential effectiveness of responses, the term 'adaptation-related responses' was used rather than the more common 'adaptations' to avoid the implication that all responses (or adaptations) are actually adaptive (i.e., reduce vulnerability and/or risk); some responses labelled as 'adaptations' might in fact be maladaptive. To be included in the review and database, documented responses must have been initiated by humans. This includes human-assisted responses within natural systems, as well

Table SM16.1 | Review objectives and key components.

Review objective	To systematically map and review human adaptation-related responses to climate change that have been documented in the scientific literature globally since 2013
Population (P)	Global human or natural Systems of importance to humans that are impacted by climate change
Interest (I)	Observed/documented adaptation responses to climate change within human systems (or human-assisted in natural systems) in the scientific literature
Context (Co)	Any empirically documented/observed adaptation response by humans
Time & Scope (T/S)	Published between 2013 and 2019

as responses taken by governments, the private sector, civil society, communities, households and individuals, whether intentional/planned or unintentional/autonomous. While unintentional/autonomous responses were included, these are likely to be under-represented unless labelled as adaptation and documented as a response to climate change owing to the infeasibility of capturing potential adaptive activities not identified as adaptations. The review excluded responses in natural systems that are not human assisted; these are sometimes referred to as evolutionary adaptations or autonomous natural systems adaptations. While important, autonomous adaptation in natural systems is distinct from adaptations initiated by humans; the GAMI review focused on responses by humans to observed or projected climate change risk. Any human responses to climate change impacts that decrease, or could decrease, vulnerability or exposure to climate-related hazards, as well as anticipatory measures in response to expected impacts, were included.

The review focused on adaptation only, and excluded mitigation (responses involving the reduction of greenhouse gas [GHG] concentrations). Adaptation responses across contexts (Co) globally were considered, focusing only on adaptation activities that are directly intended to reduce risk, exposure or vulnerability, even if later identified as maladaptation. To reflect publications since AR5 and prior to the AR6 publication cut-off, the review focused on literature published in the time period (T) between 2013 and 2019 (extended to include more recent eligible articles cited in the SOD of WGII chapters).

The review focused on the scientific literature only, and excluded grey literature and other sources of Indigenous knowledge and local knowledge (IKLK). These sources of evidence were considered relevant and important, however, and early protocols attempted to include grey literature and IKLK. The volume of scientific literature alone was huge, however, and difficult to synthesise systematically despite its relatively standardised curation. Standardised indexing is largely lacking for grey literature and IKLK sources, making their access for such a wide scope difficult within IPCC assessment timelines and resources. A lack of established methods to systematically access, review and synthesise scientific literature, grey literature and IKLK constrained more diverse knowledge synthesis. More extensive resources and time would have been needed to develop an integrated evidence synthesis programme to fully assess diverse sources of evidence. Approaches to synthesise diverse knowledges remain underdeveloped more generally.

Searching and screening for relevant literature

To ensure relevant documents were captured, initial scoping identified appropriate search terms. A list of 10 *a priori* identified publications (Araos et al., 2016; Biesbroek et al., 2018; Ford et al., 2015; Georgeson et al., 2016; Kafatos et al., 2017; Lesnikowski et al., 2015; Lwasa, 2015; Miller et al., 2018; Runhaar et al., 2018; Tanner et al., 2015) were used to construct search terms and refine the search strings (Table SM16.2). These papers were used to identify potential search terms and better understand the range of terminology used in this field. This informed the development of unique search strings for the review protocol.

Search strings were developed for each bibliographic database (Table SM16.2). The searches focus on documents combining two concepts: climate change, and adaptation or response. Given the huge number of publications referring to environment and resilience, search strings were restricted to documents including reference to climate change or global warming in their titles, abstracts or keywords; articles referring to weather, environmental variability or meteorological variables without explicit reference to climate change are thus not captured. Terms such as ‘resilience’ and ‘risk management’ were used to reflect the breadth of literature relevant to climate adaptation that is indexed using these terms. Only natural language terms were used since Scopus and Web of Science do not employ controlled vocabulary (e.g., MeSH terms).

Database searches—including bibliographic databases, organisational websites and web-based search engines—were conducted in English only, but screening did not exclude by language. This means that documents written in any language are eligible for inclusion as long as they are indexed in English within selected databases. Given the global scope of this review, it was not considered feasible to search in all global languages. In addition, the bibliographic databases typically catalogue records using translated English titles and abstracts: non-English searches are thus not largely necessary for these resources. A number of non-English documents were retrieved and included in the GAMI database.

Article screening and study inclusion criteria

Screening entailed manual (human) and machine learning to review the title and/or abstract or summary of each potentially relevant document to determine whether it could be included in a database of recent empirical research on human adaptation to climate change. Screening involved working with a huge volume of literature (close to 50,000 documents). The screening phase thus leveraged machine-learning methods to automate part of the process.

The goal of screening was to assemble a database of papers published between 2013 and 2019 on actions undertaken by people in response to climate change or environmental conditions, events and processes that were attributed or theorised to be linked, at least in part, to climate change. The focus was on adaptation; documents focusing on mitigation responses (i.e., reducing greenhouse gas emissions) were excluded. Adaptation actions could take place at any level of social organisation (individual, household, community, institution, government). Adaptation responses to perceived climate

Table SM16.2 | Key search concepts, databases and search strings used in review.

Database	Concept 1	Concept 2	Date & document type restrictions	Approximate N. documents retrieved
Key concepts & scope	Climate change	Adaptation	Articles, reviews, data papers, and letters only. Date range: 2013–2020	n/a
Web of Science	TS= (climat* or "global warming")	AND TS: (adapt* or resilien* or (risk NEAR/3 manag*) or (risk NEAR/3 reduc*))	Refined hy: DOCUMENT TYPES: (Article OR Data Paper OR Database Review OR Letter OR Review) Timespan: 2013–2019. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.	39,626
Scopus	TITLE-ABS-KEY (climat* or "global warming")	ANDTITLE-AB5-KEY (adapt* or resilien* or (risk W/3 manag*) or (risk W/3 reduc*))	AND (LIMIT-TO(PUBYEAR, 2019) OR LIMIT-TO(PUBYEAR, 2018) OR LIMIT-TO(PUBYEAR, 2017) OR LIMIT-TO(PUBYEAR, 2016) OR LIMIT-TO(PUBYEAR, 2015) OR LIMIT-TO(PUBYEAR, 2014) OR LIMIT-TO(PUBYEAR, 2013)) AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re") OR LIMIT-TO(DOCTYPE, "dp") OR LIMIT-TO(DOCTYPE, "le"))	36,183
MEDLINE	TS= (climat* or "global warming")	AND TS: (adapt* or resilien* or (risk NEAR/3 manag*) or (risk NEAR/3 reduc*))	Refined by: DOCUMENT TYPES: (Article OR Data Paper OR Database Review OR Letter OR Review) Timespan: 2013–2019. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.	8,973

Documents retrieved from searches were uploaded to a customised platform for management and screening (Zenodo.http://doi.org/10.5281/zenodo.4121525).

change impacts were eligible for inclusion. Documents synthesising climate change impacts on populations, without explicit and primary emphasis on *adaptation responses*, were also excluded except when climate *responses* were synonymous with climate *impacts* (e.g., human migration or species shifts). Documents whose contributions are primarily conceptual or theoretical were treated as non-empirical and therefore excluded. The review focused on documents that reported on responses that constituted adaptation based on a strict definition of the term: behaviours that directly aimed to reduce risk or vulnerability. Documents presenting empirical syntheses of vulnerability or adaptive capacity without primary or substantive focus on tangible adaptation responses (reactive or proactive) were excluded. Documents were considered eligible for inclusion if they explicitly documented adaptation actions that were theorised or conceptually linked to risk or vulnerability reduction. This excluded assessments of *potential* adaptation, *intentions/plans* to adapt, and discussion of adaptation constraints or barriers in the absence of documented actions that might reduce risk, exposure or vulnerability.

Documents published between 2013 and 2019 were considered, including documents reporting on adaptations undertaken prior to 2013. Documents were not excluded from screening based on language as long as they are indexed in English. Documents were not excluded by geographical region, population, ecosystem, species or sector. Grey literature was not included.

The screening team evaluated the suitability of each paper using a set of seven inclusion and exclusion criteria (Table SM16.3).

These criteria were converted to a set of decision steps to facilitate efficient screening decisions and inter-screener reliability:

1. Does the paper have anything to do with ***climate change***? If the paper does not explicitly or implicitly draw connections between the objectives, methods, or findings and global climate change, global warming, global change, or changes that are driven by global atmospheric variables, then the answer is no. If the answer is yes, proceed to criterion number 2.
2. Does the paper report on analyses of ***empirical*** data (i.e., data derived from observation or experience; not theoretical or simulated) or a systematic review of empirical research? If the paper presents concepts and theories not grounded in empirical research, puts forth propositions without clear descriptions of methods, or presents the results of simulations that are not based on empirical data, then the answer is no. If the answer is yes, proceed to criterion number 3.
3. Does the paper report on findings about changes in human systems OR human-assisted changes in natural systems intended for adaptation in human systems (i.e., what ***people*** think and do)? If the paper reports on biological/ecological conditions and processes, then the answer is no. If the answer is yes, proceed to criterion number 4.

Table SM16.3 | Inclusion and exclusion criteria applied during screening.

	Inclusion criteria	Exclusion criteria
1	Climate change related	Not climate change related
2	Adaptation	Mitigation
3	Empirical OR review of empirical	Conceptual, theoretical, simulated
4	Human system responses OR human-assisted	Natural system responses not for human adaptation
5	Response-oriented, induding factors in response	Vulnerability assessment OR impacts-focused
6	Recent or current (e.g. within past 10 yrs)	Historie OR Prehistoric OR Projected
7	Tangible responses with potential to directly reduce risk	Flanning, prioritizing, proposing responses OR Link to risk reduction tangential or unclear

4. Does the paper report on how people ***respond*** to environmental change, including factors that influence how people respond? If the paper reports the results of an assessment of vulnerability or impacts from climate change, then the answer is no. If the answer is yes, proceed to criterion number 5.
5. Do the responses have to do with ***adaptation*** through reduction of risk or impacts, or improvements in well-being or suitability to the environment beyond mitigation? If the paper only reports on efforts to prevent, slow or reverse climate change, the answer is no. If the answer is yes, proceed to criterion 6.
6. Is the time frame of the research current (e.g., within the past 10 years) or ***recent***? If the time frame was prehistoric or historic, the answer is no. If the answer is yes, proceed to criterion 7.
7. Does the paper report on ***tangible/observed behavioural responses*** (e.g., actions, practices, improved knowledge, altered social structure) that people ***have undertaken*** and that could arguably ***reduce risk*** to people or ***improve people's ability to cope with/adapt to*** environmental change? If the paper reports on planned or recommended behaviour change, the answer is no. If the answer is yes, the article should be included in the sample.

Given the large volume of documents requiring screening, machine-learning techniques were used to filter and prioritise screening of documents that were most likely to meet inclusion criteria. To identify relevant documents within the larger set of retrieved documents, supervised machine learning was used. This approach involves manually screening (human coding) a subset of documents to 'teach' an automated classifier which documents are relevant according to a set of pre-defined criteria, and then use this trained classifier to predict the 'most likely to be relevant' literature. To be labelled as relevant, documents needed to meet inclusion and exclusion criteria (Table SM16.3) based on their title, abstract and keywords.

Initial manual screening: A random sample of documents was retrieved via the search strings for initial screening. This sample of documents was reviewed by multiple team members; the documents that were labelled differently by different team members were then discussed until consensus was reached, to reduce bias and ensure consistency between team members. This initial phase created the first of several training samples used to train the machine-learning algorithm to predict relevant documents.

Iterative screening and training of algorithm: The above sample of manually screened documents was used to train a machine-learning classifier to predict the relevance of remaining documents. The algorithm generated a 'probability of relevance' for all unscreened documents, allowing the screening team to prioritise screening of documents most likely to be relevant. Batches of documents with the highest predicted probability of relevance were then screened by hand, with iterative re-training of the classifier after each batch to continuously improve prediction. All documents identified by the algorithm as potentially highly relevant were manually screened by the screening team, with these results acting to improve the algorithm's prediction of relevance with each manually screened batch.

Assessment of 'borderline' documents: The above iterative process continued until the classifier stopped predicting new relevant documents, and most documents being identified were only borderline relevant. While not all documents had been manually screened by the screening team at this stage, none of the documents being identified by the algorithm as 'likely to be most relevant' was deemed by the screening team to be highly relevant. Further manual screening of documents identified by the algorithm found increasingly borderline and irrelevant documents, suggesting that the majority of relevant documents had already been identified and screened.

Estimating proportion of relevant documents retrieved through machine learning: A random sample of the remaining unscreened documents was used to estimate how many of these documents might still be relevant. In total, 43,462 documents were not screened. Based on a sample of 200 of these documents, 3 potentially relevant documents were found, all of which were deemed as marginally relevant only. Based on these results, the predicted chance of achieving a recall of less than 68% is less than 50%, and the chance of achieving a recall of less than 50% is less than 5%. These numbers are conservative, as the three relevant documents in the sample were of only marginal relevance. The returns of additional screening are thus likely to be low.

All documents deemed eligible in the final database were manually screened by the screening team. The machine-learning component of this review means that the screening team did not, however, screen 100% of documents retrieved via the search strings. Instead, the screening team screened a non-random sample of the documents predicted to be the most relevant to inclusion criteria, as predicted by the machine learning classifier. There will therefore be some relevant documents missed by this process. These will be cases where the classifier was unable to recognise that the document met inclusion criteria. In most cases, these were borderline-relevant documents.

Inter-screener reliability: To ensure consistent interpretation of the screening criteria between screeners, the members of the screening team each screened the same initial set of 50 documents and then compared and contrasted application of the inclusion and exclusion criteria. After refining our collective interpretation of the criteria, this process was repeated with 100 documents, at which point the team was confident that they were able to apply the criteria in a similar fashion.

Table SM16.4 | Machine-learning-supported screening of iterative batches of documents retrieved from search strings.

Batch	Sample type	N. documents manually screened	Purpose of batch
1	Random	150	Screener consistency check
2	Random	2,988	Classifier training
3	Non-random predicted as most relevant	100	Second consistency check
4		1000	Screening
5		1000	Screening
6		1000	Screening
7		500	Screening
8		200	Screening
9		300	Screening
10		100	Assessing sample validity
11		100	Assessing sample validity
12	Random	50	Validity estimation
13	Random	50	Validity estimation
Total screened	n/a	4300	n/a

Sample size: Of a total of 48,816 documents retrieved following duplicate removal, the screening team manually screened 4500 documents through an iterative screening process detailed in Table SM16.4. As described above, Batches 1 and 3 were small batches of 100 documents each, and were used to train screeners and conduct consistency checking and ensure quality control of screening across team members. Batch 2 was conducted on a random sample of documents, and was used as the primary training batch for the machine classifier. From Batch 3 onwards, each screened batch represented a non-random sample of documents, selecting documents identified by the classifier as the most likely to be relevant. After each batch, the classifier was re-run to improve prediction performance. As the sample of manually screened documents increased, the classifier was increasingly able to differentiate relevance of documents to inclusion and exclusion criteria.

In later batches, the proportion of relevant documents decreased as the screeners had increasingly already screened the most relevant documents. Beginning with Batch 10, therefore, small batches were screened to iteratively assess the number of remaining relevant documents. Once this was determined to be minimised, Batches 12 and 13 were conducted on random samples of literature. These random samples of remaining documents facilitated the estimation of the proportion of relevant documents remaining that had not yet been manually screened.

Performance statistics generated by the machine-learning classifier showed negligible potential to increase recall further, meaning that the remaining unscreened documents were likely to be: (a) not relevant and would be excluded if screened manually, or (b) if relevant, would be borderline or marginally relevant, or (c) relevant but include limited reference to key climate adaptation vocabulary. A total of 347 borderline or unclear documents were double screened. A total of 2032 articles were retrieved from the screening stage and deemed potentially eligible for data extraction.

Data extraction and coding

The bibliographic information for articles meeting inclusion criteria during screening were imported into the platform SysRev (sysrev.com). Given that initial screening was conducted on title and abstract only, an additional screening step was undertaken during this phase (data extraction) to ensure documents contained sufficient full-text information to extract relevant data. Thus, data extraction included two initial screening questions:

1. *Is the document relevant according to inclusion/exclusion criteria?* This question was used to exclude books, conference proceedings and other document formats missed at the initial screening phase, and to verify relevance of borderline inclusion.
2. *Is there sufficient information detailed in the full text* (a minimum of half a page of content documenting an adaptation-related response)? This question was used to screen out documents referring to relevant adaptation responses in their title or abstract, but including no tangible detail or documentation within the article itself.

Structure of coding teams and platform

Data extraction was undertaken within the SysRev online systematic review application. SysRev is a freeware application designed to allow web-based data systematic extraction from documents. An online data extraction form was created within SysRev to enter and curate extracted data. SysRev enables management of multiple coding of documents, identifies inter-coder conflicts, and links to full-text documents for rapid and standardised review.

Bibliographic information for all documents classified as relevant to inclusion criteria during screening was imported into SysRev. Given the substantial number of documents and global scope of the review, data extraction was undertaken by small teams of researchers based on regional and sector expertise. Papers were assigned to a primary topic

OR region. While each document could be coded as relevant to multiple regions and multiple sectors, an individual document was assigned to a single region or sector to facilitate coding within distinct project teams. A total of 13 'projects' were created, reflecting all regions ($n = 7$) and sectors ($n = 7$) listed in the IPCC AR6 WGII outline of chapters. Asia and Australasia were combined since the latter had a very small volume of literature. Some coders contributed to multiple projects. Documents were independently coded by at least two individuals.

Coder recruitment focused on global researchers with expertise in climate change adaptation and one or more of the sectoral or regional topics. The majority of coders had a PhD or higher, though highly specialised researchers with lesser degrees were accepted where relevant and for under-represented topics or regions. For regional sectors, the majority of coders are based in that region, or originate from the region. Coder recruitment was based on convenience recruiting, but prioritised global diversity to seek representation by gender, region and expertise. Recruitment was based on snowballing via team networks and through social media.

An online training manual was developed for coders. The training included both contextual information on systematic review methodologies, as well as key details to guide data extraction, including a detailed codebook. Training of coders sought to expose coders to basic concepts of systematic evidence synthesis and assessment of confidence in evidence. The training manual also served to establish a consistent baseline for the concepts, vocabulary and definitions used within GAMI, recognising a wide range of often conflicting definitional uses for adaptation concepts.

Typology for data extraction

Data extraction was guided by an adaptation typology (Table SM16.5). Coding of regional and sectoral foci within documents allowed for stratified analyses for individual sectors or regions. Questions included both closed/restricted answer questions and open-ended narrative answer questions. The former facilitate quantitative categorical analysis (e.g., descriptive statistics, summarising studies in ordered tables) and mapping of adaptation (breadth), while the latter facilitate contextual understanding of adaptation and qualitative analysis. A summary of key coded variables used for AR6 assessment is provided in Table SM16.5.

Table SM16.5 | Operationalisation of adaptation typology in the form of key questions and variable categorisations used by GAMI (selected variables only, based on those used for Chapter 16 adaptation assessment).

Question	Codes	Definitions
General		
What is the geographic focus of reported responses in this document?	Africa	Africa, Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Chad, Comoros, Congo, Cote d'Ivoire, Ivory Coast, Djibouti, Egypt, Eritrea, Eswatini, Swaziland, Ethiopia, Gabon, Gambia, Ghana, Guinea, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe
	Asia	Afghanistan, Armenia, Azerbaijan, Bahrain, Bangladesh, Bhutan, Brunei, Cambodia, China, Cyprus, Georgia, India, Indonesia, Iran, Iraq, Israel, Japan, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Laos, Lebanon, Malaysia, Maldives, Mongolia, Myanmar, Burma, Nepal, Korea, Oman, Pakistan, Palestine, Philippines, Qatar, Russia, Saudi Arabia, Singapore, Sri Lanka, Syria, Taiwan, Province of China, Tajikistan, Thailand, Timor-Leste, Turkey, Turkmenistan, United Arab Emirates, Uzbekistan, Vietnam, Yemen
	Australasia	Australia, Tuvalu, Solomon Island, French Polynesia, Cocos Keeling Island, Wallis Futuna, Niue, Nauru, Fiji, Tonga, Pitcairn Island, New Zealand, Christmas Island, Vanuatu, Tokelau, Kiribati, Cook Island, Western Samoa, Papua New Guinea, New Caledonia
	Central and South America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
	North America	USA, Canada, Mexico, Greenland
	Europe	Albania, Andorra, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia, Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Kosovo, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Moldova, Monaco, Montenegro, the Netherlands, Macedonia, Norway, Poland, Portugal, Romania, Russia, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, UK, England, Scotland, Wales, Vatican
	Small Island States	Anguilla, Aruba, Antigua, Barbuda, Bahamas, Bahrain, Barbados, Bermuda, British Virgin Islands, Cayman Islands, Marianas, Belize, Comoros, Cuba, Dominica, Grenada, Guyana, Haiti, Jamaica, Saint Kitts, Nevis, Saint Lucia, Saint Vincent, Grenadines, Suriname, Trinidad, Tobago, Cabo Verde, Curacao, Comoros, Guinea, Maldives, Mauritius, São Tomé, Príncipe, Seychelles, Singapore, Cook Islands, Fiji, Kiribati, Marshall Islands, Micronesia, Nauru, Niue, Palau, Samoa, Solomon Islands, Seychelles, Timor, Tonga, Tuvalu, Vanuatu, French Polynesia, Guadeloupe, Guam, Martinique, Montserrat, New Caledonia, Puerto Rico, Saint Martin/Sint Maarten, Turks and Caicos, Virgin Islands
	Open field	Write country if country or sub-national level. If not applicable, write N/A
Which sectors/ systems are relevant to this document?	Terrestrial and freshwater ecosystems	Freshwater, lake, river, watershed, pond, wetland, stream, terrestrial, taiga, tundra, grasslands, forest, tropical, temperate
	Ocean and coastal ecosystems	Marine, mangrove, tidal, estuary, lagoon, reef, coral, sea, ocean, benthic, salt, coast
	Water and sanitation	Water, hydrology, basin, watershed, flood, drought, landslide, sanitation

Question	Codes	Definitions
	Food, fibre and other ecosystem products	Food, fibre, nutrition, medicine, aquaculture, fisheries, agroforestry, agroecology
	Cities, settlements, and key infrastructure	Cities, urban, infrastructure, industry, settlements
	Health, well-being and communities	Health, wellbeing, well-being, wellness, disease, illness, medicine, epidemics, vector, vectorborne, vector-borne, cardiovascular, respiratory, allergies, mental health, heat stress, psychosocial, nutrition, asthma, displacement, cultural integrity, migration, cultural heritage, identity, social capital, mobility, conflict, war
	Poverty, livelihoods and sustainable development	Poverty, livelihood, sustainable development, wealth, resilience, justice, equity, discrimination, conflict, diversification
Who is responding?		
Who is reported as engaging with the response activities reported in this document?	International or multinational governance institutions	Global or regional treaty body or agency (e.g., UN institutions/organisations, EU institutions, Organization of American States, African Union)
	Other	Other
	Government (national)	Countries officially recognised by the UN
	Government (sub-national)	Domestic, sub-national governing unit. Terms include state, province, territory, department, canton, Lander
	Government (local)	Terms include municipality, local government, community, urban, urban regions, rural
	Private sector (corporations)	Large national or international companies
	Private sector (SME)	Small and medium enterprises
	Civil society (international, multinational, national)	Voluntary civil society organisations. Includes charities, non-profits, faith-based organisations, professional organisations (e.g., labour unions, associations, federations), cultural groups, religious groups, sporting associations, advocacy groups (e.g., NGOs)
	Civil society (sub-national or local)	Formal community associations, including informal community networks
Is there evidence that particularly vulnerable groups were included in response planning? AND Is there evidence that particularly vulnerable groups were targeted in the responses?	Women	Minority status based on sex or gender expression (e.g., transgender)
	Youth	Individuals age 0–18
	Elderly	Individuals age 65 and over, also referred to as senior populations
	Low income	Individuals and/or groups from economically marginalised backgrounds. Lack access to basic services and experience episodes of periodic or ongoing resource scarcity. Includes homeless populations
	Disability	Individuals with persistent physical, sensory or cognitive disabilities
	Migrants	Place of origin, ancestry, cultural heritage. Refers to both to domestic migrants and individuals with an immigrant or undocumented status
	Indigenous	Self-identified Aboriginal groups, native peoples, First People and tribal groups
	Ethnic minority	Individuals and/or groups with a visible minority status
	Other	
What responses are documented?		
What category of adaptation is reported?	Behavioural/ cultural	Enabling, implementing or undertaking lifestyle and/ or behavioural change
	Ecosystem-based	Enhancing, protecting or promoting ecosystem services
	Institutional	Enhancing multi-level governance or institutional capabilities
	Technological/ infrastructure	Enabling, implementing or undertaking technological innovation or infrastructural development
What hazards is the response aimed at?	Sea level rise	Includes coastal flooding and storm surges
	No information or not assessed	
	Open field	If answered 'other', specify here. If not applicable, write N/A
	Open field	Copy relevant text here
	Extreme precipitation and inland flooding	
	Increased frequency and intensity of extreme heat	Includes urban heat island effect
	Precipitation variability	
	Drought	
	Rising ocean temperature and ocean acidification	Includes loss of coral cover
	Loss of Arctic sea ice	

Question	Codes	Definitions
	Other	Other
What types of implementation tools are reported?	Open field	What types of response tools/measures/mechanisms/instruments are reported as used? These might include, e.g., implementation of an adaptation strategy, an educational outreach programme; building infrastructure (e.g., a dam or flood control); ecosystem restoration; launching a local cooperative of fishers to change fishing behaviour; new regulation, policy or legislation (e.g., land use zoning, legal restrictions); subsidies or incentives for avoiding development in flood plains or undertaking less risky livelihood strategies; implementation of early warning systems; autonomous adaptations by households or individuals
What is the evidence base on effectiveness, adequacy and risk reduction associated with responses?		
What is the stated (or implied/assumed) link to reduction in risk?	Open field	Do the authors describe or justify why the particular response is expected to reduce risk (e.g., theory of change, assumptions about how the response might reduce risk)? If so, please describe. Note if your answer is based on the authors stating this, or if you had to infer this from the document. For example: 'Authors do not describe how the sanitation program will reduce risk due to climate change. It is inferred (and assumed) that an improved sanitation program will reduce exposure or vulnerability to the impacts of climate change on extreme events and precipitation variability.'
Is there any (implicit or explicit) evidence provided that responses reduced risk?	Yes	The change must be *documented* to respond 'yes' for this question. Anticipated or expected reduction is not sufficient for this question. Note that these do not need to be quantitative, but could involve theory of change, narrative justifications of change, or other
	No	
What maladaptations and co-benefits are reported?		
Do actors or institutions undertaking the response consider risks or mal-adaptation associated with the response?	Open field	Examples of risks or maladaptation include: (1) Unintended consequences, i.e., new or emerging risks are identified that might be created by the response activities; equity and justice, i.e., the potential for responses to create different or unequal distributions of risk is considered; (3) Limits to adaptation responses under more severe climate change, i.e., the potential for climate change to exceed the potential for the adaptation response is considered. If none, write 'None'
Do actors or institutions undertaking the response consider co-benefits?	Open field	The main focus of this question is about mitigation–adaptation co-benefits. Does adaptation have co-benefits for mitigation, or vice versa? If none, write 'None'
Evidence of transformational adaptation		

Question	Codes	Definitions
What *depth* of change for the responses reported in the document?	Open field	The depth of a response relates to the degree to which a change reflects something new, novel and different from existing norms and practices. A change that has limited depth would follow Business-As-Usual practices, with no real difference in the underlying values, assumptions and norms. This would include responses that are largely based on expansion of existing practices rather than consideration of entirely new practices. In-depth change, in contrast, might involve radically changing practices by altering frames, values, logics and assumptions underlying the system. This might involve deep structural reform, complete change in mindset by governments or populations, radical shifts in public perceptions or values, and changing institutional or behavioural norms
What is the *scope* of change for the responses reported in the document?	Open field	The scope of a response typically refers to the scale of change. A small scope might refer to local initiatives, or activities restricted to particular neighbourhoods, communities, groups or projects. Broad scope would refer to large-scale and system-wide changes that might involve an entire organisation, a country or large region, and large population. While changes of small scope might involve isolated efforts, broad scope might be multi-dimensional, multi-component and/or multi-level. Development of networks, inter-organisational coordination, and social relations within a response are more likely to lead to changes of broader scope
What is the *speed* of change for the responses reported in the document?	Open field	The speed of change refers to the dimension of time within which changes are happening. A slow or incremental change might include small changes in incremental steps, or a series of small shifts. Faster change might involve rapid jumps or what might be called 'transformative' changes in terms of relatively sudden shifts in views, perceptions, attitudes and norms
Does the document identify and describe constraints or *limits to adaptation*? Describe.	Open field	Constraints are defined as: 'factors that make it harder to plan and implement adaptation actions' (Klein et al., 2014, pg 923). Constraints can include: (1) Economic: existing livelihoods, economic structures and economic mobility; (2) Social/cultural: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice and social support; (3) Human capacity: individual, organisational and societal capabilities to set and achieve adaptation objectives over time, including training, education and skill development; (4) Governance, institutions and policy: existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity and absorption capacity; (5) Financial: lack of financial resources; (6) Information/awareness/technology: lack of awareness or access to information or technology; (7) Physical: presence of physical barriers; and (8) Biological: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events, including storms, drought and wind
Confidence in evidence		

Question	Codes	Definitions
Are methods sufficient to answer the research question?	Open field	Are there any major sources of bias in the data collection/analysis/interpretation of results, and are findings adequately and sufficiently substantiated by empirical data (qualitative or quantitative data)?
Did the article provide sufficient information to answer all of your coding questions?	Open field	Was there limited information or unclear evidence provided? Were there divergent results or outliers that made it hard to answer or that the authors seemed to ignore? Was the paper/document not directly relevant to the questions you were asking?
Please comment on the quantity and quality of data upon which findings in this article/document are based (e.g., sample size and/or depth of research).	Open field	This question will help us assess confidence in findings. We are less confident about a finding when the underlying data only come from a small number of participants, locations or settings, or in the case of case studies do not contain sufficient detail/richness to make a meaningful assessment
Are the results of this study relevant to a particular context only?	Open field	Are the results relevant only to a particular region, population or context? Describe the context within which these results are valid/relevant in the open field.

Missing data and outcome reporting bias: There is likely to be substantial reporting bias given that many activities that reduce vulnerability and risk are not reported or not labelled as adaptations, particularly in the case of autonomous responses to climate risks. Given the conceptual complexity of the adaptation literature, there are currently no feasible options to overcome this reporting bias at the global scale.

Assessment of confidence in evidence

Quality appraisal was undertaken on all documents/studies meeting inclusion criteria, and was part of the assessment of confidence in evidence. Critical appraisal was not used for article inclusion or exclusion since the GAMI review included literature with a range of methods. Appraisal was thus conducted to fulfil the requirements of assessment of confidence in evidence. The appraisal was guided by components of the GRADE-CerQual (https://www.cerqual.org/) approach to evaluating confidence in evidence for qualitative data. Quantitative data were not appraised or extracted. The following critical appraisal questions were included in the data extraction form:

i) **Are there any major methodological limitations?** For example, are methods sufficient to answer the research question, and are findings adequately and sufficiently substantiated by empirical data (qualitative or quantitative data)? Are there any major sources of bias in the data collection, analysis or interpretation of results? Comments on methodological limitations.
ii) **Assessing coherence: Did the article provide sufficient information to answer all of your coding questions?** Were there particular questions for which you felt that there was: (1) limited information or unclear evidence provided, (2) divergent results or outliers that made it hard to answer or that the authors seemed to ignore, or (3) the paper/document was not directly relevant to the questions you were asking? This question will help us assess confidence in findings. Please highlight any of your answers that may be less reliable compared with others.
iii) **Assessing adequacy: Please comment on the quantity and quality of data upon which the findings in this article/document are based** (e.g., sample size and/or depth of research). Did the article/document contain sufficient and adequate data (quantity and/or richness) for you to feel confident answering these questions? This question will help us assess confidence in findings. We are less confident about a finding when the underlying data only come from a small number of participants, locations or settings, or in the case of case studies do not contain sufficient detail/richness to make a meaningful assessment.
iv) **Assessing relevance: Are the results of this study relevant to a particular context only** (e.g., a particular region, population or context)? If so, describe the context within which these results are valid/relevant.

Quality assurance of coding

A quality assessment was undertaken for each coder to identify those who had missed entries or skipped significant questions within the SysRev data extraction platform. Sixteen key questions were identified that had closed-option responses and no logical conditions (i.e., were not answered only if a previous question were true). Any coder who left >10% of these key questions blank was asked to complete their codes. Response rates were calculated using R. The code is available on GitHub: doi.org/10.5281/zenodo.4010763. Any coder who was unable to complete their codes was deemed to have unreliable codes. To be included in the database, a document must have had at least one set of reliable codes. In cases where a document did not have at least one set of reliable codes, a third coder was sought.

All coders were contacted at the end of initial coding to ask them to ensure completeness of all codes and to flag key areas of potential error. This included, for example, avoiding blank entries that should instead be listed as 'not relevant' or 'no information'; ensuring that multiple relevant sectors and regions are recorded, regardless of project team; and avoiding exclusion of non-English language articles. Articles assigned to coders without relevant language abilities were re-assigned to another coder with appropriate language skills.

Reconciliation of double codes

Over 100 GAMI team researchers coded more than 2500 articles. In total, 482 articles were excluded (book chapters, not human adaptation, etc.). At least two individuals coded 2177 articles (the remaining 16 articles were coded by a single reliable coder). To consolidate multiple responses into a single entry for each article, a script in R was used, following a series of if/then statements. The full code and rationale are available on GitHub (doi.org/10.5281/zenodo.4010763). For open-ended questions that asked coders to provide quotes or evidence, all responses were compiled. For True/False questions, if either coder responded True, the answer was coded as True because these questions ask about the absence or presence of certain topics in each article, and it is more likely that one coder overlooked the presence of an item (gave a false negative) than that a coder imagined the presence of something not actually present (gave a false positive). For questions with multiple responses (e.g., hazards addressed), similar logic led us to take all responses because false negatives were more likely than false positives. In all cases, decisions were made to be conservative, that is, to overestimate the degree and amount of adaptation being documented. Reconciliation stages were systematically biased to include rather than exclude, so as to retain the most detail possible.

A final database was compiled with a single line entry for each article. Authors and title names were used to double-check for duplicates within the database (duplicate entries were merged). Articles were assigned to IPCC regions based on the countries identified during coding. In most cases, these aligned with the GAMI-assigned regions, but some island states, for example, were assigned to different regions, and a few errors in regional assignment were corrected. The final GAMI database contained 1682 articles and 70 columns (70 data points for each article).

Post-GAMI updates to database

For AR6, we extend the GAMI database to include articles cited in the Second Order Draft (SOD) of AR6 regional and sectoral chapters (Chapters 2–15) that meet inclusion criteria for the systematic review. Any article used as a citation for an explicit statement referencing an implemented or observed adaptation action was screened consistent with GAMI eligibility criteria. We included articles published from 2013 onwards. Eligible articles were coded and included in 16.3.1 assessment results.

Sectoral and regional stratification of assessment

For analyses, 14 region × sector combinations were created, as per WGII chapters. Each article was assigned to one or more sector × region. All subsequent analyses were stratified by these 14 region × sector combinations to generate results across regions and/or sectors. Articles relevant to more than one region or sector were considered in multiple analyses. That is, an article reporting on adaptation responses relevant to food and poverty in Africa and Asia would be included in any summary analyses of Africa × Food, Africa × Poverty, Asia × Food, and Asia × Poverty, as well as any sectoral or regional summary analyses for Africa, Asia, Food and Poverty.

Assessment of hazards, actors and adaptation types

Heat maps summarising the relative volume of literature on different hazards (Figure 16.3) were generated for each sector × region combination. Aggregate heat maps for each region and sector were created to summarise reporting on levels and types of actors engaged in adaptation responses (Figure 16.4). A radar graph was used to visualise the relative proportion of the assessed literature in each region reporting on different types of adaptation responses (technological/infrastructural, institutional, behavioural/cultural, nature-based). The heat maps and radar graph presented visualise the relative volume of literature reporting on adaptation, but do not necessarily represent the importance of adaptation trends or needs. The patterns are also based only on reporting in the scientific literature, and cannot be inferred to imply intensity of adaptation on the ground. The heat maps and radar graph do, however, provide a valuable visualisation of the relative evidence base in the peer-reviewed literature for adaptation responses by hazard, actor and adaptation type.

Methodology for assessment of evidence of transformational adaptation

Here, we summarise the methodological process used to assess evidence of transformational adaptation in global sectors and regions based on a systematic review of adaptation literature. Assessment of transformational adaptation was conducted within GAMI and is presented in Berrang-Ford et al. (2021). Results in 16.3.1 provide an update to this assessment by including additional SOD citations (as described above), plus inclusion of a formal assessment of confidence in evidence on transformational adaptation.

As the effects of climate change become increasingly apparent and severe, adaptation actions may need to shift from incremental responses to more transformative actions. Transformational adaptation is defined as adaptation that changes the fundamental attributes of a social–ecological system in anticipation of climate change and its impacts. The operational definition of transformational adaptation remains contested as it reflects a range of conceptual factors; a city might implement radical new policies which do not extend beyond its area, while an entire nation may undertake 'incremental' but persistent and widespread change. The term 'transformational' is not a one-dimensional scale, but rather a multi-dimensional scale integrating different aspects of change. The assessment used Termeer et al. (2017) conceptualisation of transformational change, consisting of three components from Termeer (scope, depth, speed) plus a fourth component: challenge to adaptation limits, the extent to which adaptation challenges or overcomes the limits that are known to constrain adaptation. These four components were used to conceptualise the multi-dimensional space within which adaptation responses can be more or less transformative.

Depth relates to the degree to which change reflects something new, novel and different from existing norms or practices. Scope refers to the scale of change—geographic or institutional. Speed of change refers to the dimension of time within which changes are happening. Challenge to adaptation limits reflects evidence that adaptation limits are being challenged or overcome. For each article in our database, evidence on the overall scope, depth, speed and challenge to limits reflected in the adaptation response(s) documented in that article were assessed. These assessments were then collated by global sector and region to assess overall evidence for each region and sector that adaptation responses were transformational in nature.

Operationalising assessment of transformational adaptation

Drawing on Termeer et al. (2017) and others, operational descriptions of *robust*, *medium* and *limited evidence* of transformational adaptation for each of the four components (depth, scope, speed, limits) were developed. Narrative evidence on depth, scope, speed and limits were available and coded in the GAMI database. A summary of descriptions for *robust*, *medium* and *limited evidence* of transformational adaptation is provided in Table SM16.6.

Table SM16.6 | Defining high, medium and low categories for evidence of transformational adaptation, based on depth, scope, speed and limits of adaptation.

Depth	*Question 4.4 in GAMI Protocol*
Depth relates to the degree to which change reflects something new, novel and different from existing norms or practices, and the extent to which actions offer potential to lead to positive systemic change. Incremental actions are taken to tackle the source of risk and reduce risk, while transformation goes beyond the source of risk, e.g., farmers seeking alternative livelihoods when farming is not feasible anymore in the face of drought.	
High	High depth (in-depth) change is more transformational: it might involve radically changing practices by altering frames, values, logics and assumptions underlying the system. This might involve deep structural reform, complete change in mindset, radical shifts in perceptions or values, and changing institutional or behavioural norms. Adaptation actions are increasingly radical (depth of change), including altering of values, re-framing of problems, and dramatic changes in practices.
Medium	Medium (moderate) depth describes incremental changes: a shift away from existing practices, norms or structures, but only to a limited degree. Perspectives, values and practices are changing to involve novel or more radical approaches (depth of change). Changes in risk perception may be medium depth.
Low	Low (limited) depth follows Business-As-Usual practices, with no real difference in underlying values, assumptions or norms. This includes practices that are largely expansions of existing practices. Adaptations largely are incremental by expanding existing practices, with *limited evidence* of novel change beyond Business-As-Usual practices (depth of change).
Scope	*Question 4.5 in GAMI Protocol*
Scope refers to the scale of change—geographic or institutional.	
High	High (broad, large) scope refers to large-scale and system-wide changes that involve an entire organisation, a country or large region, and large populations. Broad scope efforts may be multi-dimensional, multi-component and/or multi-level. Development of networks and inter-organisational coordination are more likely to lead to changes of broad scope. Adaptation is implemented at or very near its full potential across multiple dimensions. Adaptations are widespread and substantial, including most of the possible sectors, levels of governance and actors (e.g., nationally implemented legislation or policy), or reflect widespread changes in behaviour (scope of change). For example, this may include numerous cities or national-level changes, or institution-wide change. It may also address shifts in underlying norms and behaviours across entire populations.
Medium	Medium scope could describe multiple communities or households acting without coordination, a single sector taking action, or a small regional action. Adaptation is expanding and increasingly coordinated. There are growing efforts that exceed Business-As-Usual practices and challenge the fundamental attributes of the social–ecological system. There is some expansion and/or mainstreaming of change (scope of change) to include a wider region, or involvement of coordinated, multi-dimensional, multi-level adaptation.
Low	Low (small) scope might refer to local initiatives, activities taken by individuals or households. Adaptation is largely localised. There are primarily disjointed adaptation initiatives, with *limited evidence* of coordination or mainstreaming across sectors, jurisdictions or levels of governance (scope of change). This could be a single city or government department.
Speed	*Question 4.6 in GAMI Protocol*
Speed of change refers to the dimension of time within which changes are happening.	
High	High (fast) speed adaptation actions are either (a) those described as being fast for their type of action (e.g., building a bridge in a year might still be considered fast) or (b) those that can take place and see results within 1–3 years.
Medium	Medium (moderate) speed adaptations are those that occur or see results over 3–5 years. Adaptations are increasingly exceeding Business-As-Usual behavioural or institutional change to reflect accelerated adaptive responses (speed of change).
Low	Low (slow) speed adaptations are those that take 5 years or more to be executed or to see results. Adaptations are largely slow, consistent with existing behavioural or institutional change, and there is *limited evidence* of accelerated adaptive response (speed of change). Change is evident, but not rapid.
Limits	*Question 6.4.2 in GAMI Protocol*
Evidence that limits are being challenged or overcome.	
High	Soft limits are present (as identified in questions 6.1.1 and 6.2.1), and there is evidence that these soft limits are being overcome. (The occurrence of adaptation is not itself evidence that limits are being overcome.) Hard limits are being approached, if not overcome. Adaptations exceed soft limits and begin to approach hard limits. If no hard limits, exceed soft limits by a substantial margin.
Medium	Soft limits are present and are being addressed or challenged, but there is *limited evidence* that they are being overcome. Adaptations may overcome soft limits but do not challenge or approach hard limits.
Low	Limits are present and are a current or potential future limit on the level of adaptation possible. Adaptations may approach but do not exceed or substantively challenge soft limits.

Article-level assessment of transformational adaptation

Narrative data from the GAMI database on depth, scope, speed and limits were used to re-code each article based on the categories outlined in Table SM16.6. Each article was assigned as high, medium or low for each of the four dimensions of transformational adaptation. Examples of adaptation actions coded for the four components as high, medium and low, are presented in Table SM16.7.

Adaptation actions taken at the individual or household level were frequently high speed. For example, changes in crop timing or type produce results within a single year and were therefore considered high speed. Individual or household level actions could also be considered high depth if they were novel, and high speed if they (a) were broadly adopted by numerous individuals across a region, (b) were supported by government or non-government policies that enabled widespread adoption across a large geographic area, or (c) affected numerous sectors or aspects of life (e.g., not only crop yield but also water availability).

Table SM16.7. | Examples of high, medium and low depth, scope and speed.

Category	Action	Article
Depth		
High	Village relocated to high ground and built a new life	Ha'apio et al., 2018
High	Artificial glaciers provide irrigation, which changes numerous aspects of life: increased agriculture, herding, environmental benefits, green belt cover, increased tree plantations (changing the way they build), reduced conflict	Sudan et al., 2015
High	Diverse stakeholders create compensation programmes to protect water resources, resulting in changed perceptions and norms for governance and water use	Lindsay et al., 2018
Medium	People changed traditional livelihoods; ceased using subsistence practices and used a government programme to create a palm oil plantation to supplement with cash; migration with remittances; temporary migration to higher ground; transitioning from smallholder famer to non-farm jobs for cash	Pischke et al., 2018
Medium	Changes in gender norms and gender roles as women take on wage labour; may also be empowering women although increasing their burdens	Khan et al., 2018
Medium	Some Business-As-Usual actions (e.g., fishing for longer times), but also some more structural changes like shifting livelihoods, selling assets, mortgaging lands	Monwar et al., 2018
Low	Farmers use a new yam variety, use different mulch materials, use other seed types, use livestock manure, change their planting and harvesting dates	Oluwasusi et al., 2013
Low	Elevate homes in floodplains or make some structural changes to address hurricanes (e.g., storm shutters)	Javeline et al., 2019
Low	Using a fan, drinking more water, or turning on the air conditioning, wearing a sun visor or sunglasses, during a heatwave to deal with the heat	Zhaou et al., 2014
Scope		
High	Bangladesh Comprehensive Disaster Management Programme and National Adaptation Programme of Action along with other funds and plans described to address multiple sectors throughout the nation	Doelle et al., 2014
High	Mainstreaming climate change concerns into existing sectoral networks in North and South Carolina, USA; mobilising networks facilitated information dissemination and activities for specific interest groups and affects multiple sectors and spin-off projects	Dow et al., 2013
Medium	New forestry management approaches for Victoria, Australia, to assist with ecosystem health, conservation of water, and socioeconomic benefits across the region	Keenan et al., 2016
Medium	Development of informal farmer-led water management strategies and social rules and a government registration system for water rights in Kathmandu, Nepal	Shrestha et al., 2018
Medium	Government programme addressing farmers in a region of India	Adam et al., 2018
Low	Individuals stay indoors or avoid hot places during heatwaves; men and women respond differently; Leipzig, Germany	McCall et al., 2019
Low	Individual farmers take actions on their personal plots to avoid drought and flood; 390 interviews in two districts of northwest Cambodia	Touch et al., 2016
Speed		
High	Increased irrigation or an earlier crop planting date can increase yield in the same season, so adaptation is planned and executed, and results are seen within a single year	Jain et al., 2015
High	Water consumption patterns are changed in response to a drought (within a year or a few years if the drought is slow onset); planned and implemented, and results seen between 2007 and 2008	Dinares et al., 2015
Medium	Eco-districts can be planned and created, and results seen within a few years	Fitzgerald & Lenhart, 2015
Medium	A community-based financing mechanism has been established over 5 years	Archer, 2016
Low	A 10-year plan to relocate portions of the population	Lei et al., 2017
Low	Creation of forest reserve areas takes several years, or many years in some cases (4 years and 10 years are mentioned)	Hellin et al., 2018
Limits		
High		Theoretically overcoming hard limits; no examples of this
Medium	Creating alternative financial mechanisms that pool community resources, challenges the limits posed to the urban poor by financial constraints	Archer, 2016
Medium	Additional government funding overcame financial constraints	Ha'apio et al., 2018
Medium	Strategic efforts by Indigenous Peoples to overcome governance and institutional barriers	Maldonado et al., 2013
Medium	Government programmes to provide weather forecasts have overcome the lack of information that limited ability of farmers to adapt	Son et al., 20
Low	'Responses documented by donors and community level were not portrayed as reducing the perceptive, resource or institutional limitations for the long-term. Short-term structural initiative mentioned was maladaptive.' (from coder)	Betzold, 2015
Low	Absence of agricultural workers was noted to have made the situation worse (to not have overcome the barrier)	Ullah et al., 2019

Each article was assigned to one or more sector × region. For each region × sector combination, an overall score of low, medium or high was assigned to each of the four dimensions of transformational adaptation (depth, scope, speed, limits). This aggregate score reflects a conceptual average of the overall state of evidence of transformational adaptation within a region–sector. For example, there may be a small number of highly transformational adaptation examples in a particular region or sector, but if the overall profile of adaptations across all articles in our data set is low, then the aggregate score will be low. These scores thus reflect the overall profile for a sector–region of the extent to which evidence suggests that adaptation responses are transformational.

Table SM16.8 | Confidence assessments standards.

Level of agreement	
Level of agreement across the papers assessed (how many of the papers assessed agreed, e.g., what was the spread) Example: All studies provide evidence of autonomous adaptation. There is variation in the details of these processes, but no general disagreement over the generalised statement of evidence on this. Studies 67–70 additionally address the sufficiency of evolutionary adaptation. All studies indicate consensus that the pace of adaptations does not appear to be sufficient to keep pace with the rate of climate change.	
High	No or very minor concerns about the extent to which the underlying literature is consistent with your key statement; this could be assessed by number cut-offs but also requires judgement. For example, if a supermajority of studies agree to the answer (e.g., >70% of studies agree that adaptation is high depth, 20% medium, and 10% low)
Medium	Minor to moderate concerns about the extent to which the underlying literature is consistent with your key statement; this could be assessed by number cut-offs but also requires judgement. For example, if a majority of studies agree to the answer (e.g., 50% of studies agree that adaptation is high depth, 40% medium, 10% low); this could also include the case where the answers are split between two close answers (e.g., 45% high, 45% medium, 10% low)
Low	Moderate to serious concerns about the extent to which the underlying literature is consistent with your key statement; this could be assessed by number cut-offs but also requires judgement. For example, if studies are evenly split between the categories with no clear pattern (e.g., 33% high, 33% medium, 33% low); or categories are split bimodally (e.g., 45% high, 10% medium, 45% low)
Robustness	
Robust evidence considers the number of articles assessed, the type of articles, relevance of articles (e.g., do they address the question directly or is it inferred by coders) and adequacy of methods. *Types* of articles (all articles in the database are scientific peer-reviewed publications, so high). *Adequacy* of evidence relates to quantitative or qualitative volume of evidence base, and this is based on the richness of the information (e.g., is speed barely mentioned or discussed in depth). *Relevance* of the literature relates to the extent that the literature provides a range of contexts and reflects what I am really asking (e.g., can the papers in the Africa × Cities category really reflect the entire range of adaptation in African cities? Or do they only address East Africa, or mostly address Europe and mention Africa?). Database questions that can help with this assessment: Quotes for each question; Summary; Description of Response and Implementation Tools (Sections 3.1.1–3.2.2); Methods (Section 7.1); Adequacy (Section 7.2); Coherence (Section 7.3); Relevance (Section 7.4)	
Robust	No or very minor concerns about the extent to which the underlying literature is consistent with your key statement; you feel certain that there is good-quality evidence upon which to base the conclusions drawn; numerous articles provide an answer to the question; they address the issue directly (not inferred by coders) and have no methodological concerns (e.g., they have large sample sizes or detailed case studies)
Medium	Minor to moderate concerns about the extent to which the underlying literature is consistent with your key statement; you feel reasonably sure there is good evidence upon which to base the conclusions drawn; multiple articles provide an answer to the question; at least some of them address the issue directly; there are only a few studies with methodological concerns or the concerns are minor
Limited	Moderate to serious concerns about the extent to which the underlying literature is consistent with your key statement; you are not entirely certain that the evidence upon which conclusions are based is solid; only a few articles address this topic (must be more than five or we do not assess, and label this as 'Insufficient information'); They may not address the topic directly, or they may have methodological concerns (either concerns are frequent or severe or both)

Confidence		
How confident are we in our ultimate conclusion (e.g., that adaptation in African cities is occurring with limited depth)? This will be a combination of the level of agreement and robustness of the evidence provided.		
High agreement *Limited evidence* (e.g., *medium confidence*)	*High agreement* *Medium evidence* (e.g., *high confidence*)	*High agreement* *Robust evidence* (high) (e.g., *very high confidence*)
Medium agreement *Limited evidence* (e.g., *low confidence*)	*Medium agreement* *Medium evidence* (e.g., *medium confidence*)	*Medium agreement* *Robust evidence* (high) (e.g., *high confidence*)
Low agreement *Limited evidence* (e.g., *very low confidence*)	*Low agreement* *Medium evidence* (e.g., *low confidence*)	*Low agreement* *Robust evidence* (high) (e.g., *medium confidence*)

Assessing confidence in evidence

For AR6, we extended the analyses of transformational adaptation within GAMI to include formal assessment of confidence in evidence. This section describes the methods we used to add confidence levels to the assessment of transformational adaptation for each of the 14 sector–region combinations.

The volume of evidence to assess transformation adaptations varied between sectors and regions, and between dimensions of transformational adaptation. There was much more evidence to confidently code depth and scope, for example, than speed of adaptations. Evidence also varied in its quality and consistency. To assess confidence in the evidence underpinning our assessment, we used the IPCC's uncertainty framework, extended to integrate the GRADE-CERQual approach to assessing confidence in qualitative evidence. For each sector–region–dimension of adaptation, we conducted a formal confidence assessment, considering both level of agreement and robustness of evidence.

We developed a protocol to assess robustness of each dimension. For every article, we assigned four robustness scores: one each for depth, scope, speed and limits based on the quality of the paper and the relevance of the paper to the issue (e.g., how clearly and explicitly it addressed speed of adaptation). We discussed this protocol as a group and went over an example to ensure we all had a similar understanding of the criteria.

For each region–sector combination (n = 49), team members then filled out a summary table that provides the following information:

- Region and sector
- Variable (depth, scope, speed, limits)

- Ranking on evidence of transformational adaptation (high, medium, low)
- Number of papers that support the ranking (e.g., number of papers in Africa × Ocean combination that demonstrated high depth adaptation)
- Number of papers that assessed the variable in question (i.e., number of papers that actually addressed depth; often less than the total number of papers in that region × sector because some papers were unable to be assessed)
- % of papers assessed that support the ranking (divide number of papers support by number assessed)
- Citations (a list of author name, title and journal for all articles that, e.g., documented high-depth adaptation)
- Level of agreement (see Table SM16.8 for specifics, generally *high agreement* if a supermajority of papers assessed agreed on the ranking, medium if a majority agreed, and low if a general spread of responses); a justification for the agreement assessment
- Robustness ranking (*robust, medium, limited*) (see Table SM16.8 for specifics, draws on the robustness rankings for the given variable by article and also considers overall region × sector evidence); a justification for the agreement
- Overall confidence ranking (see Table SM16.9)

If fewer than five studies addressed the element in question (e.g., speed), either because there were too few papers in the region × sector (e.g., Central and South America, Oceans), or because many of the papers did not provide enough information to assess a given element, then the ranking in the final table was given as 'Insufficient information to assess'.

Level of agreement, robustness at the region–sector level, and overall confidence were assigned based on the criteria found in Table SM16.8. Our confidence assessment was informed by the GRADE-CERQual guidelines for assessment of confidence in qualitative evidence, adapted and simplified to align with the IPCC's uncertainty guidance language.

The ranking for each variable was collected in a table, along with the overall confidence ranking. An 'overall' evidence of transformation adaptation score for each region–sector combination was assessed based on the rankings for each element (depth, scope, speed, limits) and given a confidence assessment based on the confidence for each element. The four scores for ranking and four scores for confidence were compiled using the logic in Table SM16.9.

Table SM16.9 | Assessment of ranking and confidence

Overall high ranking/ confidence if there are:	Overall medium ranking/confidence if there are:	Overall low ranking/ confidence if there are:
4 high rankings/confidence	4 medium	4 low
3 high; 1 medium	1 high; 3 medium	1 high; 3 low
3 high; 1 low	3 medium; 1 low	1 medium; 3 low
2 high; 2 medium	2 medium; 2 low	
	2 high; 2 low	
	2 high; 1 medium; 1 low	

Thus, a region–sector that had medium depth, medium scope, low speed and low limits assessment with medium, high, low and medium robustness scores, respectively, would be assessed an overall medium level of evidence of transformational adaptation with *medium confidence*. *Very low confidence* or insufficient information assessments were treated as *low confidence* for purposes of assessing overall evidence of transformational adaptation.

A narrative description was added to each by selecting illustrative examples for each element within each region–sector. These examples are not necessarily representative of the category (especially for sectors with a large number of studies).

Methodology for assessment of co-benefits

Co-benefits are defined as benefits for other Sustainable Development Goal objectives derived from adaptation actions. Outcomes for risk and vulnerability reduction that achieve the intended benefits of adaptation actions are therefore not considered co-benefits, but rather the primary benefits of adaptation actions. Chapter 16 synthesised current evidence about the occurrence of co-benefits of implemented adaptation in different sectors and regions. The evidence was assessed in six stages:

1. Identification of peer-reviewed articles that describe co-benefits of implemented adaptation actions

Articles were identified from two sources: the Global Adaptation Mapping Initiative data set and content on co-benefits in the other AR6 chapters. Each article was analysed to identify the hazards and vulnerabilities being addressed through the adaptation action described in the study. Articles were only included in the co-benefits analysis where there were additional benefits described beyond the primary intended outcomes of the adaptation action. Articles that only described multiple benefits for those hazards or vulnerabilities targeted through the action were excluded because they only indicate that the action is achieving its intended adaptation outcomes, not necessarily that it is also achieving co-benefits. Of the 1957 articles initially reviewed, only 408 articles were retained for further analysis. A total of 158 articles met the criteria to be included in 16.3: they documented additional benefits for Sustainable Development Goals (SDGs) that go beyond the desired adaptation outcome and were observed for implemented adaptation responses.

2. Identification of the adaptation action that generates co-benefits

All 408 articles were reviewed to identify the adaptation action that is reported to generate co-benefits. The actions were recorded based on the description in the article, not according to a pre-determined set of adaptation categories. The specificity of the action therefore varies from the more general (e.g., climate-smart agriculture) to the specific (e.g., cover cropping). Where articles documented multiple adaptation actions, all actions were recorded.

The actions were then grouped into meta-categories for ease of analysis. The meta-categories were identified based on similarities between the different types of action. Table SM16.10a summarises adaptations with co-benefits that have *high confidence* (based on the assessment described in this protocol).

3. Identification of the co-benefit observed

In the next stage of the analysis, the specific type of co-benefit effect was coded. Again, the specific of the co-benefit varied from more general (e.g., mitigation) to more specific (e.g., carbon sequestration). Where articles documented multiple co-benefits, all co-benefits were recorded. The co-benefits were then grouped into meta-categories for ease of analysis. The meta-categories were identified based on similarities between the different types of co-benefits. Table SM16.10b summarises co-benefits that have *high confidence* (based on the assessment described in this protocol).

4. Assessment of the robustness of the evidence for co-benefits in each article

Each individual article was assessed for its adequacy of evidence on the link between the adaptation action and the specified co-benefit. Each article was assessed as having low, medium or high level of robustness:

- Low: Passing mention of a co-benefit
- Medium: Some theoretical discussion on assumed links or references to secondary sources about the existence of a co-benefit
- High: Primarily evidence that empirically demonstrates a co-benefit

Table SM16.10 | Meta-action and meta-benefit categories.
a) Meta-action categories.

Meta-action	Described actions	Article count
Agricultural practices	Climate-smart agriculture; Farming practices; Conservation agriculture; Agricultural land management practices; Crop diversification irrigation techniques; Conservation agriculture; Direct crop seeding; Agro-ecology; Sheep cross-breeding; Traditional farming practices; Soil conservation and farmland enhancements; Livestock and land sales; Urban and peri-urban agriculture and forestry; Silvopasture systems; Maple syrup production; Agrobiodiversity; Management intensive rotational grazing; Riparian buffer strips; Cover cropping; Climate-resilient agriculture; Conservation agriculture-based wheat production system (CAW); Local food production Livestock pasture management; Green winter fields; Buffer zones; System of rice intensification; Water loss reduction measures; Site-specific nutrient management strategies; Ratoon rice production; Sustainable fishing practices	63
Building technologies	Building efficiency standards; Cool roofs; Floating homes; Local building materials	8
Conservation	Conservation; Biodiversity conservation; Conservation areas; Farmer-managed natural regeneration; Land restoration	6
Ecosystem-based adaptation	Ecosystem-based adaptation; Ecosystem-based disaster risk reduction; Coastal flood protection infrastructure; Sustainable flood risk management; Stormwater management; Windbreaks	15
Grey infrastructure	Hydrodam construction; Redesigning transportation infrastructure; Infrastructure construction to reduce saltwater intrusion; Alternative energy sources for public health infrastructure (e.g., hospitals); Microhydro dams	9
Land use management	Agroforestry; Afforestation; Adaptive forest management; Community forest management; Forest management (tree trimming); REDD+; Traditional fire practices; Watershed management; Traditional land use management practices	43
Migration	Relocation	1
Social	Family planning; Universities as community hubs of climate change research; Capacity building	3
Urban planning and design	Urban greening; Strategic urban densification; Retention ponds; Construction of artificial lakes; Walkable neighbourhoods	16
Water management	Water management; Flood protection measures	5
Other	Cook stoves; Bioenergy production systems; LED lanterns	8

b) Meta-benefit categories.

Meta-benefit	Described co-benefits	Article count
Conservation	Ecosystem protection; Conservation; Reduced deforestation; Biodiversity protection; Habitat protection; Habitat creation; Marine ecosystem protection	30
Disaster risk reduction	Disaster risk reduction	3

Meta-benefit	Described co-benefits	Article count
Economic growth	Job creation; Economy; Increased land values; Economic development; Enhanced socioeconomic development	9
Energy security	Energy efficiency; Improved access to firewood, timber, fruit and fodder; Energy generation; Energy security; Fuel provision	7
Food security	Extended growing seasons; Reduced pest and disease problems; Food provision	7
Housing provision	Floating home construction	1
Livelihood security	Lower household expenditure pressures; Lower dependence on agriculture; Provision of local income	19
Mitigation	Mitigation; Carbon sequestration; Reduced fossil fuel use; Energy efficiency	126
Public health	Mental health and well-being; Air pollution reduction; General public health; Reduced urban heat island effect; Opportunities for recreation and exercise	16
Public realm	Local aesthetics and added beauty	4
Recreation/tourism/ cultural protection	Creation of recreational space; Tourism; Landscape aesthetics; Inspiration; Cultural, religious and emotion value; Ecotourism	15
Social capital & equity	Social awareness; Education; Creation of education centres; Social cohesion; Social integration; Social capital; Knowledge; Improved gender equity	13
Water management	Improved drinking water; Water quality; Water conservation; Water management	15

The number of articles with a medium or high level of robustness was counted for each meta-action/meta-benefit relationship. The median level of robustness was calculated for each meta-action/meta-benefit relationship (rounded down where necessary), which was then used as the summary assessment of evidence robustness for that co-benefit.

5. Assessment of the agreement of the evidence on co-benefits for each adaptation–co-benefit relationship

The level of article agreement was assessed based on whether the articles agreed on the co-benefit existed between a meta-action and meta-benefit. There is a high level of agreement in the articles assessed, though this is likely reflecting a reporting bias in the literature, where co-benefits will likely only be reported when they are positively substantiated.

Disagreements are qualitatively noted for the relationship between certain areas of land use management and mitigation:

- The paper suggests that watershed activities can have mitigation co-benefits, but these benefits are not empirically assessed in the developing country context. (Siraw, Degefu and Bewket 2018)
- 'Though agroforestry shows promise for co-delivery of adaptation (high biodiversity and resulting ecosystem services by diversified farming) to, and mitigation (carbon sequestration) of, climate change, there is a lack of hard evidence justifying this, particularly in the context of a developing country like Bangladesh.' (Rahman and Alam 2016)
- 'Local strategies for adaptation based on land-use changes result in co-benefits and tradeoffs at the global scale. Three of four land-use strategies increased local and regional benefits (more products and cleaner water), but also global benefits for climate mitigation (more carbon stocks). Such strategies met the converging interests of local and global stakeholders for solutions to climate change. However, local strategies can also result in trade-offs for carbon sequestration, as for conversion of forests to rubber plantations (L1), where interests of local people to strengthen livelihoods diverged from the global priority to reduce carbon emissions. Understanding the impact of local adaptation strategies on ecosystem services that can have benefits at the global scale, can help implement successful actions for climate change that account for different stakeholders' interests. International policy initiatives on climate change mitigation (e.g., REDD+, climate-smart agriculture) that consider local ecosystem benefits are more likely to be legitimate and long-lasting. At the same time, such initiatives should be aware of local adaptation strategies that might affect forests and carbon permanence (Fedele et al. 2018).

6. Overall confidence assessment

Overall confidence was only assessed where the meta-action/co-benefit had at least five articles (see example in Table SM16.11). Confidence statements were based on Table 16.8.

Table SM16.11 | Example of analysis and overall confidence assessment results

a) Meta-action/meta-benefit categories with high confidence

CONFIDENCE STATEMENT	Conservation	Disaster Risk Reduction	Economic growth	Energy security	Food security	Housing provision	Livelihood security	Mitigation	Public health	Public realm improvements	Recreation/ tourism/ cultural protection	Social Capital & equity	Water management
Agricultural practices								High confid.					
Building technologies								High confid.					
Conservation								High confid.					
Ecosystem-based adaptation (EBA)	High confid.							High confid.					
Grey infrastructure								High confid.					
Land use management	High confid.						High confid.	High confid.					High confid.
Migration													
Social													
Urban planning & design								High confid.	High confid.		High confid.		
Water management													
Other								High confid.					

b) Relationship of meta-action/meta-benefit categories to the Sustainable Development Goals (SDGs)

ONFIDENCE STATEMENT	Conservation (SDG15)	Disaster Risk Reduction (SDG11)	Economic growth (SDG8)	Energy security (SDG7)	Food security (SDG2)	Housing provision (SDG11)	Livelihood security (SDG1)	Mitigation (SDG13)	Public health (SDG3)	Public realm improvements (SDG11)	Recreation/tourism/ cultural protection (SDG8)	Social capital & equity (SDG5 & SDG10)	Water management (SDG15)
Agricultural practices								High confid.					
Building technologies								High confid.					
Conservation								High confid.					
Ecosystem-based adaptation (EBA)	High confid.							High confid.					
Grey infrastructure								High confid.					
Land use management	High confid.						High confid.	High confid.					High confid.
Migration													
Social													
Urban planning & design								High confid.	High confid.		High confid.		
Water management													
Other								High confid.					

c) Co-occurence in co-benefits corresponding to Sustainable Development Goals (SDGs)

Article count	No poverty	Zero hunger	Good health and well-being	Quality education	Gender equality	Clean water and sanitation	Affordable and clean energy	Decent work and economic growth	Industry, innovation, and infrastructure	Reduced inequalities	Sustainable eitles and communities	Responsible consumption and production	Climate action (mitigation)	Life below water	Life on land	Peace, justice, and strong institutions
No poverty																
Zero hunger	8															
Good health and well-being	1	4														
Quality education	2	1	1													
Gender equality	2	2														
Clean water and sanitation		1	1	1												
Affordable and clean energy	6	7	2	2	2											
Decent work and economic growth	4	2	4	1	1		2									
Industry, innovation, and infrastructure								1								
Reduced inequalities	4	4	2		2			3								
Sustainable cities and communities	3	5	14	2		1	3	5		2						
Responsible consumption and production																
Climate action (mitigation)	7	73	12	4	2	1	13	6		5	23					
Life below water																
Life on land	15	32	6	5	2	1	10	6		5	12		54			
Peace, justice, and strong institutions	1	1	1							1			1		1	

Methodology for assessment of maladaptation

The Fifth Assessment Report of the IPCC sees maladaptation as a cause of increasing concern to adaptation planners, where intervention in one location or sector could increase the vulnerability of another location or sector, or increase the vulnerability of the target group to future climate change. The definition of maladaptation changed subtly in AR5 to recognise that maladaptation arises not only from inadvertent badly planned adaptation actions, but also from deliberate decisions where wider considerations place greater emphasis on short-term outcomes ahead of longer-term threats, or that discount, or fail to consider, the full range of interactions arising from the planned actions. In a general sense, maladaptation refers to actions, or inaction, that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future.

Temporal, spatial and governance scales matter for the assessment of maladaptation. Maladaptation may become evident in the intermediate and long term but not in the short term. Some adaptations are effective at a local scale but maladaptive at a broader scale (e.g., for community, city, region). Hence, researchers assessing a project may not always have the empirical evidence for maladaptation but may infer this based on logical reason or experiences from other projects. As noted by Adger and Vincent (2005), certain adaptation may reduce risks over the short term yet cause an increase in exposure to risk in the long term. Adaptations that work with current and past variability and change may be maladaptive in the future. Maladaptation is usually an unintended consequence. Identifying maladaptive actions, process and outcomes is thus often difficult.

For this assessment, we used the GAMI database (with extended addition of articles from the SOD that met inclusion criteria). Using this database, we identified articles reporting evidence of maladaptation. We did not re-assess or critically appraisal the validity of the maladaptation claims, which would not have been practical or feasible. Using the GAMI database, we coded all articles based on their inclusion of evidence on maladaptation. Articles were coded within one of the following five categories:

A. Clear evidence of maladaptation
B. Maladaptation reported but not directly related to climate change
C. Theoretical link to maladaptation is mentioned or inferred by author or coder, but no clear evidence is provided
D. Maladaptation is reported in association with an adaptation

not implemented (typically due to a lack of follow-through with guidelines and practices for adaptation or other factors such as perceptions and political views about climate change, refusal to adapt, lack of funding)

E. No evidence of maladaptation

All results presented in Chapter 16 are based on analyses using articles classified as category 'A' only (clear evidence of maladaptation). We extracted relevant quotes, examples and details of evidence provided in each article on maladaptation. Based on key trends in these data, we inductively developed categories and sub-categories of dominant forms of observed maladaptation. Major categories included agricultural and forestry practices, fisheries and water management, built environment, and migration and relocation. We assembled examples and key citations for each category of maladaptation.

SM16.2 Section 16.4.1: Methodology for Assessing Limits and Constraints to Adaptation Across Regions and Sectors

To assess the vast literature on limits and constraints to adaptation across sectors and regions, we used the Global Adaptation Mapping Initiative database: https://osf.io/ps6xj/. This database of implemented adaptation reported in scientific literature consists of 1682 articles published between 2013 and 2019. Further details on the protocols used to identify and code these papers are found in Thomas et al. (2021).

Using the GAMI database as an input, we developed regional evidence packages. The papers that corresponded to each region were put into an Excel spreadsheet with different tabs for each of the sectors. This allowed for a focused assessment of how each coded paper responded to each region and sector combination.

We then followed the following steps:

SM16.2.1 Section 16.4.1.1: Determining Level of Evidence on Limits to Adaptation

Each coded paper was assigned a Relevance Score. Using the Evidence Package Excel spreadsheet, we assessed information in Column 6.2 Limits-Describe and Column 6.4.2 Approach-JUSTIFY. The Relevance Score was determined by assessing whether the article specifically discussed limits to particular adaptation responses using our framing of soft and hard limits. The following were the possible scores:

3 = Yes. The limits for a particular adaptation response(s) are clearly stated. Limit, threshold and tipping point are terms that are used explicitly referring to limits to adaptation. Information is provided on the level of socioeconomic or environmental change that would lead to limits being reached.

2 = Somewhat. There is discussion about constraints, barriers or impediments to adaptation that may lead at some point to adaptation limits. Limits to adaptation are discussed in a general sense. The article does discuss that constraints will lead to limits.

1 = No. There is no discussion of limits, thresholds or tipping points. There is discussion of constraints, barriers or impediments to adaptation, but none of these issues is directly related to limits to adaptation being reached at some point. Note that some articles use the words limit or limitation but are referring to constraints. Some of the coders may have made the connection between constraints identified in the article and potential limits. However, the quotes from the article itself must have made this connection.

For each region and sector combination, we assigned an evidence value:

Limited evidence: <20% of total number of studies for that region/sector have a Relevance Score of 3

Medium evidence: 20–40% of total number of studies for that region/sector have a Relevance Score of 3

Robust evidence: >40% of total number of studies for that region/sector have a Relevance Score of 3

SM16.2.2 Section 16.4.1.2: Determining Constraints by Region and Sector

We then categorised the constraints identified in each article. Using each regional Evidence Package Excel spreadsheet, we assessed information in Column 6.2 Limits-Describe and Column 6.4.2 Approach-JUSTIFY. We placed an 'x' in the appropriate constraints column that corresponded to the constraints identified in the paper, using our categories of constraints.

We determined the total number and percentage of articles for each region/sector that identified the different constraints. We assigned each constraint a value:

Insufficient data: there is not enough literature to support an assessment (fewer than five studies available)

Minor constraint: <20% of assessed literature identifies this constraint

Secondary constraint: 20–50% of assessed literature identifies this constraint

Primary constraint: >50% of assessed literature identifies this constraint

SM16.3 Section 16.5.2: Method for the Identification of Representative Key Risks (RKRs)

SM16.3.1 Section 16.5.2.1: Method Description

The method for identifying RKRs is ultimately based on the expert judgement of Chapter 16 authors, informed by the identification of underlying KRs by WGII chapter authors, a quantitative mapping of KRs to potential RKR categories by chapter 16 authors, and consideration of broader criteria including representativeness, overlap across RKRs, and value added to key risk assessments in the sectoral and regional chapters. It also builds on the process used to identify the RKRs in the First Order Draft (prepared in October 2019), where Chapter 16 identified a set of 10 RKRs intended to reflect both the key risk clusters identified in the AR5 and the range of initial KRs identified by the AR6 WGII chapters. The FOD RKR list was reviewed as part of the formal IPCC Review process as well as discussed (formal and informal discussions) with chapters during the WGII 3rd Lead Author Meeting (January 2020). Based on updated chapters' KRs (mid-February 2020), the identification of the final RKR list involved three main steps:

- Eight Chapter 16 authors conducted a quantitative mapping of the full list of KRs to potential RKRs, also providing qualitative comments on possible RKR definitions (end-February 2020). This exercise was important not only for the mapping itself, but also to familiarise authors with the full span of KRs under consideration.
- Two Chapter 16 Lead Authors synthesised the results and put together an initial proposal for a revised set of RKRs (late February 2020). Chapter 16 authors discussed the proposal, which led to a further revision of the proposed list of RKRs, agreed to by the chapter team (early March 2020).
- The Chapter 16 proposal was then discussed with the Consultative group (i.e., people from other WGII chapters closely involved in the KR–RKR process, list below) (early March 2020). Based on this discussion, the final RKR list was decided (mid-March 2020).

List of Consultative group members: Richard Betts, Rachel Bezner Kerr, Martina Caretta, Richard Dawson, Jackie Dawson, Simon Donner, Toshihiro Hasegawa, Kirstin Holsman, Katherine Mach, Timon McPhearson, Veruska Muccione, Aditi Mukerjee, Steve Rose, Daniela Schmidt.

Main Chapter 16 authors involved: Halvard Buhaug, Matthias Garschagen, Alexandre Magnan, Guy Midgley, Alisher Mirzabaev, Brian O'Neill, Maarten van Aalst.

SM16.3.2 Section 16.5.2.2: Results

Summary of mapping method: Each assessor mapped the full list of 122 KRs to the 8 AR5 and 10 AR6 FOD RKRs and were also free to propose (and map to) new RKRs. The following scoring system has been used: 1 for 'some fit' between a KR and an RKR, 2 for 'moderate to good fit', 3 for 'very good fit' and NA when 'not enough expertise to judge'. A guidance sheet was provided to allow for a consistent assessment approach among the assessors. For example, assessors were to rely on what was expressed in the KR description by the original WGII chapter, and not on the assessor's own estimation of potential indirect consequences of a given KR, and a given KR could fit with several RKRs.

SM16.4 Section 16.5.2: Guideline for RKR Assessments and for the Cross-RKR Synthesis

SM16.4.1 Section 16.5.2.1: RKR Team Members

A total of 47 authors contributed to the RKR assessments (Table SM16.12).

Table SM16.12 | Section 16.5.2.1: RKR team members. A total of 50 authors contributed to the RKR assessments.

Surname, name (in bold, leads)	Country	RKR							
		A	B	C	D	E	F	G	H
DONNER Simon	Canada	▨							
DUVAT Virginie	France	▨							
FORD James	UK	▨							
GARSCHAGEN Matthias	Germany	▨							
MAGNAN Alexandre	France	▨							
SPENCER Tom	UK	▨							
WABNITZ Colette	Canada	▨							
STEVENS Nicola	South Africa		▨						
GONZALEZ Patrick	USA		▨						
MIDGLEY Guy	South Africa		▨						
MAHARAJ Shobha	Trinidad and Tobago		▨						
VALE Mariana	Brazil		▨						
PRICE Jeff	UK		▨						
OMETTO Jean	Brazil		▨						
DAWSON Richard	UK			▨					
DIAZ Delavane	USA			▨					
GARSCHAGEN Matthias	Germany			▨					
ROZENBERG Julie	USA			▨					
VAN AALST Maarten	The Netherlands			▨					
BUHAUG Halvard	Norway				▨				
CARLETON Tamma	USA				▨				
CAVANAGH Connor	Norway				▨				
HALIM Sharina	Malaysia				▨				
HALLEGATTE Stéphane	France				▨				
JAFINO Bramka	Indonesia				▨				
O'NEILL Brian	USA				▨				
PINHO Patricia	Brazil				▨				
CISSE Gueladio	Mauritania/ Switzerland/ France					▨			
HESS Jeremy	USA					▨			
LEVY Karen	USA					▨			
O'NEILL Brian	USA					▨			
ROCKLÖV Joacim	Sweden					▨			
VICEDO CABRERA Ana	Spain					▨			
PRADHAN Prajal	Nepal						▨		
WREFORD Anita	New Zealand						▨		
HASEGAWA Toshihiro	Japan						▨		
BEZNER KERR Rachel	USA						▨		
MIRZABAEV Alisher	Uzbekistan						▨		
BETTS Richard	UK							▨	
BEZNER KERR Rachel	USA							▨	
CARETTA Martina	USA							▨	

Surname, name (in bold, leads)	Country	RKR							
		A	B	C	D	E	F	G	H
CISSE Gueladio	Mauritania/ Switzerland/ France							▨	
GURNEY-SMITH Helen	Canada							▨	
LISSNER Tabea	Germany							▨	
McLEMAN Robert	Canada							▨	
MUKHERJI Aditi	India							▨	
VAN ALAST Maarten	The Netherlands							▨	
BUHAUG Halvard	Norway								▨
GEMENNE Francois	Belgium								▨
HENDRIX Cullen	USA								▨
SINGH Chandni	India								▨

SM16.4.2 Section 16.5.3.2: General Guidelines

- **Clearly define what criteria and metrics you use to define ‘severe’** for your RKR. To improve consistency across RKRs, **use the key risk criteria** defined in Chapter 16 (listed below). The revised definition should identify which of these criteria were most important to defining severe outcomes for the **most prominent key risks that compose your RKR**. The ‘severity’ table in the template for draft 2 is proposed as a supporting tool for accomplishing this task.
    1. Importance of the affected system or dimension of the system
    2. Magnitude of adverse consequences (judgement based on *pervasiveness and degree of change, as well as, depending on the cases: irreversibility of consequences, potential for impact thresholds or tipping points, and potential for effects beyond system boundaries)*
    3. Likelihood of adverse consequences
    4. Timing of the risk
    5. Ability to respond to the risk

For any criteria you use, define the quantitative or qualitative metric(s) you employ for judging severity. For example, number of projected additional deaths due to climate change could be the metric used for the magnitude of a health impact, and some threshold might be used to indicate a severe outcome.

- **Focus on conditions under which your RKR could become severe.** In general, RKRs early drafts (May 2020) tended to describe a broad range of projected impacts rather than focusing on severe outcomes and the conditions under which they occur. Projected impacts should be limited to those characterising severe outcomes, and illustrating the conditions under which they occur (which we call here ‘severity conditions’). The analysis of a wider range of future risk levels is the focus of the burning embers exercise (Section 16.6).

Chapter 16 suggests that RKR teams (Table SM16.12) identify and assess severe outcomes and the conditions under which they occur using the five steps below.

- **Address the potential for complex risks.** In many RKRs, the most severe potential outcomes could result from interactions among or co-occurrences of individual key risks, which together challenge the capacity of the system to cope or adapt. Make sure to consider this possibility to the extent that the literature allows.
- **Consider a wide range of latitudes and ecological and human/development contexts.** About half of the RKR early drafts (May 2020) tended to focus on severe outcomes for developing countries, but did not say anything on the potential for severe outcomes in developed countries. It is important, when relevant of course, to consider all the settings in which severe risks are possible, although with differences in magnitude, timing and likelihood of adverse consequences, or adaptive capacity (you recognise the above-mentioned key risk criteria). Do not hesitate to use contrasting real-world examples well covered in the literature.
- **Account for risks that may be severe in more limited contexts.** RKR assessments should pay attention to avoiding giving the impression that, when risks are local and do not concern a huge number of people, they are not ‘key’ or ‘severe’ or ‘representative of dangerous interference with the climate system’. This involves specifying ‘severe risks to whom’. This point relates to several issues, including justice and the avoidance of westernised value judgements. That does not mean that global-scale quantitative thresholds, for example, are not useful for some RKRs or as one type of measure of severity, but risks that are severe in a more limited context should also be identified and assessed.
- **Focus on risks due to climate change, not absolute levels of risk.** The IPCC risk definition, and the definition of key risks, specifies that risks are those that are due to climate change or responses to climate change. In an absolute sense, risks are driven by climate and non-climate-related drivers, but our task is to assess the change in risk due to climate change. The effect of climate change will itself depend on non-climate conditions (exposure, vulnerability, adaptive capacity), and that can and should be taken into account (e.g., climate impacts on food security will depend on assumed underlying societal conditions). In addition, some measures of the severity of climate risks might involve comparison with absolute risk metrics (e.g., does climate change cause people to fall below an absolute poverty line?). But our outcome of interest is always the effect of climate change on risks, not on absolute risk levels.
- When you describe **future climate hazard conditions** based on the literature, please draw on, and cite where relevant, **AR6 WGI Chapter 12** (Ranasinghe et al., 2021). Chapter 12 indeed develops an assessment specifically designed for supporting WGII, and Chapter 16 in particular. It provides recently updated information on a wide set of projected climate hazards for all regions.

Five main steps to identify and assess severe outcomes and conditions for your RKR:

Step 1. Identify the **most prominent key risks** that are, according to your team, the main ones within your RKR with the potential to become severe. For example, for RKR (*D*) on Living Standards: livelihoods (key risk 1), aggregated economic outcomes (key risk 2), and equity (key risk 3). The number of risks is up to each RKR, but due to space limitations it is unlikely to be possible to treat more than three in sufficient detail.
Step 2. Use the 'severity conditions' table in the Draft 2 template (SM16.5.3.3) to identify which criteria are important to judging the severity of each key risk, and to help you organise the assessment.
Step 3. As much as possible, identify for each most prominent key risk a **set of risk drivers** that you will use to concretely discuss the conditions under which each key risk will contribute to the severity of the RKR (see the top row of the 'severity conditions' table in the Draft 2 template, SM16.5.3.3). Combining a set of risk drivers will help **highlight the cumulative and/or compounding and/or cascading effects underlying each risk component, and explaining why some current/future trends could lead to severity**. For example, for RKR (A) on coasts: climate impacts on coastal ecosystems (driver 1) will combine, partly through implications on ecosystem services such as coastal protection, with trends in settlements in flood-prone areas (driver 2) and deficiencies in coastal risk reduction policies (driver 3) to explain why flooding-related risk to human settlement (e.g., key risk 1) can become severe under all or a given sea level change scenario (driver 4).
Step 4. Organise the **assessment of severe outcomes and conditions** by each key risk in turn (one paragraph each), and structure it around the extent to which the combination of risk drivers illustrates the relevant risk criteria identified for this component in the severity table. Due to space limitations, you could decide to focus only on the criterion you estimate is the most influential one, or decide to include several or all of the criteria you identified.
Step 5. At the end, a final paragraph of your assessment will bring together the main conclusions of your assessment of severity conditions per underlying key risk, and assess the potential (if relevant) for severe outcomes due to the interactions among the prominent underlying key risks of this RKR.

SM16.4.3 Section 16.5.2.3: Template and Guidance for RKR Assessment

Briefing Notes

Introduction

This section will describe the purpose of the risk literature assessment. An introductory paragraph **defines the scope** (which most prominent key risks will this RKR focus on) and **identifies links with chapters** that reported related key risks and with previous IPCC reports

Criteria

This section will ask experts to consider the criteria and metrics for risk levels, for example, define what **'severe'** means in your context (i.e., which criteria, which metrics)

Assessment guidance

This section will provide guidance for the assessment. It is an **assessment of severe outcomes and conditions under which they occur related to key risks 1, 2 and 3** (one separate paragraph per risk). Typically, a paragraph explains why/how the RKR key risk considered could become severe and brings evidence using critical impacts projections (i.e., impact outcomes focused on severe outcomes, not ranges of possible outcomes in general).

Conclusion

A concluding paragraph develops a **synthesis** highlighting the potential for severe outcomes due to the interactions among the prominent underlying key risks of this RKR.

References

Provide the details (IPCC format) of all the references you use.

SM16.4.4 Section 16.5.2.4: Guidance for Cross-RKR Synthesis Figure (Figure 16.10)

Here below are the guidance developed to design Figure 16.10 in the main chapter. The background material for the development of Figure 16.10 is available in Table SM16.14.

General idea: develop a synthesis figure to gather the assessments of severity conditions across the eight RKRs, based on the work already done (no additional assessment expected). Basically, each RKR would summarise the assessment text in a few sets of severity conditions (combinations of warming/exposure–vulnerability/adaptation + low/medium/high), as illustrated in the mock-up figure (mock-up at that moment, now Figure 16.10 in the main chapter). Basically, the work consists of having team exchanges within your RKR team to identify some sets of severity conditions (bubble trios) that are described in your textual assessment and then fulfil the following table (Excel file format, now Table SM16.14 below).

Guidance:

- Most of the points below will be specified as bullet points in a specific panel within the figure, to guide readers and avoid misinterpretations (e.g., in terms of comparability across RKRs);
- The basic idea is to **attribute a level** (High–Medium–Low) to warming, exposure/vulnerability and adaptation conditions. For adaptation, and given the fact that literature is often thin on this element, please only use High–Low to simplify things. Except for warming (see below), the definition of these levels critically

Table SM16.13 | Template for RKR draft 2. RKR title. Severity: The table is mainly used to, first, help you define and assess severity conditions across the main key risks of your RKR and, second, to enhance consistency across RKRs assessments. Note that not all criteria similarly apply to all key risks; it is up to your team to decide which one(s) to involve depending on the specific risk (see examples in comment bubbles).

Key risk criteria	Set of risk drivers 1	Set of risk drivers 2	Set of risk drivers 3
	RKR prominent underlying key risk 1	RKR prominent underlying key risk 2	RKR prominent underlying key risk 3
(1) Importance of the affected system or dimension of the system	*No need to mark this one*		
(2) Magnitude of adverse consequences	X	X	
(3) Likelihood of adverse consequences	X		
(4) Timing of the risk		X	X
(5) Ability to respond to the risk	X	X	
	The cross-‘X’ analysis serves to describe the conditions under which RKR key risk 1 could become severe	The cross-‘X’ analysis serves to describe the conditions under which RKR key risk 2 could become severe	The cross-‘X’ analysis serves to describe the conditions under which RKR key risk 3 could become severe

depends on your RKR context and how you framed this in your discussions over the last 3 years and in your final text. So, it is important to understand here that severity condition levels are relative to other levels within a RKR but are not necessarily meaningful across the RKRs; we do not intend in this figure to harmonise H–M–L definitions across the RKR. The figure legend warns against such comparisons, and panel B will be explicit on that point. Note that there is also a column (column I) in the synthesis table (excel sheet) that asks for precision, if available in the RKR assessment text, on any specific temperature level a given set of conditions refers to;

- Keep in mind that the idea here is just to **provide a summary understanding of your assessments**, not to develop another one or enter too much complexity. So, as much as possible, do not enter too much into new questions raised by this exercise (methodological, but also maybe conceptual; broadly applicable conditions versus specific circumstances; etc.);
- Time horizon: the teams agreed to try reporting in the synthesis table on risk conditions **in mid-century (~2050) and end-century (~2100)**, and possibly on risks that are already considered severe. Column J in the synthesis table helps you report on the time horizon associated with a given set of severity conditions (present-day, mid-century, end-century). We will then see which information to display and how, given the figure is already quite busy;
- **Generic versus specific conditions**: most of the RKR teams highlight various sets of severity conditions depending on whether the global scale or specific areas/sectors/groups of population are considered, that is, broadly applicable versus specific. We need to report on this granularity. In the figure, we will use stars to distinguish between broadly applicable (one star) and specific (two stars) set(s) of severity conditions. Specific contexts cannot be explained in the figure, but they are in the RKR texts.
- For **warming condition levels**: given that we consider the end of the century, High refers to RCP8.5 (~4.4°C GMST), Low to RCP2.6 (~1.6°C GMST) and Medium to intermediary climate scenarios;
- **Exposure and vulnerability condition levels**: level definition will depend on the way you framed this in your RKR, but should reflect conditions by the end of this century. These levels need to be meaningful at the level of your RKR (along with text) but not necessarily across all RKRs (variable definitions);
- **Adaptation condition levels**: the choice has been made here to stick to a simple approach distinguishing High (i.e., at/near maximum potential) and Low (i.e., continuation of today’s trends) adaptation. These levels need to be meaningful at the level of your RKR (along with text) but not necessarily across all RKRs (variable definitions);
- **Confidence level**: as reported in your text; High (H), Medium (M), Low (L);
- **Traceability**: it is critical that we ensure the sets of severity conditions are derived from the RKR assessment texts. That is why it is important to fulfil the ‘traceability’ column of the table above, along with each set of conditions.

Table SM16.14 | Background information for Figure 16.10. Key guidance to RKR team in order to fulfil this table: (A) Fulfil the cells with Low (L), Medium (M) or High (H), based on what you developed in the assessment text. Comparability across RKR raises as a critical issue here, so please refer to the guidance below on how to interpret L–M–H levels for warming, exposure/vulnerability, and adaptation. (B) Sets of conditions: captures conditions that, in combination, make for severe risk, not just any condition. There is no standard number of sets of conditions; it is up to the team to decide how many makes sense. For each set of conditions, RKR teams provide the sentences in the text, specifying when possible (C), (EV) and (A) when referring to the climate, exposure–vulnerability and adaptation scenarios.

	Sets of severity conditions	Warming	Vulnerability and exposure	Effective adaptation	Confidence level (as in your RKR text)	Broadly applicable versus specific (G for broadly applicable, S for specific)	Traceability (cf. key sentences in RKR assessment text)
RKR-A (Risk to low-lying coasts)	**1**	H	H	Not fully assessed	M	G	(C, EV, A) 'Severe risks generally occur at the nexus of high levels and rates of anthropogenic-driven change in climate hazards (16.2.3.2), concentrations of people and things that societies value such as physical and intangible assets, non-climate hazards such as sediment mining and ecosystem degradation (3.4.2.1), and the reaching of adaptation limits (16.4) (*medium evidence*, *high agreement*).' **AND** 'Consequently, the combination of high warming, continued coastal development and low adaptation levels will challenge the habitability of many low-lying coastal communities in both developing and developed countries over the course of this century (*limited evidence*, *high agreement*)'
	2	L	H	H	H	S	(C, EV) 'In some Arctic communities and in communities reliant on warm-water coral reefs, even 1.5–2°C warming will lead to severe risks from loss of habitat and ecosystem services (3.4.2.2; CCP6) (*high confidence*)' **AND** "In some contexts, (…) even lower warming will induce severe risks to habitability, which will not necessarily be offset by ambitious adaptation (*limited evidence*, *medium agreement*)" (A) 'In some contexts (…) even lower warming will induce severe risks to habitability, which will not necessarily be offset by ambitious adaptation (*limited evidence*, *medium agreement*)' **AND** about the example of atoll islands: 'habitability transitions from Moderate-to-High under RCP2.6 for most island types (urban and rural) to High to Very High under RCP8.5, even under a high adaptation scenario, due to declining sediment supply, increased annual flooding, and other drivers.'
	3	L	H	L	M	S	(C) Refers to 'already severe' and therefore to warming as of today, here considered in the 'Low warming' category. (EV) 'In some contexts, climate risks are already considered severe (*medium evidence*, *medium agreement*)' **AND** 'Catastrophic examples that may foreshadow the future include Hurricane Sandy in 2012 (Strauss and al. 2021) and super Typhoon Haiyan in 2013 (>6,000 deaths and inequities in access to safe housing) (6.2.2, 6.3.5.1)' **AND** 'Some of the largest fish-producing and fish-dependent ecoregions have already experienced losses of up to 35% in marine fisheries productivity due to warming.' **AND** 'Critical transport infrastructure is already suffering from structural failures in polar regions, for instance, due to permafrost thaw and increased erosion associated with ocean warming, storm surge flooding and loss of sea ice' **AND** 'While difficult to measure, current climate-driven losses to (Indigenous) knowledge, traditions and well-being, indicate such risk as already severe in some regions (*limited evidence*, *medium agreement*), jeopardising communities' realisation of their rights to food, health and culture. In the Arctic, climate-driven changes to ice and weather regimes have substantially affected traditional coastal-based hunting and fishing activities, and where permafrost thaw, SLR and coastal erosion are contributing to threatening cultural sites'. (A) As for (C), 'Low adaptation' category is used to describe adaptation efforts as for today
RKR-B (Risk to terrestrial and marine ecosystems)	**1**	M	H	L	M	G	(C) 'Ten percent of biodiversity globally at risk of extinction, abrupt impacts like local biodiversity loss (10% at risk of extinction) and mass population mortality events, and ecological disruption due to novel species interactions, are all projected at global warming levels below 4°C, with insular systems and biodiversity hotspots at risk below 3°C (*medium confidence*).' (EV) ? (A) 'Adaptation potential for many of these risks is low due to the projected rate and magnitude of change, and to the requirement of significant amounts of land for terrestrial ecosystems'

	Sets of severity condi-tions	Warming	Vulnera bility and exposure	Effective adapta-tion	Confidence level (as in your RKR text)	Broadly applicable versus specific (G for broadly applicable, S for specific)	Traceability (cf. key sentences in RKR assessment text)
	2	L	H	L	H	G	(C) Already observed mass population-level mortality (>50% of individuals or colonies killed) and resulting abrupt ecological changes can be caused by simple or compound climate extreme events, such as exceedance of upper thermal limits by vulnerable terrestrial species, marine heatwaves that can cause mortality, enhance invasive alien species establishment, and damage coastal ecological communities and small-scale fisheries (*high confidence*)
	3	L	H	L	M	G	(C) Ecological disruption (order-of-magnitude increases or abrupt reductions of population numbers or biomass) due to potentially multiple novel inter-species interactions with unpredictable outcomes as species shift their geographic ranges in response to climatic drivers, exacerbated by introduced invasive species (*medium confidence*)
	4	M	H	M	H	G	(C) Landscape- and larger-scale shifts in ecosystem structure and function (order-of-magnitude increases or abrupt decreases in cover and/or biomass of novel growth forms or functional types) are very likely to occur in non-equilibrium ecosystems (systems which exist in multiple states, often disturbance-controlled) in response to changing disturbance regime, climate and rising CO_2 (*high confidence*)
	5	L	H	L	H	G	(C) Already observed increased frequency and extent of single and compound disturbances such as storm surges, wildfires, droughts and insect infestations, threatening populations dependent on habitat availability, with abrupt ecological changes more widespread and increasing in frequency (*high confidence*)
RKR-C (Risk to critical infrastructure)	**1**	H	M	L	H	G	Risks related to direct impacts on critical infrastructure would become severe with high warming, current infrastructure development regimes and minimal adaptation (*high confidence*), with severity defined as infrastructure damage and required maintenance costs exceeding multiple times the current levels
	2	M	M	L	M	S	Risks related to direct impacts on critical infrastructure would become severe […] in some contexts even with low warming, current vulnerability and no additional adaptation (*medium confidence*), with severity defined as infrastructure damage and required maintenance costs exceeding multiple times the current levels
RKR-D (Risk of aggregate economic impacts)	**1**	H	Not fully assessed	L	M	G	'Risks to aggregate economic output would become severe at the global scale with high warming and minimal adaptation (*medium confidence*)'
	2	H	H	L	M	S	'Annual economic output losses in developing countries could exceed the worst country-level losses during historical economic recessions (*medium confidence*)'
RKR-D (Risk of increased poverty)	**1**	M	H	L	M	G	'Under medium warming pathways, climate change risks to poverty would become severe if vulnerability is high and adaptation is low (*limited evidence, high agreement*).'
RKR-D (Risk of loss livelihoods)	**1**	H	H	L	M	G	'More widespread severe risks would occur at higher levels of warming (with high exposure/vulnerability and low adaptation) where there is additional potential for one or more social or ecological tipping points to be triggered, and for severe impacts on livelihoods to cascade from relatively more climate-sensitive to relatively less climate-sensitive sectors and regions (*medium confidence*).'
	2	L	H	L	H	S	'Climate change poses severe risks to livelihoods at low levels of warming, high exposure/vulnerability, and low adaptation in climate-sensitive regions, ecosystems, and economic sectors (*high confidence*), where severity refers to the disruption of livelihoods for tens to hundreds of millions of additional people.'

	Sets of severity condi-tions	Warming	Vulnera bility and exposure	Effective adapta-tion	Confidence level (as in your RKR text)	Broadly applicable versus specific (G for broadly applicable, S for specific)	Traceability (cf. key sentences in RKR assessment text)
RKR-E (Risk from heat-related mortality)	**1** – global heat-related mortality	H	H	Not fully assessed	H	G	(C, EV) 'Risks of heat-related mortality would become severe at global and regional scales with high levels of warming and vulnerability (*high confidence*).'
RKR-E (Risk from vector-borne diseases)	**1** – global burden of vector-borne disease	H	H	Not fully assessed	M	S (children and sensitive regions)	(C, EV) 'Risks of vector-borne disease would become severe with high warming and current vulnerability, concentrated in children and in sensitive regions (*medium confidence*).'
RKR-E (Risk from water borne diseases)	**1** – regional risk for diarrhoea	Not fully assessed	H	L	M	S (children and sensitive regions)	'Climate change would lead to severe risks of morbidity and mortality caused by water-borne diseases, particularly for diarrhoea in children in many lower- and middle-income countries (LMICs) and where vulnerability remains high (*medium confidence*).'
RKR-F (Risk to food security)	**1**	H	H	L	H	G	(C) 'Climate change will pose severe risks in terms of increasing the number of undernourished people, affecting tens to hundreds of million people under high vulnerability and high emission scenarios, particularly among low-income populations in developing countries' (EV) 'Under high vulnerability-high warming scenario (i.e., SSP 3-RCP 6.0), up to 183 million additional people are projected to become undernourished in low income countries due to climate change by 2050. Climate-related changes in food availability and diet quality are estimated to result in crude mortality rate of about 54 deaths per million people with about 2°C warming by 2050 (SSP2, RCP8.5), most of them projected to occur in South and East Asia (67–231 deaths per million depending on the country)' (A) 'The inclusion of adaptation measures into modelling estimates remains selective and arbitrary.'
	2	H	H	L	H	G	(C) 'Climate change risks of micronutrient deficiency will become severe in high vulnerability development pathways and in the absence of societal adaptation, leading to hundreds of millions of additional people lacking key nutrients for atmospheric CO_2 levels above 500 ppm' (EV). 'The decline in zinc content is projected to lead to additional 150–220 million people being affected by zinc deficiency with increasing existing deficiencies in more than 1 billion people (Myers et al., 2017). Similarly, decrease in protein and micronutrient content in rice due to a higher CO_2 concentration (568 to 590 ppm) can lead to 600 million people with rice as a staple at risk of micronutrient deficiency by 2050 (Zhu et al., 2018). Additionally, the impact on protein content of increased CO2 concentration (>500 ppm) can lead an additional 150 million people with protein deficiency by 2050 (within the total of 1.4 bln people with protein deficiency) in comparison to the scenario without increased CO_2 concentration'. (A) 'The inclusion of adaptation measures into modelling estimates remains selective and arbitrary.'
	3	H	L	L	M	G	(C, EV) 'Previously SRCCL indicated that under a low vulnerability development pathway (SSP 1), climate change starts posing a moderate risk to food security above 1°C of global warming, while beyond 2.5°C the risk becomes high' (A) 'The inclusion of adaptation measures into modelling estimates remains selective and arbitrary.' Line of site for the confidence level is SRCCL.
	4	H	M	L	L	G	(C, EV) 'In a medium vulnerability-high warming scenario (SSP2, RCP6.0), Hasegawa et al. (2018) projects that the number of undernourished people increases by 24 million in 2050, compared to outcomes without climate change and accounting for the CO_2-fertilization effect.' (A) 'with appropriate socioeconomic and policy responses, the negative impacts of climate change on food security can be minimized'

	Sets of severity condi-tions	Warming	Vulnera bility and exposure	Effective adapta-tion	Confidence level (as in your RKR text)	Broadly applicable versus specific (G for broadly applicable, S for specific)	Traceability (cf. key sentences in RKR as-sessment text)
RKR-G (Risk of water scarcity)	**1**	L	M	H	H	G	(C) 'We define a severe outcome as more than 1 billion people experiencing "chronic" water scarcity, defined as the availability of less than 1000 m^3 of freshwater per person per year. For example, the global number of people experiencing chronic water scarcity is projected to be approximately 800 million to 3 billion for 2°C warming…' (EV) Severe outcomes are projected to occur even with no changes in exposure: present-day exposure is defined here as 'medium' since either an increase or decrease in exposure could be possible. Vulnerability is not quantified in the literature assessed here, so in this assessment it is considered that severe outcomes could occur with present-day levels of vulnerability, again defined here as 'medium'. (A) 'The avoidance of these consequences at high levels of water scarcity would require transformational adaptations including large-scale interventions such as dams and water transfer infrastructure. Since these require many years or even decades for planning and construction, and are also costly and irreversible and can potentially lead to lock-in and maladaptation, the potential for inadequate policy decisions made in the context of high uncertainties in regional climate changes brings the risk of a shortfall in adaptation.'
RKR-G (Risk from water-related extreme events and disasters)	**1**	L	M	M	H	G	(C) '… we define severe outcomes as more than 100 million people affected by flooding. At 2°C global warming, between approximately 50 million and 150 million people are projected to be affected by flooding, with figures rising to 110 million to 330 million at 4°C global warming.' (EV) 'These projections assume present-day population and no additional adaptation, so no changes in exposure. Many of these consequences depend on the vulnerability of individuals, households or communities, e.g. through the presence or absence of measures to safeguard health and livelihoods, such as through infrastructure services, insurance or community support.' (A) 'Other consequences of floods that already occur include deaths by drowning, loss of access to freshwater, vector-borne diseases, mental health impacts, loss of livelihoods, loss of or damage to property, so the risks associated with these could increase if there were no local adaptations to counter the effect of increased levels of hazard by reducing exposure and/or vulnerability.'
RKR-G (Risks to cultural uses of water)	**1**	L	H	H	M	S	(G/S) 'severe outcomes would be defined locally rather than globally.' (C, EV) 'Communities that lost a dominant environmental characteristic deeply associated with its cultural identity would be considered to be severely impacted. For example, due to the central role that travel on sea ice plays in the life of Inuit communities, providing freedom and mental well-being, loss of sea ice can be argued to represent environmental dispossession of these communities. Similarly, changes in streamflow affecting the availability of species for traditional hunting can also negatively impact Indigenous communities. Such changes are already being seen at current levels of warming. Reduced snow cover is projected in mid-to-high latitudes and high mountain regions with *robust evidence* and *high agreement*, with spring snow cover equivalent projected to decline by approximately 4% yr^{-1} over the 21st century, and mass loss in individual glacier regions is projected to be between approximately 30% and 100% by 2100 under high scenarios. Stream flows are projected to change in most major river basins worldwide by several tens of percent at 4°C global warming.' (A) 'Traditional ways of life are therefore threatened and resulting changes would be transformative rather than adaptive.'
RKR-H (Armed conflicts)	**1**	H	H	L	L	G	'global warming of 4°C would produce severe risks to peace under present societal conditions (*low confidence*)'

	Sets of severity condi-tions	Warming	Vulnera bility and exposure	Effective adapta-tion	Confidence level (as in your RKR text)	Broadly applicable versus specific (G for broadly applicable, S for specific)	Traceability (cf. key sentences in RKR assessment text)
RKR-H (Involuntary mobility)	**1**	L	H	L	M	G	'Such risks can become severe even with limited levels of warming under low adaptation among populations whose settlements and livelihoods are critically sensitive to environmental conditions (*medium evidence*, *high agreement*)'
	2	M	H	L	H	S	'There is *high agreement* that even moderate levels of future SLR will severely amplify involuntary migration and displacement in small islands and densely populated low-lying coastal areas in the absence of appropriate adaptive responses (*high confidence*)'
	3	M	H	L	M	S	'risk of involuntary immobility could become severe for highly vulnerable populations with limited resources even under moderate levels of warming (*limited evidence*, *high agreement*)'

Table SM16.15 | Benchmark comparisons for various health outcomes of interest. This table supports Representative Key Risk E, Risk to Human Health, Section 16.5.2.3.5. Metrics are shown for various health outcomes, which can be used to help understand the potential for severe health risks associated with climate change. Increased morbidity and mortality associated with climate change for any of the health outcomes discussed in the text will unlikely ever present as severe a risk as represented by the annual global burden of, for example, cancer, but with only small increases over baseline could quickly become severe for certain sub-populations. Examples are shown for sub-groups of the four health outcomes discussed in the text for which severe risk of climate change would and would not be a concern. All values based on data for 2019 from the Institute for Health Metrics and Evaluation (IHME) (http://ghdx.healthdata.org/gbd-results-tool), with the exception of data for COVID-19, values which were taken from Our World in Data through April 2021 (https://ourworldindata.org/coronavirus).

	Annual crude mortality rate (CMR) per 10,000	Annual incidence per 10,000	Annual number of deaths
Comparator health outcomes			
Disasters (related to natural hazards)[a]	0.01	0.24	6076
Traffic accidents[b]	1.56	133.4	1,198,289
COVID	3.81	94.5	2,970,000
Cancer[c]	13.03	394.3	10,079,637
All causes	73.06	–	56,526,959
Health outcomes discussed in the text (baseline rates, not taking into account anticipated changes in morbidity and mortality associated with future climatic changes)			
	Crude mortality rate per 10,000	Incidence per 10,000	Deaths
Environmental heat	0.06	9.7	47,460
All ages, WHO EURO Region	0.20	–	18,553
All ages, WHO PAHO Region	0.02	–	2211
Malaria	0.83	299	643,381
<1-year-olds in WHO AFRO Region	37.49	–	130,823
<1-year-olds in WHO EURO Region	0.00	–	0
Dengue	0.05	73.5	36,055
<1-year-olds in WHO SEARO Region	0.68	–	2192
<1-year-olds in WHO EURO Region	0.00	–	0
Diarrhoea	1.98	8506	1,534,443
<1-year-olds in WHO AFRO Region	53.05	–	185,188
<1-year-olds in WHO EURO Region	0.99	–	1031

Notes:

(a) IHME Cause: C.2.10. Exposure to forces of nature

(b) IHME Cause: C.1. Transport injuries

(c) IHME Cause: B.1. Neoplasms

SM16.5 Section 16.6.1: Development of Figure 16.12

SM16.5.1 Section 16.6.1 Relationship of the Representative Key Risks to the Sustainable Development Goals, Data Source for Development of Figure 16.12

Figure 16.12 is developed from WGI AR6 Chapter 12, Tables 12.3–12.9 (Ranasinghe et al., 2021), the Sustainable Development Report 2021 (Sachs et al., 2021) and text analysis of RKR literature to the 247 indicators, targets and goals of the Sustainable Development Goals (SDGs) (UNSD, 2020; A/RES/71/313, E/CN.3/2020/2) (Table SM16.16).

The text evaluated comprises abstracts, summaries and keywords from some 950 documents identified by the RKR teams. These are matched to words or synonyms based on the indicators, targets and goals of each SDG. The keywords used for each SDG indicator, the documents analysed and the text used are deposited in Mendeley Data, V1 (Ibrahim et al., 2021a). Linkages are identified from keyword extraction and analysis for each of the SDG indicators. A table of average standardised counts of keywords is generated for each SDG. Strength of linkages are evaluated based on the relative number of counts for the respective RKR literature category. This approach has the advantage of efficiency, objectivity and quantitative assessment of the RKR body of literature. A value of 1 means that all documents contain at least one keyword related to the targets and indicators of the respective SDG. Linkages are categorised as 'Some' for values of greater than 0 to <0.2, 'Moderate' for values of 0.2 to <0.4 and 'Strong' for values of 0.4 and greater. Nevertheless, some drawbacks anticipated are that synergistic interactions between key risks will not be accounted for, nor will reinforcing or disconsonant interactions between SDGs be considered. Cascading and compounding effects would also be beyond the capability of the analysis. As a verification of the results of the text analysis approach, the final text under each of the RKRs (from Section 16.5) is assessed for linkages with the SDG keywords. A comparison of results is made, and the information is used to check for any issues in the selection of SDG keywords used as well as to assess the content of the text of the literature assessed. The results (Table SM16.16) are used to develop Figure 16.12 panel d.

Table SM16.16 | Results of SDG keyword analysis from documents relevant to the Representative Key Risks (RKRs).

Goal	RKR SDG	RKR-A Coastal	RKR-B Terres-trial	RKR-C Infra-structure	RKR-D Living standards	RKR-E Human health	RKR-F Food	RKR-G Water	RKR-H Peace, human mobility	Number of strong linkages (≥0.4)
1	No poverty	0.43	0.22	0.37	0.76	0.26	0.38	0.41	0.41	4
2	Zero hunger	0.42	0.37	0.36	0.67	0.27	0.92	0.40	0.45	5
3	Good health and well-being	0.26	0.15	0.24	0.30	0.64	0.19	0.45	0.12	2
4	Quality education	0.13	0.12	0.13	0.29	0.13	0.12	0.20	0.26	0
5	Gender equality	0.27	0.14	0.24	0.41	0.14	0.24	0.26	0.27	1
6	Clean water and sanitation	0.34	0.23	0.35	0.24	0.10	0.28	0.63	0.23	1
7	Affordable and clean energy	0.14	0.04	0.40	0.07	0.03	0.06	0.10	0.04	1
8	Decent work and economic growth	0.46	0.16	0.41	0.61	0.25	0.47	0.47	0.51	6
9	Industry, innovation and infrastructure	0.32	0.10	0.90	0.23	0.16	0.15	0.19	0.15	1
10	Reduced inequalities	0.15	0.03	0.10	0.33	0.05	0.14	0.16	0.27	0
11	Sustainable cities and communities	0.46	0.27	0.59	0.62	0.39	0.40	0.57	0.46	5
12	Responsible consumption and production	0.12	0.05	0.13	0.23	0.11	0.20	0.18	0.10	0
13	Climate action	0.80	0.87	0.86	0.92	0.93	0.95	0.75	0.78	8
14	Life below water	0.65	0.52	0.27	0.32	0.66	0.41	0.60	0.27	5
15	Life on land	0.26	0.65	0.07	0.23	0.08	0.16	0.13	0.06	1
16	Peace, justice and strong institutions	0.11	0.00	0.11	0.16	0.03	0.10	0.14	0.44	1
17	Partnerships for the goals	0.08	0.06	0.14	0.23	0.07	0.15	0.16	0.13	0
	Number of strong linkages (≥0.4)	6	3	5	6	3	4	8	6	
	Number of at least moderate linkages (≥0.2)	11	7	11	15	7	9	10	11	
	Total sum of linkages	5.42	3.98	5.66	6.62	4.32	5.31	5.80	4.96	
	Rank[a]	3	7	4	2	6	5	1	4	

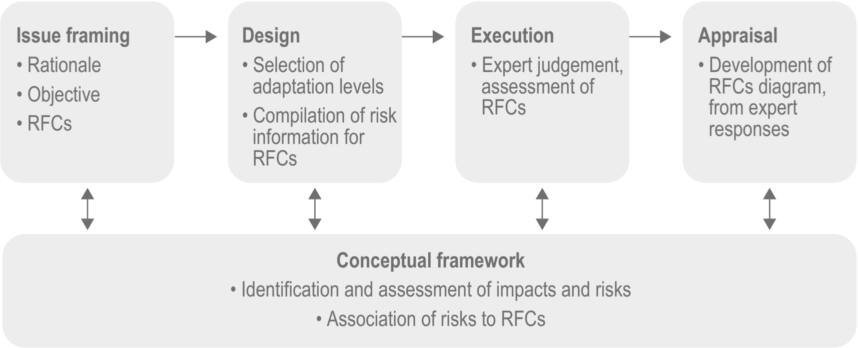
Note:
(a) Rank is based on the number of Strong linkage category; if tied, then number of Moderate category; if tied, then on total sum of linkages.

SM16.6 Section 16.6.2: Evaluation of Risk Accrual to the Reasons for Concern with Global Warming

SM16.6.1 Section 16.6.2: Methodology for Assessing RFC Burning Embers by Expert Elicitation

The framework for the expert elicitation process is presented here together with information on the materials and the final results used to produce the risk transition ember diagrams. Table SM16.17 presents the framework for the elicitation process following the phases for expert judgement for health risk impact assessment identified by Briggs (2008) and Knol (2010). The first phase is represented by the conceptual framework (Section 16.6.2). Issue framing relates to hazards, impacts and the key risks and their relation to the Reasons for Concern. Design comprises selection of experts, materials and preparation of information, and the elicitation structure, including the tables used for the elicitation. Execution comprises the elicitation process itself. Appraisal comprises the analysis of responses and the development of the visual representation of expert assessment using the final tabulated results.

Table SM16.17 | Framework for expert elicitation for the Reasons for Concern.

Phases of the Protocol	We explain the framework for the expert elicitation conducted to evaluate and update the Reasons for Concern. The phases of the protocol broadly follow four phases: (i) issue framing, (ii) design, (iii) execution and (iv) appraisal, underlain by the conceptual framework of the assessment. (Figure SM16.1). The main phases for expert judgement in impact assessment  **Figure SM16.1 | The main phases for expert judgement in impact assessment (after Knol, 2010 and Briggs, 2008).**
Issue Framing	Rationale The 'burning embers' figure, and the broader Reasons for Concern framework, was first developed during the IPCC's Third Assessment Report (TAR) (Smith et al., 2001) and has since been included in subsequent IPCC assessments, including the 2014 Summary for Policymakers (SPM) of the Fifth Assessment Report (AR5) (O'Neill et al., 2017) and the 2018 Special Report on Global Warming of 1.5 °C (SR1.5) (IPCC, 2018). From TAR to AR5, including the SR1.5, this process has been based on a literature review of estimated impacts at different global mean surface temperature levels (O'Neill et al. 2017), integrated with expert judgement. Recent applications of this risk assessment process (SRCCL [IPCC, 2019a], SROCC [IPCC, 2019b]) have focused on improving the transparency, reliability and replicability of the methodology.
	Objective The 'burning embers' figure illustrates scientific assessment of risks from climate change to society as a function of global temperature change, exposure and vulnerability of people and ecosystems. Diagrams indicate transitions between undetected, moderate, high and very high risks to humans and ecosystems through changes in colours.
Design	We follow and modify the procedure followed in the SRCCL, Chapter 7 and Supplementary Material (Hurlbert et al., 2019a; Hurlbert et al., 2019b), for developing the risk assessment and synthesis. The modification comprises a pre-briefing session prior to formal start of the elicitation, based on the experiences of the SRCCL team who had conducted the elicitation process. Elicitation methodology Expert elicitation processes are commonly used in situations when the state of knowledge is not yet sufficient to support informed near-term decision making, including well-established systematic methods used in the medical sciences. The Delphi method is a well-known technique of expert elicitation commonly used in medical sciences to develop research priorities, clinical practice and reporting guidelines, and quality indicators, among other uses. It provides a structured, systematic approach for experts to independently and anonymously state their judgements, and then to iteratively modify them based on other experts' views. The point of departure is the methodology applied in the IPCC Special Report on Climate Change and Land (SRCCL) (Zommers et al., 2020), which conducted a formal expert elicitation protocol, based on the modified Delphi technique (Mukherjee et al., 2015) and the Sheffield Elicitation Framework (Oakley and O'Hagan, 2010; Gosling, 2018). For this report, a similar protocol was developed to identify expert judgement on risk transition thresholds. Input into the development of the elicitation process and pilots were provided by Zinta Zommers, Mark Howden, Sean Grant, Katherine Mach and experts from RKR-B and RKR-H.

Facilitation team and selection of experts

The Facilitation team was Rachel Warren, Zelina Z. Ibrahim and Rhosanna Jenkins.

Teams were allocated to each RFC, consisting of five to seven members of the author team of IPCC AR6 and subject matter experts. The list of experts who participated as respondents or facilitation team subject experts during the elicitation process are listed below.

RFC1

Guy F. Midgley (Lead), Chapter 16 (South Africa); Shobha Maharaj, Chapter 15 and CCP Biodiversity Hotspots (Germany/Trinidad and Tobago), Nicola Stevens, Chapter 2 and CCP Deserts, Semiarid Areas, and Desertification (South Africa); Mariana M. Vale, Chapter 12 (Brazil); Jeff Price, Chapter 2 and CCP Biodiversity Hotspots (UK); Jean P. Ometto, Chapter 12 and CCP Tropical Forests (Brazil); David Obura, Chapter 16 (Kenya); Christopher Trisos, Chapter 9 (South Africa); Camille Parmesan, Chapter 2 (UK/USA); Rachel Warren, Chapter 16 (UK)

RFC2

Sonia Seneviratne (Lead), WGI Chapter 11 (Switzerland); Kristie Ebi, Chapter 16 (USA); Friederike Otto, WGI Chapter 11 (UK/Germany); Xuebin Zhang, WGI Chapter 11 (Canada); Alex C. Ruane, WGI Chapter 12 (USA)

RFC3

Rachel Warren (Lead), Chapter 16 (UK); Alisher Mirzabaev, Chapter 16 (Uzbekistan/Germany); Marco Springmann, Chapter 16 (UK); Maria Cristina Tirado, Chapter 7 and CCP Deserts, Semiarid Areas, and Desertification (Spain/USA); Rachel Bezner Kerr, Chapter 5 (USA); Richard A. Betts, WG I Chapter 11 (UK); Toshihiro Hasegawa, Chapter 5 (Japan)

RFC4

Delavane Diaz (Lead), Chapter 16 (USA); Franziska Piontek, WGIII Chapter 3 (Germany); Guy F. Midgley, Chapter 16 (South Africa); Steven Rose, WGII Chapter 18 (USA); Rachel Warren, Chapter 16 (UK)

RFC5

Chris D. Jones, WGI Chapter 4 (UK); Francois Engelbrecht, WGI Chapter 4 (South Africa); Gerhard Krinner, WGI Chapter 9 (France); Helene Hewitt, WGI Chapter 9 (UK); Richard Betts, WGI Chapter 11 (UK); Sybren S. Drijfhout, WGI Chapter 9 (the Netherlands)

Materials and preparation

To strengthen the rigour of developing expert consensus on risk transitions (Hasson and Keeney, 2011), the protocol pre-specified the following prior to beginning the elicitation exercise (Grant et al., 2018): the research question, eligibility criteria and strategy to recruit experts, research materials, data collection procedure and analysis plan.

We prepared briefing materials on the elicitation process to provide to experts, comprising a brief introduction to the method, description of the elicitation questions, video and voiced-over slideshows, and examples of the elicitation question form and rationale for judgements.

Before the formal start of the elicitation, in the first part of the briefing meeting, experts are introduced to the elicitation approach and terms and definitions used to develop common understanding. Participants in the expert elicitation process are presented with a briefing package explaining the process. Videos and slideshows are made available. Definitions of risk, vulnerability and adaptation are provided together with a glossary of relevant terms. Experts are reminded of the IPCC uncertainty guidance on evaluating level of confidence. The elicitation questions are discussed with experts.

We provide the experts with relevant background information—typically evidence informing parameters similar to the quantity to be elicited ('indirect evidence') (Figure SM16.2). Most studies focus on changes in hazards as a function of climate change, while some focus on changes in risk as a function of both RCPs and SSPs (climate and socioeconomic change and adaptation decisions). Experts are invited to share additional literature for use in the assessment exercise. The observed impacts (from Section 16.2) and identified Representative Key Risks (from Section 16.5), together with information about adaptation (from Section 16.3 and 4), form the basis for evaluation of the Reasons for Concern (RFCs). Experts also receive definitions of key risk criteria, levels of risk and a tabulation of literature cited in IPCC AR6 chapters, but will also bring their own unique knowledge and expertise into the process. A full description of these adaptation levels, characterised by scope, depth and speed of change, plus limits, is discussed in Section 16.3.

For a full definition of adaptation levels, see Table SM16.18a. Note that many modelling studies refer to Shared Socioeconomic Pathways (SSPs); although these do not explicitly indicate adaptation levels, they do communicate the level of challenge to adaptation that exists and, hence, can usefully inform the assessment.

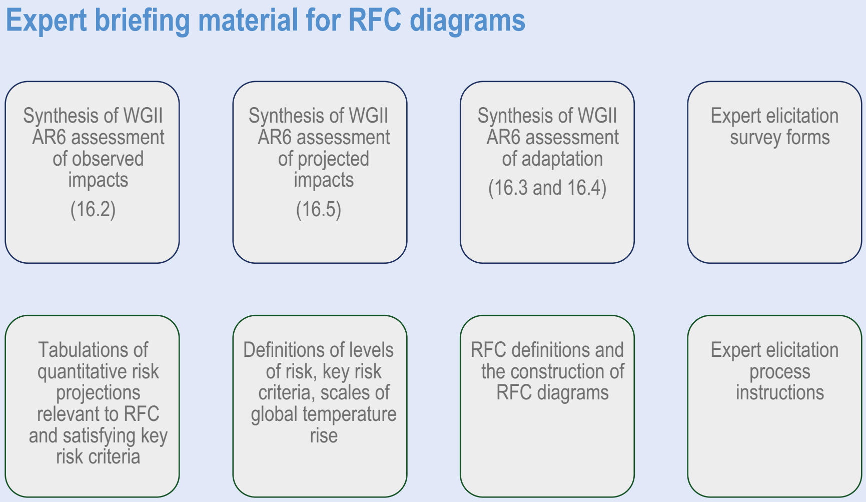

Expert briefing material for RFC diagrams

Figure SM16.2 | Material used for the development of RFC diagrams in AR6, and shared with experts participating in the elicitation process.

Although summary information of observed impacts from 16.2 and RKR assessments from 16.5 are provided, experts are also expected to draw upon their wider knowledge of the literature. Experts are requested to include any additional literature for consideration and to inform the elicitation team to ensure that the correct GSAT values are used. The association of literature with precise levels of GSAT in the tables has been carried out by the Chapter 16 team, to ensure that this is done consistently across the WGII Report.

The final list of literature used by experts for the assessment is deposited in Mendeley Data, V1 (Ibrahim et al., 2021b).

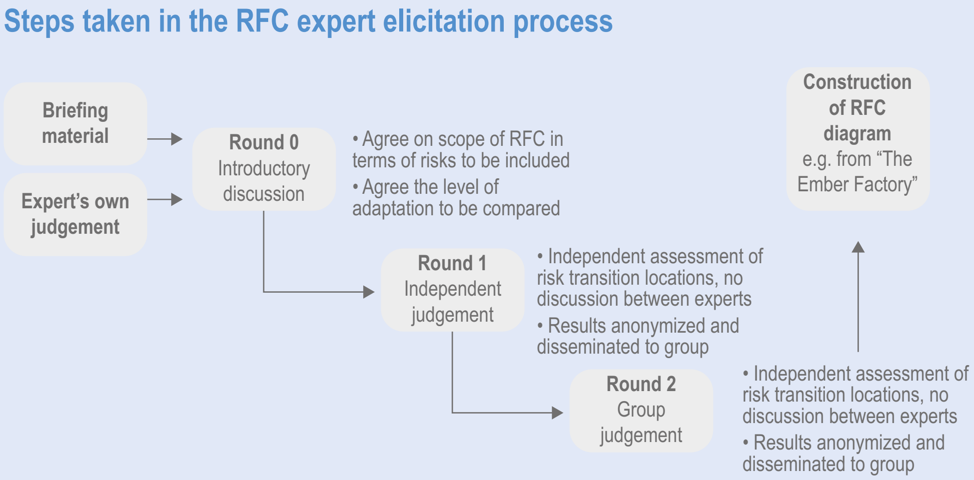
	Elicitation structure Experts are asked to contribute to two rounds of elicitation conducted over an approximately 4–6-week period. The first round comprises individual expert assessments and is conducted offline. In Round One elicitation, experts are requested to provide lower and upper bounds, and then their best estimate (defined as the median), for the transition between the different risk levels, by filling in a question form (Table SM16.19). To facilitate expert assessment, at the start, participants are provided with a summary of some relevant papers and the papers themselves. Participants are requested to evaluate the literature provided, and any other material, drawing from their experience in order to provide four data points of temperature thresholds across each risk. RFC expert teams are requested to evaluate for no to low adaptation or low adaptation. At the end of Round One, experts provide their assessments to the facilitator who compiles the results. The anonymised results are then returned to the experts for their review and evaluation. Subsequently, the second round, Round Two, is held as an online discussion of the results obtained from Round One in order to build consensus. In Round Two, the discussion is not anonymous. Experts are expected to provide the rationale for their assessments during the discussion and to act as a Rational Impartial Observer (RIO) in order to reach consensus discussion (von der Gracht, 2012) to arrive at a final version of the risk transition values. By taking the perspective of an RIO, experts can reach agreement on a distribution that represents a rational impartial view of their combined knowledge. This follows the SHeffield ELicitation Framework (SHELF) approach (O'Hagan, 2019).
Execution	Prior to the elicitation, experts are provided with literature tables to ensure common knowledge of the relevant literature as assessed in Chapter 16's synthesis of observed impacts, adaptation responses and key risks (Sections 16.2, 16.3, 16.4 and 16.5). The Round One briefing session ensures a common understanding of the process of assigning risk levels as low, moderate, high or very high, the associated key risk criteria, the global temperature scale and the overall method used to construct RFC diagrams. This briefing session also ensures that each team member understands the definition and scope of the RFC in question. Experts participating in the elicitation are next provided a briefing document explaining the purpose of the elicitation, background information on risk and adaptation levels, level of confidence, glossary of terms, elicitation instructions and consideration when making judgements. For the purpose of the elicitation, experts are invited to share additional literature which they think may be useful for inclusion into the pool of literature for assessment.  **Figure SM16.3 | Steps taken in the RFC expert elicitation process.** Experts are provided with a form to complete in Round One with the survey questions for their responses (Table SM16.19). The form invites experts to independently provide the median estimates of where risk levels transition between moderate to low, low to high, and high to very high. They are also asked to provide the lower and upper bounds of these transition levels, and the confidence they have in each judgement (as high, medium or low). Experts are strongly encouraged not to rely solely on the literature tables circulated, but to also use their own knowledge of the underlying subject and broader literature. However, the literature tables assist with avoiding bias that might otherwise result from experts not being fully aware of the range of literature pertaining to a particular risk element. For some RFCs, where there are multiple elements of risk, individual experts provide information only about the types of risk elements in which they are most knowledgeable. In this case, in the first round the elicitation is used to collate independently the experts' judgements on particular risk elements, and the second round is used to discuss how to aggregate these into a single set of judgements representative of all risk elements contained within that RFC. The forms also collate the experts' knowledge pertaining to the key risk criteria for each risk element, that is, the magnitude of the risk, its pervasiveness and severity (capturing various metrics of risk estimation, including frequency, intensity, stock/capital/lives at risk), its timing, its likelihood, its irreversibility and any transboundary effects, and the ability to adapt. Experts are strongly encouraged at the Round One stage to suggest additions to the provided literature tables to capture specific additional references of particular importance. In Round Two, a group discussion achieves consensus across the group about the location of risk transitions, including the synthesis of different elements of risk contributing to a given RFC ember (Figure 16.15). The final product is a table of consensus values of risk accrual with global warming for each RFC (i.e., Table SM16.20), which is used to plot a changing sequence of colours along a gradient representing global surface annual mean temperature rise (GSAT).
Appraisal	The elicitation process uses input materials of the format shown in Figure SM16.2. Expert judgement, as described in this protocol, is used to complete Table SM16.19 and Table SM16.20, to produce 'burning ember' diagrams shown in Figure 16.15. The process for developing the final figure follows the guidance provided by the WGII Technical Support Unit in Author's Handbook: Guideline for AR6 WGII figures (Alegría and Langsdorf, 2020). An alternative process is to use the software of 'The Ember Factory' provided by Phillipe Marbaix at https://climrisk.org/emberfactory/. We retain the colour scheme employed in the most recent assessment reports (Oppenheimer et al., 2014; Hoegh-Guldberg et al., 2018), where white, yellow, red and purple indicate undetectable, moderate, high and very high additional risk, respectively. Undetected risk (white) indicates that no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Very high risk (purple) indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.

Table SM16.18 | Information provided to the experts prior to the elicitation.

a) Description of adaptation levels, characterised by scope, depth and speed of change, plus limits, based on Section 16.3 (Table 16.1)

Category	Scope of change	Depth of change	Speed of change	Challenge on limits
None	There are no to minimal additional adaptation activities implemented. In the best case, risks of climate change are recognised, and vulnerability assessments and adaptation planning may be undertaken, but there has been negligible implementation of adaptation efforts or change in vulnerability.	Negligible implementation of adaptation efforts or change in vulnerability.		
Low	Adaptation is largely localised and does not change the fundamental attributes of the social–ecological system. There are primarily disjointed adaptation initiatives, with *limited evidence* of coordination or mainstreaming across sectors, jurisdictions, or levels of governance.	Adaptations are largely incremental by expanding existing practices, with *limited evidence* of novel change beyond Business-As-Usual practices.	Adaptations are largely slow, consistent with existing behavioural or institutional change, and *limited evidence* of accelerated adaptive response. Change is evident, but not rapid.	Adaptations may approach but do not exceed or substantively challenge soft limits.
Medium	Adaptation is expanding and increasingly coordinated. There are growing efforts that exceed Business-As-Usual practices and challenge the fundamental attributes of the social–ecological system. That is, rapid, radical and novel initiatives are taking place. There is some expansion and/or mainstreaming of change to include a wider region, or involvement of coordinated, multi-dimensional, multi-level adaptation.	Perspectives, values and practices are changing to involve novel or more radical approaches.	Adaptations are increasingly exceeding Business-As-Usual behavioural or institutional change to reflect accelerated adaptive responses.	Adaptations, however, approach but do not exceed soft limits.
High	Adaptation is implemented at or very near its full potential across multiple dimensions. Adaptations are widespread and substantial, including most of the possible sectors, levels of governance and actors (e.g., nationally implemented legislation or policy), or reflect widespread changes in behaviour.	Adaptation actions are increasingly radical, including altering of values, re-framing of problems, and dramatic changes in practices.	The speed of adaptive change is rapid, involving changes in governance or behaviour that reflect shifts in values or practices to reduce vulnerability at substantially faster rates than Business-As-Usual.	Adaptations exceed soft limits and begin to approach hard limits.

b) Glossary

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperatures (SST) over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period.

Global mean surface air temperature (GSAT): Global average of near-surface air temperatures over land and oceans. Changes in GSAT are often used as a measure of global temperature change in climate models but are not observed directly.

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST).

Risk (AR6 updated definition): The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

Risk = (probability of events or trends) × consequences

Risk results from the interaction of vulnerability, exposure and hazard. In this report, the term risk is used primarily to refer to the risks of climate-change impacts.

Key vulnerability, key risk: A vulnerability, risk or impact relevant to the definition and elaboration of 'dangerous anthropogenic interference (DAI) with the climate system', in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policymakers in that context. Key risks are potentially severe adverse consequences for humans and social–ecological systems resulting from the interaction of climate-related hazards with vulnerabilities of societies and systems exposed. Risks are considered 'key' owing to high hazard or high vulnerability of societies and systems exposed, or both. Vulnerabilities are considered 'key' if they have the potential to combine with hazardous events or trends to result in key risks. Those that have little influence on climate-related risk, due to lack of exposure to hazards, would not be considered key. Many impacts, vulnerabilities and risks merit particular attention by policymakers because of characteristics that might make them 'key'. The identification of potential key vulnerabilities is intended to provide guidance to decision makers for identifying levels and rates of climate change that may be associated with DAI. Ultimately, the definition of DAI cannot be based on scientific arguments alone, but involves other judgements informed by the state of scientific knowledge.

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. A broad set of factors such as wealth, social status and gender determine vulnerability and exposure to climate-related risk.

Impacts: (Consequences, Outcomes) Effects on natural and human systems. The impacts of climate change on geophysical systems, including floods, droughts and sea level rise, are a subset of impacts called physical impacts.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.

c) Level of confidence

Experts are referred to the information pertaining to confidence levels from the IPCC uncertainty guidance note (Mastrandrea et al., 2010) available online at https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

d) Definition of risk levels and colour code for the risk transition diagram

We retain the colour scheme employed in the most recent assessment reports (Oppenheimer et al., 2014, Hoegh-Guldberg et al., 2018), where white, yellow, red and purple indicate undetectable, moderate, high and very high additional risk, respectively.

Undetectable (white): No associated impacts are detectable and attributable to climate change.

Moderate (yellow): Associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks.

High (red): Severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks

Very high (purple): Very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.

The colour palette follows the guidance provided by the WGII Technical Support Unit in Author's Handbook: Guideline for AR6 WGII figures (Alegría and Langsdorf, 2020).

e) Criteria for key risks (Section 16.5.1)

Key risks (KRs) are determined not just by the nature of hazards, exposure, vulnerability and response options, but also by values which determine the importance of a risk. Because values can vary across individuals, communities or cultures, as well as over time, what constitutes a KR can vary widely from the perspective of each of these groups, or across individuals. Four criteria for what may be considered potentially severe are listed here:

Magnitude of adverse consequences. Magnitude measures the degree to which particular dimensions of a system are affected, should the risk materialise. Magnitude can include the size or extent of the system, the *pervasiveness of the consequences* across the system (geographically or in terms of affected population), as well as the *degree of consequences*. Consequences can be measured by a wide range of characteristics. For example, risks to food security can be measured as uncertain consequences for food consumption, access or prices. The magnitude of these consequences would be the degree of change in these measures induced by climate change and accounting for the interaction with exposure and vulnerability. In addition to *pervasiveness* and *degree of change*, several other aspects can contribute to a judgement of magnitude, although they refer to concepts that are difficult to capture and highly context specific:

Irreversibility of consequences. Consequences that are irreversible, at least over long time scales, would be considered a higher risk than those that are temporary. For example, changes to the prevailing ecosystem in a given location may not be reversible on the decade-to-century scale.

Potential for impact thresholds or tipping points. Higher risks are posed by the potential for exceeding a threshold beyond which the magnitude or rate of an impact substantially increases.

Potential for cascading effects beyond system boundaries. Higher risks are posed by those with the potential to generate downstream cascading effects to other ecosystems, sectors or population groups within the affected system and/or to another system, whether neighbouring or distant.

Likelihood of adverse consequences. A higher probability of high-magnitude consequences poses a larger risk *a priori*, whatever the scale considered. This probability may not be quantifiable, and it may be conditional on assumptions about the hazard, exposure or vulnerability associated with the risk.

Temporal characteristics of the risk. Risks that occur sooner, or that increase more rapidly over time, present greater challenges to natural and societal adaptation. A persistent risk (due to the persistence of the hazard, exposure and vulnerability) may also pose a higher threat than a temporary risk due, e.g., to a short-term increase in the vulnerability of a population (e.g., due to conflict or an economic downturn).

Ability to respond to the risk. Risks are more severe if the affected ecosystems or societies have limited ability to reduce hazards (e.g., for human systems, through mitigation, ecosystem management and possibly solar radiation management); to reduce exposure or vulnerability through various human or ecological adaptation options; or to cope with or respond to the consequences, should they occur.

Table SM16.19 | Section 16.6.2 Survey questions for the elicitation responses. Experts are requested to provide the risk transition temperature levels as well as the confidence for their assessment during Round One of the elicitation. Three values of the transition range (e.g., lowest, median, highest temperature level) are elicited for each transition. The questions for the first transition, undetectable risk to moderate risk, are shown below; these questions are repeated for moderate to high risk, and again for high to very high risk). Experts are asked to provide reasons for their judgements and include citations to key references. Experts are reminded of the criteria for key risks as given in Table SM16.18e.

1.	What is the **lowest GSAT value** for the risk level to transition from undetectable risk to moderate risk, in which you have at least *medium confidence*? Tell us if you wish to provide this with *high* or *very high confidence* instead.	Temperature: Confidence[a]:
	Please provide the rationale behind your answer, if possible. You may give reference to the specific findings in the publications which lead you to provide this judgement.	
2.	What is the **highest GSAT value** for the risk level to transition from undetectable risk to moderate risk, in which you have at least *medium confidence*? Tell us if you wish to provide this with *high* or *very high confidence* instead.	Temperature: Confidence[a]:
	Please provide the rationale behind your answer, if possible. You may give reference to the specific findings in the publications which lead you to provide this judgement.	

3.	Your **best estimate (median) of the GSAT value** for the transition from undetectable risk to moderate risk. This means that it is equally likely that the GSAT transition value is above or below this value. You think that this GSAT value is most representative of when the transition would occur. Remember, the best estimate value is not necessarily in the middle of your lowest to highest plausible range, but it is, in your opinion, equally likely that the GSAT transition lies above, or below, this value.	Temperature: Confidence[a]:
	Please provide the rationale behind your answer, if possible. You may give reference to the specific findings in the publications which lead you to provide this judgement.	

Note:

(a) IPCC guidance on confidence language posted here: https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

SM16.6.2 Section 16.6.3: Values of Risk Accrual to the Reasons for Concern with Global Warming

Table SM16.20 | Section 16.6.3 Consensus values of risk accrual with global warming for five RFCs. These data were used to develop Figure 16.14.

A) RFC1 Unique and threatened systems

Risk transition	Global surface air temperature change (°C) above pre-industrial levels (1850–1900)		Confidence
Undetectable to moderate	Min	0.4	*Very high*
	Best estimate (median)	0.5	
	Max	0.7	
Moderate to high	Min	0.7	*Very high*
	Best estimate (median)	0.9	
	Max	1.2	
High to very high	Min	1.2	*High*
	Best estimate (median)	1.5	
	Max	2.0	

B) RFC2 Extreme weather events

Risk transition	Global surface air temperature change (°C) above pre-industrial levels (1850–1900)		Confidence
Undetectable to moderate	Min	0.5	*Very high*
	Best estimate (median)	0.5	
	Max	0.7	
Moderate to high	Min	1.0	*High*
	Best estimate (median)	1.2	
	Max	1.5	
High to very high	Min	1.8	*Medium*
	Best estimate (median)	2.0	
	Max	2.5	

C) RFC3 Distribution of impacts

Risk transition	Global surface air temperature change (°C) above pre-industrial levels (1850–1900)		Confidence
Undetectable to moderate	Min	0.7	*High*
	Best estimate (median)	0.8	
	Max	1.0	
Moderate to high	Min	1.5	*Medium*
	Best estimate (median)	1.8	
	Max	2.0	
High to very high	Min	2.0	*Medium*
	Best estimate (median)	3.0	
	Max	3.5	

D) RFC4 Global aggregate impacts

Risk transition	Global surface air temperature change (°C) above pre-industrial levels (1850–1900)		Confidence
Undetectable to Moderate	Min	1.0	*Medium*
	Best estimate (median)	1.3	
	Max	1.5	
Moderate to high	Min	1.5	*Medium*
	Best estimate (median)	2.0	
	Max	2.5	
High to very high	Min	2.5	*Medium*
	Best estimate (median)	Between 2.7 and 3.7*	
	Max	4.5	

E) RFC5 Large-scale singular events

Risk transition	Global surface air temperature change (°C) above pre-industrial levels (1850–1900)		Confidence
Undetectable to moderate	Min	0.7	*High*
	Best estimate (median)	0.9	
	Max	1.0	
Moderate to high	Min	1.5	*Medium*
	Best estimate (median)	2.0	
	Max	2.5	
High to very high	Min	2.5	*Low*
	Best estimate (median)	Not determined**	
	Max	4.0	

* experts provided a range, and not a single value, for the best estimate (median) of when the transition from high to very high risk might occur for RFC4 and a mid-point value of 3.2 was used for input as the 'median' in the spreadsheet for upload into The Burning Ember Factory (https://climrisk.org/emberfactory/) application for development of the RFC4 ember diagram

** experts did not provide a value for the best estimate (median) of when the transition from high to very high risk level might occur and no value was used for input as the 'median' in the spreadsheet for upload into The Burning Ember Factory (https://climrisk.org/emberfactory/) application for development of the RFC5 diagram

SM16.7 Large Tables

SM16.7.1 Details of Studies on Detection and Attribution Studies of Observed Changes in Climate-Related Systems

Table SM16.21 | Detection and attribution of changes in the climate-related systems (grey symbols in Figure 16.2.): Assessment statements relate to 'climate attribution' i.e. the identification and quantification of the contribution of anthropogenic forcings to the observed changes in the climate-related systems. The subtitles of the grey symbols in Figure 16.2 and associated numbers can be found here as titles of associated sections. Each section provides the background information (references and associated evidence) behind the ratings in the Figure (direction of change and level of confidence). The summary statements in the orange cells of the table are displayed in Figure 16.2.

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Atmosphere—Increase in CO_2 concentration:			
Global	**Observations:** Atmospheric CO_2 concentrations are increasing by 1.6 ppm yr^{-1} from 1960 to 2019.	IPCC AR6 WGI Chapter 2 (Gulev et al., 2021), rate calculated from Annex III information	*Very high confidence* in the growth of CO_2	
	Last time concentrations were as high as today was 2 million years ago, and current rates of change (since 1850) are unprecedented in the last 800 ka.	IPCC AR6 WGI Chapter 2 (Gulev et al., 2021)	*High confidence*	
	The amplitude of the seasonal cycle of atmospheric CO_2 concentrations has increased.	IPCC AR6 WGI Chapter 3 (Eyring et al., 2021)		
	Attribution: The increase reflects the net balance of fossil fuel and cement production and uptake in oceans and terrestrial vegetation. Increased plant activity because of CO_2 fertilisation responsible for the increase in the amplitude of the seasonal cycle.	IPCC AR6 WGI Chapter 2 (Gulev et al., 2021) and Chapter 5 (Canadell et al., 2021)	Anthropogenic CO_2 emissions are the main driver of the observed increase in atmospheric CO_2 concentrations, *virtually certain* (***)	Fossil fuel burning and cement production
	Atmosphere—Warming			
Global	**Observations:** Global mean surface temperatures (GMST) have increased since the late 19th century. GMST increased by 0.85 [0.69 to 0.95] °C between 1850–1900 and 1995–2014 and by 1.09 [0.95 to 1.20] °C between 1850–1900 and 2011–2020.	IPCC AR6 WGI Chapter 2 (Gulev et al., 2021), Cross Chapter Box 2.3	*Virtually certain*	Dominated by GHG emissions
	Attribution: Best estimate of human induced warming since pre-industrial is approximately equal to the observed warming.	IPCC AR6 WGI Chapter 3 (Eyring et al., 2021)	Major contribution of anthropogenic emissions of climate forcers to observed global warming, *virtually certain* (***)	
S05a	Atmosphere—Mean rainfall (annual or seasonal mean)			
Global	**Observations:** Global land precipitation has likely increased since the middle of the 20th century, with faster increase since 1980. 1901–2019: Global averaged land precipitation shows a significant increase in two out of three available data sets (GPCCv2020 and GHCNv4, no significant trend in CRU TS 4.04). 1980–2019: General increase in annual precipitation over land, significant in three out of four available precipitation data sets.	IPCC AR6 WGI Chapter 2 (Gulev et al., 2021), Ren et al. (2013) (1900–2010), Adler et al. (2017) (1979–2014)	*Medium confidence* in increasing global averaged land precipitation	
	Attribution: It is likely that human influence has contributed to large-scale precipitation changes since 1950. 1900–2010: After removing aerosol effects the effect of anthropogenic GHG on global mean precipitation has been quantified with 2.3% K^{-1} respectively 0.071 $\text{mm d}^{-1}\text{ century}^{-1}$ (0.072 $\text{mm d}^{-1}\text{ century}^{-1}$ over ocean and 0.069 $\text{mm d}^{-1}\text{ century}^{-1}$ over land).	IPCC AR6 WGI Chapter 3 (Eyring et al., 2021), Gu and Adler (2015) (1900–2010)	Anthropogenic GHG emissions are the main drivers of the observed increase in global mean precipitation, *high confidence* (***), while aerosol emissions may have dampened the global mean increase.	The increase in global mean precipitation does not follow the increase in atmospheric water vapour but is constrained by the global energy budget, leading to a slower increase per degree of global warming.

Detection and attribution of observed changes in climate-related systems
('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
	Despite large decadal variability, there is *medium confidence* that rainfall over the wet regions of the tropics has increased due to enhanced greenhouse gas forcing. Yet, there is also growing evidence and *medium confidence* that this tropical precipitation increase has been partly muted by anthropogenic aerosols.	Gu and Adler (2013) (1988–2010), Gu et al. (2016) (1979–2012)		
Africa	**Observations:** The Horn of Africa has experienced a significant long-term decrease in rainfall in the rain seasons from March to May, while rainfall intensity throughout the rainy season increased in the Sahel region during the period 1980–2010.	IPCC AR6 WGI Atlas (Gutiérrez et al., 2021)	*High confidence*	
	Attribution: Enhanced rainfall intensity over the Sahel in the last two decades is associated with anthropogenic climate forcing, while East African drying is associated partly with decadal natural variability in SSTs over the Pacific Ocean and partly with anthropogenically forced rapid warming of Indian Ocean SSTs.	IPCC AR6 WGI Atlas (Gutiérrez et al., 2021)	Moderate long-term increase in rainfall intensity (over the Sahel) to minor reduction in rainfall (over East Africa) induced by anthropogenic climate forcing compared with effects of internal climate variability, *low confidence* (*)	
Asia	**Observations:** Mean precipitation has shown significant trends in many parts of Asia, especially increases across higher latitudes; however, spatial variability remains high.	IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*Medium confidence*	
	Summers in eastern China have become wetter in the south but drier in the north in the past 50 years.	Zhou et al. (2021)		
	Attribution: Aerosols play an important role in weakening (monsoonal) precipitation intensity, as opposed to greenhouse gases that have an enhancing effect on precipitation. Another driver of the observed changes is natural variability. Changed circulation patterns due to anthropogenic forcing can explain a large part of the precipitation trends over eastern China.	IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021), Chapter 3 (Eyring et al., 2021) and Atlas (Gutiérrez et al., 2021), Zhou et al. (2021)	Moderate increases and decreases in precipitation induced by anthropogenic climate forcing depending on the regions, *low confidence* (*)	
Australasia	**Observations:** *Australia:* Northern Australian rainfall has increased since the 1970s, while April–October rainfall has decreased 16% since the 1970s in southwestern Australia and 12% from 2000 to 2019 in southeastern Australia. Australian average rainfall was lowest on record in 2019.	Chapter 11, Table 11.2a Dey et al. (2019) BoM and CSIRO (2020), BoM (2020)	*Medium confidence*	
	New Zealand: From 1960 to 2019, almost half of the 30 sites had an increase in annual rainfall (mostly in the south) and 10 sites (mostly in the north) had a decrease. Rainfall increased by 2.8% per decade in Whanganui, 2.1% per decade in Milford Sound and 1.3% per decade in Hokitika. Rainfall decreased by 4.3% per decade in Whangarei and 3.2% per decade in Tauranga.	Chapter 11, Table 11.2b MfE (2020)		
	Attribution: Decreased rainfall over southwestern and southeastern Australia is partly attributable to anthropogenic climate change. Increased rainfall over northwestern Australia is partly attributable to an increase in anthropogenic aerosols rather than greenhouse gases.	Delworth and Zeng (2014), Timbal and Drosdowsky (2013) ; Post et al. (2014); Hope et al. (2017); Dey et al. (2019)	Moderate reduction in rainfall due to anthropogenic greenhouse gases in southwestern and southeastern Australia, *medium confidence* (**), moderate increase in rainfall due to anthropogenic aerosols in northwestern Australia, *low confidence* (*)	
Central and South America	**Observations:** Precipitation trends are diverse in Central and South America, with small increasing trend in Central America, decreasing trend in southeast Brazil and increasing trend in southern South America.	IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021)		
	Attribution: Positive rainfall trends over southern South America have been attributed to ozone depletion and GHG.	IPCC AR6 WGI Chapter 3 (Eyring et al., 2021)	Moderate contribution of anthropogenic climate forcing to increasing rainfall over Southern South America, *low confidence* (*) No assessment elsewhere	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
Europe	**Observations:** Precipitation has generally increased in Northern and decreased in Southern Europe.	IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence*	
	Attribution: This pattern in mid-to-high-latitude land precipitation over the Northern Hemisphere has been attributed to human influence.	IPCC AR6 WGI Chapter 3 (Eyring et al., 2021)	Moderate increase in Northern and moderate decrease in Southern Europe induced by anthropogenic climate forcing, *medium confidence* (**)	
North America	**Observations:** There is evidence of long-term declines in precipitation over northwestern Mexico and the southwestern USA. Significant increases in rainfall are observed in the northern portions of the continent.	IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*Medium confidence*	
	Attribution: The precipitation observing network is spatially inadequate and temporally inconsistent over some regions of North America, so that detection and attribution of multi-decadal trends is difficult.	IPCC AR6 WGI Atlas (Gutiérrez et al., 2021)	Inconsistent findings	
Small Islands	**Observations:** Observation data sets have revealed no significant long-term trends in rainfall in the Caribbean over the 20th century when analysed at seasonal and inter-decadal time scales. Over the western Pacific, recent analysis of station data showed spatial variations in the mostly decreasing annual total rainfall from 1961 to 2011, trends mostly non-significant.	IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*Low confidence*	
	Attribution: No dedicated studies.		No assessment	
S05b	Atmosphere—Heavy precipitation			
Global	**Observations:** Over the last three decades, the number of record-breaking events has increased significantly in the global mean. Globally, this increase has led to 12% more record-breaking rainfall events over 1981–2010 compared with those expected in stationary time series. From 1951 to 1999, observations of heavy precipitation show an overall increasing trend in the total Northern Hemisphere, with 65% and 61% of the total data-covered areas having positive trends for both daily maximum precipitation and 5-d consecutive precipitation.	Lehmann et al. (2015), Zhang et al. (2013)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Attribution: On a global scale, the increase can be explained by the warming of air and associated increasing water holding capacity. While the number of rainfall record-breaking events can be related to natural multi-decadal variability over the period from 1901 to 1980, observed record-breaking rainfall events significantly increased afterwards consistent with rising temperatures. Climate model simulations indicate that global warming primarily induced by anthropogenic forcing has increased the probability of heavy precipitation events (daily rainfall >99.9 percentile of pre-industrial distribution) by about 18% (fraction of attributable risk). Anthropogenic climate forcing is estimated to have intensified annual maximum 1 d precipitation in sampled Northern Hemisphere locations by 3.3% (1.1% to 5.8%, >90% confidence interval) on average.	Lehmann et al. (2015), Fischer and Knutti (2015), Zhang et al. (2013)	Moderate contribution of anthropogenic climate forcings to the observed increase in the occurrences of extreme precipitation events, *medium confidence* (**)	Atmospheric warming increases the water holding capacity of the air and therefore the potential for more intense precipitation events. While changes in global average precipitation are constrained by the global energy budget, levels of extreme precipitation are expected to increase at a higher rate in line with the Clausius–Clapeyron relationship. In addition to these thermodynamic changes, heavy precipitation events are subject to dynamic changes depending on the regions. Dynamic circulation changes include the weakening of the large-scale monsoon circulation, the modulation of regional monsoon circulation by changes in land–sea thermal contrast and the SST patterns, and changes in tropical synoptic disturbances such as monsoon depression and tropical cyclones.
Africa	**Observations:** Precipitation extremes show non-homogeneous trends over the African continent where data are available. Over the Sahara and Sub-Saharan Africa, increases in the frequency and intensity of extreme precipitation have been observed. A larger percentage of stations shows increases than decreases. Significant upward trends for extreme precipitation-related indices are identified.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021)	There are insufficient data to assess trends in heavy precipitation over the continent but *medium confidence* in increased heavy precipitation in Southern Africa.	
	Attribution: Individual heavy precipitation extremes have not been attributed in West Africa and Southern Africa where studies exist.	Lawal et al. (2016), Parker et al. (2017), Fučkar et al. (2020)	Minor contribution of anthropogenic climate forcing where studies exist (West Africa, Southern Africa), *low confidence* (*); largely missing assessments	

Detection and attribution of observed changes in climate-related systems (‘Climate Attribution’)

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
Asia	**Observations:** There is an observed increase in precipitation extremes over Central Asia, most of South Asia, the southern and northern Tibetan Plateau, the northwest Himalaya, Indochina and east-central Philippines, Jakarta, eastern and northwestern China, Japan and Korea.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021)	Heavy precipitation *likely* increased.	
	Attribution: Studies on extreme precipitation events mostly found that anthropogenic climate forcing has increased the observed probability or magnitude of observed precipitation events. A study on the 2018 summer persistent heavy rainfall in central western China found that anthropogenic forcing has reduced the probability of persistent rainfall, but increased that of daily extremes.	Burke et al. (2016) (China), Sun and Miao (2018) (China), Zhou et al. (2017) (China), Yuan et al. (2018), Sun et al. (2019), Li et al. (2017a) (daily precipitation extremes over China), Ma et al. (2016) (shift from light to heavy precipitation over eastern China), Zhang et al. (2020b) (western China daily precipitation), Rimi et al. (2019) (probability of pre-monsoon extreme rainfall events in Bangladesh), Kawase et al. (2020) (heavy rain event of 2018 in Japan)	Anthropogenic climate forcing has contributed to the observed increase in heavy precipitation, *high confidence* (***).	
	In other cases, a contribution of climate could not be identified.	Zhou et al. (2013) (2012 extreme rainfall in North China), van Oldenborgh et al. (2016) (heavy precipitation event of 2015 in India)		
Australasia	**Observations:** *Australia:* Daily rainfall associated with thunderstorms has increased from 1979 to 2016, particularly in northern Australia. Daily rainfall intensity increased in the northwest from 1950 to 2005 and in the east from 1911 to 2014, and decreased in the southwest and Tasmania from 1911 to 2010. Hourly extreme rainfall intensities increased by 10–20% in many locations between 1966–1989 and 1990–2013.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Table 11.2a; Dey et al. (2019), Alexander and Arblaster (2017), MfE (2020), Donat et al. (2016), Dunn et al. (2020a), Evans et al. (2017), Dowdy (2020), Guerreiro et al. (2018)	There is *limited evidence* for an increase in heavy precipitation for the continent as a whole, but *medium confidence* for an increase in heavy precipitation in northern Australia.	
	New Zealand: The number of days with extreme rainfall increased at 14 of 30 sites and decreased at 11 sites from 1960 to 2019. Most sites with increasing annual rainfall had more extreme rainfall, and most sites with decreasing annual rainfall had less extreme rainfall.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Table 11.2b, MfE (2020)	*Low confidence*	
	Attribution: *Australia:* Anthropogenic greenhouse gas influence on extreme rainfall events in southern and eastern Australia is highly uncertain. In southeast Australia, ENSO has a much stronger influence on extreme precipitation than anthropogenic climate change. In northwest Australia, the extreme rainfall increase since 1950 can be related to increased monsoonal flow due to increased anthropogenic aerosol emissions, but cannot be attributed to an increase in greenhouse gases.	Christidis et al. (2013), King et al. (2013), Lewis and Karoly (2015), Dey et al. (2019), Tozer et al. (2020), Lewis et al. (2017)	Mostly minor contribution of anthropogenic climate forcing to observed changes in extreme precipitation, *low confidence* (*)	
	New Zealand: The risk of an extreme 5-d July rainfall event over Northland, New Zealand, such as was observed in early July 2014, has likely increased due to anthropogenic influence on climate.	Rosier et al. (2015), MfE (2017)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
Central and South America	**Observations:** Extreme precipitation has increased in South America, though trends (both upward and downward) in precipitation indices are not statistically significant at most stations.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021)	There are insufficient data to assess trends in heavy precipitation for the whole region, but *high confidence* for increase in Southeastern South America.	
	Attribution: Attributable increase in extreme rainfall in most parts of South America, apart from Southwestern South America.	Li et al. (2020c)	Moderate contribution of anthropogenic climate forcing to increase in extreme rainfall, *low confidence* (*)	
	In the Uruguay River Basin, anthropogenic climate change has increased the risk of the April–May 2017 extreme rainfall by at least two-fold.	de Abreu et al. (2019)		
	The extremely wet March of 2017 in Peru is partly attributable to anthropogenic climate change, which made such an event at least 1.5 times more likely than under baseline conditions.	Christidis et al. (2019)		
Europe	**Observations:** There is an observed increase in extreme precipitation events over Europe as a whole with strong regional differences even at local scales. Over Northern Europe, rainfall extremes in winter have increased.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021)	*Likely* intensification of heavy precipitation	
	Attribution: Some studies found that climate change mostly increased the probability or magnitude of observed extreme precipitation events, including European winters. Wet summer of 2012 not attributable to climate change.	Extreme winter rainfall: Otto et al. (2018a), Schaller et al. (2016), Vautard et al. (2016) High summer rainfall: Otto et al. (2015d) (wet summer 2012), Schaller et al. (2014) (heavy precipitation in May–June 2013 in the upper Danube and Elbe basins), Wilcox et al. (2018) (European summer of 2012) IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021)	Anthropogenic climate forcing has contributed to the observed intensification of heavy precipitation, *high confidence* (***) in particular in Northern European winter but not in the summer, *medium confidence* (**) (*robust evidence*).	
North America	**Observations:** Precipitation extremes have increased throughout North America since 1950, especially in the eastern half of the USA.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Hall and Kossin (2019) (for rainfall associated with hurricanes)	*High confidence* *Likely* intensification of heavy precipitation	
	Attribution: Some studies found an increasing effect of anthropogenic climate forcing on the probability or magnitude of observed extreme precipitation events for parts of the USA for individual events. Results depend on framing. Studies of Hurricane Harvey severely affecting the Houston metropolitan area in August 2017 found a 15–38% increase in storm total precipitation attributable to global warming. Anthropogenic climate forcing is estimated to have increased the precipitation associated with Hurricane Katrina severely affecting the Gulf Coast of the USA in August 2005 by 4–9%, and by 6% for Irma affecting the Florida Keys in 2017. Increased rainfall associated with hurricanes may partly be induced by increased stalling near the coast.	Knutson et al. (2014), Szeto et al. (2015), Emanuel (2017), Van Oldenborgh et al. (2017), Risser and Wehner (2017), Wang et al. (2018) (all three on Hurricane Harvey), Patricola and Wehner (2018) (Hurricanes Katrina, Irma, Maria), Trenberth et al. (2015) (Boulder floods, 2013), Eden et al. (2016) (Boulder floods, 2013), Wang et al. (2015) (extreme precipitation over the southern Great Plains, May 2015), IPCC WGI Chapter 11, (Seneviratne et al., 2021)	Anthropogenic climate forcing has contributed to the observed increase in frequency or intensification of heavy precipitation, *medium confidence* (**), *high confidence* with regard to hurricanes (***).	.

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
Small Islands	**Observations:** Record-breaking rainfall associated with Hurricane Maria over Puerto Rico in 2017 (highest total averaged precipitation of 129 storms that have impacted the island since 1956). Heavy precipitation associated with Hurricane Irma heavily affecting the Virgin Islands.	Keellings and Ayala (2019)		
	Attribution: The probability of precipitation of Maria's magnitude is estimated to have increased due to long-term climate changes by about a factor of 5 (best estimate). Anthropogenic climate forcing is estimated to have increased the rainfall associated with Maria and Irma by 9% and 6%, respectively.	Keellings and Ayala (2019), Patricola and Wehner (2018)	Moderate increase in precipitation associated with tropical cyclones, *high confidence* (***) No assessment elsewhere	
S05c	Atmosphere—Drought			
Global	**Observations:** There is *medium/high confidence* in increasing drought conditions in several parts of the world, such as the Mediterranean, West Africa, the Caribbean and Central Asia, while drought conditions have become less severe in Northern Europe, central North America and northwest Australia.	Section 4.2.5.1	There is *medium confidence* that drought conditions have increased moderately in several regions on all continents.	
	Attribution: Anthropogenic climate forcing has increased the frequency and the severity of droughts over the last decades in the Mediterranean, western North America, southwestern Australia, southern Africa and southwestern South America. Event attribution studies suggest that anthropogenic climate change increased the likelihood of several major drought events that had substantial societal impacts in North America, South America, Africa and Asia.	Section 8.3.1.6	Anthropogenic climate forcing has contributed to increasing drought conditions in the Mediterranean, western North America, southwestern Australia, southern Africa and southwestern South America, *medium* to *high confidence* (**) and reduced of drought conditions in Northern Europe, *medium confidence* (**).	Human influence has contributed to changes in water availability during the dry season over land areas, including decreases over several regions due to increases in evapotranspiration (*medium confidence*). The increases in evapotranspiration have been driven by increases in atmospheric evaporative demand induced by increased temperature, decreased relative humidity and increased net radiation over affected land areas (*high confidence*). WGI Chapter 11, Section 11.6.4.5 (Seneviratne et al., 2021).
Africa	**Observations:** In West Africa, increases in drought duration and intensity, as well as the duration and intensity of drought in southern Africa are observed. In eastern Africa, an increase in meteorological drought has been observed. Cape Town, South Africa experienced a serious drought during 2015–2017, where annual mean rainfall fell below 50% of long-term mean in some areas.	Kasei et al. (2009) (West Africa), Masih et al. (2014) (entire continent), Otto et al. (2018c) (Cape Town)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Attribution: The increased drying in West Africa is attributable to climate change over 1901–2010 and 1951–2010 time frames, but there is an unexplained trend reversal for 1981–2010. A relatively large number of attribution studies on drought in eastern Africa found no significant change due to anthropogenic climate change. However, in southern Africa, recent meteorological droughts have been attributed to anthropogenic climate change. Cape Town drought has become three times more likely due to anthropogenic climate forcing.	AR6 WGI Table 11.6 (West Africa) (Seneviratne et al., 2021), Funk et al. (2018), Otto et al. (2018a), Philip et al. (2017), Uhe et al. (2018) (all on East Africa), Otto et al. (2018c) (Cape Town drought), Bellprat et al. (2015) (South Africa), AR6 WGI Chapter 8 (Section 8.3.1.6) (Douville et al., 2021)	Minor contribution of anthropogenic climate forcing to increasing drought conditions in East and West Africa, *low confidence* (*), Moderate contribution of anthropogenic climate forcing to increasing drought conditions in southern Africa, *medium confidence* (**)	
	Further high-impact drought events that have been attributed to anthropogenic climate forcing (increased likelihood): East Africa, 2017; Southern Africa 2016; East Africa, 2014.	Section 4.2.5, Table 4.4		
Asia	**Observations:** *China:* Since the 1950s, some regions of China have experienced a drying trend and more intense and longer droughts, in particular in northern China, but in some (sub-)regions, droughts have become less frequent, less intense, or shorter.	Qin et al. (2015a) (southwestern China), Zhao and Dai (2016), Qin et al. (2015b), Liu et al. (2015) (all three on northern China), Dai and Zhao (2017), Zhang et al. (2018), Li et al. (2020b) IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021)	*Medium confidence* in increase in drought observed in West Central Asia, East Central Asia, and East Asia	
	South Asia: Drought frequency is increasing in some areas, whereas it is decreasing in the Tibetan Plateau.			
	Middle East: Between 2006/2007 and 2010/2011, the Fertile Crescent region experienced the most severe drought in the instrumental record. Persistent drought in southern Levant during 2014 rainy season.	Hoerling et al. (2012), Gleick (2014), Kelley et al. (2015), Bergaoui et al. (2015) (Middle East)		
	Attribution: There is evidence that drought occurrence, severity and regime have changed as a result of anthropogenic climate forcing. In some regions in Southeast Asia, droughts have been attributed to El Niño, but not climate change. *Middle East:* There is a long-term winter drying trend in the Mediterranean and Levant region that can only be explained taking into account anthropogenic emissions-related forcings. The magnitude of the 2006/07 to 2010/11 drought would have been highly unlikely without this trend. The 2014 drought was also made more likely by anthropogenic emissions-related forcings.	Chen and Sun (2017b), Chen and Sun (2017a) (China), McBride et al. (2015) (no link to climate change for the 2015 drought in Singapore/Malaysia), King et al. (2016) (drought in Indonesia made more likely by El Niño and climate change) (Southeast Asia), Hoerling et al. (2012), Gleick (2014), Kelley et al. (2015), Bergaoui et al. (2015) (Middle East)	Minor contribution (e.g., Southeast Asia) of anthropogenic climate forcing to increasing drought conditions, *low confidence* (*), to strong contribution of anthropogenic climate forcing to increasing drought conditions (e.g., Middle East), *medium confidence* (**)	
	China: Anthropogenic climate forcing has increased the likelihood of some high impact droughts in China: Yunnan, Southwestern China, 2019; Southwestern China, 2019; South China, 2019; South China, 2018. Anthropogenic climate forcing has decreased the likelihood of the high-impact drought in the middle and lower reaches of the Yangtze River, China.	Section 4.2.5, Table 4.4		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Thailand: Anthropogenic climate forcing has increased the likelihood of high-impact drought in Thailand, 2016.	Section 4.2.5, Table 4.4		
Australasia	**Observations:** *Australia*: Major Australian droughts occurred in 1895–1902, 1914–1915, 1937–1945, 1965–1968, 1982–1983, 1997–2009 and 2017–2019. The 2019 annual mean precipitation set a dryness record (since 1900) for Australia as a whole and southeastern Australia where it was associated with extreme wildfires. Fewer droughts have occurred across most of northern and central Australia since the 1970s, more droughts in the southwest since the 1970s, and mixed drought trends in the southeast since the late 1990s. An increase in extreme fire weather and in the length of the fire season since the 1950s, especially in southern Australia. More dangerous conditions for extreme pyro convection events since 1979, particularly in southern and eastern Australia. Far-southwest Western Australia has a statistically significant increase in drought intensity, and southeast Australia has shown a significant increase in the average length of droughts.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Table 11.2a, BoM (2021); Kirono et al. (2020), Gallant et al. (2013), Delworth and Zeng (2014), Alexander and Arblaster (2017), Knutson and Zeng (2018), Dey et al. (2019), Dunn et al. (2020a), Spinoni et al. (2019), Rauniyar and Power (2020), Dai and Zhao (2017), Dowdy and Pepler (2018), BoM and CSIRO (2020)	*Medium confidence* in decrease in agricultural drought in northern Australia and increase in southern Australia.	
	New Zealand: Inconsistent trends. Drought frequency increased at 13 of 30 sites from 1972–2019 and decreased at 9 sites. Drought intensity increased at 14 sites, 11 of which are in the north, and decreased at 9 sites, 7 of which are in the south.	Table 11.2b, MfE (2020)		
	Attribution: *Australia:* Reduced drought frequency in northern Australia and increased drought frequency in southwestern Australia have been partly attributed to anthropogenic climate change. Extreme fire weather in southeastern Australia in 2019–2020 was 30% more likely due to anthropogenic climate change. *New Zealand:* A study of the 2013 North Island New Zealand drought found a 0.2–0.4 fraction of attributable risk to anthropogenic climate change.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Delworth and Zeng (2014), Dey et al. (2019); Knutson and Zeng (2018), Harrington et al. (2014) (New Zealand), van Oldenborgh et al. (2021) (fire weather), IPCC AR6 WGI Chapter 8 (Section 8.3.1.6) (Douville et al., 2021)	Anthropogenic climate forcing has partly contributed to the reduction in drought probability in northern Australia, *low confidence* (*). Anthropogenic climate forcing has contributed to the increase in drought conditions in southwestern Australia, *medium* to *high confidence* (**).	
Central and South America	**Observations:** There is *medium* to *high confidence* in a mostly upward trend in meteorological droughts in four out of nine AR6 regions of Central and South America (mixed signals elsewhere, *low confidence*).	IPCC AR6 WGI Table 11.15 (Seneviratne et al., 2021)	There is *medium* to *high confidence* for an increase in droughts in several regions.	
	Mega-Drought in Central Chile, 2010: The region has experienced an uninterrupted sequence of dry years since 2010 with mean rainfall deficits of 20–40%. The Mega-Drought (MD) is the longest event on record and with few analogues in the last millennia.	Garreaud et al. (2020)		
	Attribution: In South America, attribution of two droughts in Northeast Brazil found no role of climate change: For the droughts in the larger São Paulo area in 2014 and 2016, factors other than climate change have been found to be the main drivers of the drought.	Otto et al. (2015c), Martins et al. (2018)	Minor (Northeast Brazil) to moderate (southwestern South America) increase of drought probability/intensity induced by anthropogenic climate forcing, *medium confidence* (**)	
	Mega-Drought in Chile, 2010: Event has been partly attributed to anthropogenic greenhouse gas emissions and ozone depletion. There is *medium confidence* that drying in central Chile can be attributed to human influence.	IPCC AR6 WGI Chapter 8 (Section 8.3.1.6) (Douville et al., 2021)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
Europe	**Observations:** In Europe, there are overall small changes observed with respect to droughts, and they depend on the drought metric, the season and region. For the Mediterranean, there is *medium confidence* in an observed drying trend. There is an increase in the probability and intensity of agricultural and ecological droughts caused by an increase in atmospheric evaporative demand and increase of hydrological droughts in Southern and Southeastern Europe.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), CCP4	There is *medium confidence* in an increase in drought in the Mediterranean and decrease in Northern Europe.	Increased evapotranspiration
	Mediterranean France: The Canadian Fire Weather Index, an indicator based only on climate, increased from 1958 to 2017.	Barbero et al. (2020)		
	Attribution: Anthropogenic influences on increased drought in the Mediterranean.	SR1.5 (Hoegh-Guldberg et al., 2018), IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Section 8.3.1.6, Douville et al. (2021)	Anthropogenic climate forcing has increased in drought conditions in the Mediterranean region and reduced drought conditions in northern regions, *medium* to *high confidence* (**).	
	Mediterranean France: Anthropogenic climate change accounting for nearly half the increase in fire risk index.	Barbero et al. (2020)		
North America	**Observations:** Droughts have become less frequent, less intense, or shorter in central North America since 1950. There are inconsistent trends in other regions, although some heatwaves have reached record intensity in western regions of the USA.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Chapter 8 (Section 8.3.1.6) (Douville et al., 2021)	There is *medium confidence* in an increase in ecological and agricultural drought in western North America.	
	California 21st century drought conditions: Southwestern North America has been anomalously dry and warm in the 21st century (2000–2018) relative to the 20th century, with reduced river flow and lake levels and declines in groundwater availability.	Williams et al. (2020), Xiao et al. (2018) (Colorado river flow), Rodell et al. (2018), Faunt et al. (2016) (both on groundwater reduction)		
	Attribution: Anthropogenic climate change accounts for half the severity of the strong soil moisture deficits in the last two decades in western North America. Increased atmospheric evaporative demand played a dominant role in the intensification of the 2014 drought in California: Anthropogenic climate forcing has increased the probability of co-occurring warm–dry conditions like those that created the 2012–2014 drought. Even in the absence of trends in mean precipitation, or trends in the occurrence of extremely low-precipitation events, the risk of severe drought in California has increased due to extremely warm conditions induced by anthropogenic global warming.	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021), Chapter 8 (Section 8.3.1.6) (Douville et al., 2021), Diffenbaugh et al. (2015), Williams et al. (2015)	Anthropogenic forcing has contributed to recent droughts and drying trends in western North America, *medium* to *high confidence* (**). No broad assessment elsewhere	
	Anthropogenic climate forcing has increased the probability of the following high-impact droughts: USA, Northern Great Plains, 2017; USA, Washington State, 2015	Section 4.2.5, Table 4.4, Lee et al. (2021)		
Small Islands	**Observations:** In the Caribbean, the self-calibrating Palmer Drought Severity Index (scPDSI) calculated for the years from 1950 to 2016 shows a clear drying trend in the region and shifts to increasing dry conditions. The trend is –0.09 per decade ($p < 0.05$, negative values indicate drought conditions, while 0 indicates normal conditions) The most severe drought was recorded in the 2013–2016 period.	Herrera and Ault (2017), Herrera et al. (2018)		
	Attribution: Anthropogenic climate forcing has contributed ~15–17% to the severity and ~7% to the spatial extent of the 2013–2016 drought.	Herrera et al. (2018)	Anthropogenic climate forcing has contributed to drought conditions in the Caribbean, *low confidence* (*). No assessment elsewhere	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
	Ocean—Warming			
Global	**Observations:** More than 90% of the Earth's energy imbalance between 1971 and 2010 has been stored as heat in the ocean and has warmed its water masses.	IPCC AR6 WGI Section 7.2.2.2 (Forster et al., 2021)	*High confidence*	
	Sea surface temperatures (SSTs) have risen at global scales, at a rate of 0.15°C per decade over the satellite era (1980–2020), and at an average rate of 0.09°C per decade for the period 1900–2020. SST has warmed in all ocean sectors, with the exception of some regions such as the eastern Pacific Ocean, the North Atlantic Ocean, and the Southern Ocean, which have warmed slowly or cooled owing to regional ocean dynamics.	IPCC AR6 WGI Section 9.2.1.1, Figure 9.3 (Fox-Kemper et al., 2021)	*High confidence*	
	Since the early 1970s, ocean has been warming at average rates of >0.1°C per decade in the upper 75 m and 0.015°C per decade at 700 m depth.	Reid (2016) (ocean heat uptake), AR5 (ocean warming)		
Below 2000 m	Strong warming in the Southern Ocean, warming in the North Atlantic and cooling throughout most of the Indo-Pacific over the 21st century at 2000–4000 m.	Desbruyères et al. (2017)	*Medium confidence*	
Below 4000 m	Warming is detectable throughout the Southern Ocean basin, with a global mean trend of 0.53°C yr^{-1} from 1990 to 2010.	IPCC AR6 WGI Section 9.2.2.1, Purkey and Johnson (2010) Desbruyères et al. (2016)		
	Attribution: Basin-scale temperature changes in the upper 0–700 m of the ocean since 1955 are induced by anthropogenic forcing.	IPCC AR6 WGI Section 9.2.2.1 (Fox-Kemper et al., 2021)	Strong contribution of anthropogenic climate forcing in ocean warming, *virtually certain* (***)	
	Improved Southern Ocean observations have revealed that large-scale 0–2000 m temperature changes can be attributed to mainly anthropogenic greenhouse gases.	IPCC AR6 WGI Section 9.2.2.1 (Fox-Kemper et al., 2021)	*Medium confidence*	
S06	Marine ecosystems—Marine heatwaves			
Global	**Observations:** From 1925 to 2016, marine heatwaves have become more frequent (+34%) and longer (+17%), resulting in an increase in the number of marine heatwave days at the global scale over the same period (+54%). From 1981 to 2017, the frequency, duration and intensity of large marine heatwaves increased: In the first decade, 27 large marine heatwaves occurred with an average duration of 32 d, an average peak temperature anomaly of 4.8°C. By contrast, 172 large marine heatwaves occurred in the past decade, with an average duration of 48 d, an average peak temperature anomaly of 5.5°C.	Bond et al. (2015), Zhou and Wu (2016), Jackson et al. (2018), Oliver et al. (2017), Oliver et al. (2018a), Oliver et al. (2018b), Benthuysen et al. (2018), Kim and Han (2017), Holbrook et al. (2019), Smale et al. (2019), Smale et al. (2015), Frölicher et al. (2018), Frölicher and Laufkötter (2018), Munari (2011), Laufkötter et al. (2020), Oliver et al. (2021)	*Very high confidence* in increasing frequency and intensity of marine heatwaves	
	Attribution: These trends in marine heatwaves are explained by an increase in ocean mean temperatures, and 87% of marine heatwaves are attributable to human-induced warming. Examples relevant for impact attribution below:	IPCC AR6 WGI Cross-Chapter Box 9.2 (Fox-Kemper et al., 2021), Frölicher et al. (2018), Oliver et al. (2018b) Laufkötter et al. (2020)	Major contribution of anthropogenic climate forcing to the observed increase in the frequency and duration of marine heatwaves, *very high confidence* (***)	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
Polar seas	**Observations:** *Marine heatwave in the Northwest Atlantic 2012* (partly polar partly temperate) with an intensity of 2.15°C (temperature anomaly above the baseline climatology averaged across the area of the heatwave and its duration) and a duration of 57 d (number of days where temperatures are above the 99.9th percentile of the baseline climatology); *Marine heatwaves in the Southern Ocean 2016* with an intensity of 1°C and a duration of 183 d.	Laufkötter et al. (2020)		
	Attribution: *Marine heatwave in the Northwest Atlantic 2012:* Likelihood of an event of this intensity occurring now is estimated to be more than 30 times higher than under pre-industrial conditions; likelihood for an event of this duration has increased 25-fold. *Marine heatwaves in the Southern Ocean 2016:* No significant effect of climate change on the likelihood for the occurrence of an event of this intensity or duration.	Laufkötter et al. (2020)	Major to minor increase of occurrence probabilities of some recent major marine heatwaves induced by anthropogenic climate forcing, *low confidence* (*)	
Temperate ocean	**Observations:** *Marine heatwave in Western Australia, 2011* (partly temperate, partly tropical) with an intensity of 2.26°C (temperature anomaly above the baseline climatology averaged across the area of the heatwave and its duration) and a duration of 101 d (number of days where temperatures are above the 99.9th percentile of the baseline climatology); *Marine heatwave in the Northwest Atlantic 2012* (partly polar, partly temperate, discussed above); *Marine heatwave in the Northeast Pacific from 2013 to 2015* with an intensity of 1.56°C and a duration of 367 d; *Marine heatwave in the Tasman Sea 2015 and 2016* with an intensity of 1.49°C and a duration of 175 d; *Marine heatwave in the Southwest Atlantic 2017* with an intensity of 1.96°C and a duration of 82 d.	Laufkötter et al. (2020), Oliver et al. (2021)		
	Attribution: *Marine heatwave in Western Australia, 2011:* Likelihood of an event of this duration occurring now is estimated to be about five times higher than under pre-industrial conditions, but the change is not significant; *Marine heatwave in the Northwest Atlantic 2012:* see above; *Marine heatwave in the Northeast Pacific from 2013 to 2015:* Likelihood of an event of this intensity and an event of this duration has increased more than 100-fold; *Marine heatwave in the Tasman Sea 2015 and 2016:* Likelihood for an event of this intensity and an event of this duration has increased about 50-fold and more than 100-fold, respectively. *Marine heatwave in the Southwest Atlantic 2017:* Likelihood of an event of this intensity and an event of this duration has increased more than 100-fold.	Laufkötter et al. (2020)	Moderate to major increase of occurrence probabilities of some recent major marine heatwaves induced by anthropogenic climate forcing, *low confidence* (*)	
Tropical ocean	**Observations:** *Marine heatwave in Western Australia, 2011* (partly temperate, partly tropical, discussed above). *Marine heatwave in the Indo-Australian Basin 2016* with an intensity of 1.67°C (temperature anomaly above the baseline climatology averaged across the area of the heatwave and its duration) and a duration of 90 d (number of days where temperatures are above the 99.9th percentile of the baseline climatology). The 2015–2016 North Australian Marine heatwave was the most intense and the second longest in the 35-year-long record of satellite measurements. *Marine heatwave in tropical Indian Ocean in 2015:* Heat stress exceeded the threshold for coral bleaching for >60% of reefs. *Marine heatwaves in the tropical Atlantic in 2005, 2010 and 2016:* 39–61% of reefs under heat stress exceeding bleaching thresholds.	Laufkötter et al. (2020), Park et al. (2017), Oliver et al. (2018b), Donner et al. (2007), Oliver et al. (2021)		
	Attribution: *Marine heatwave in Western Australia, 2011* (discussed above); *Marine heatwave in the Indo-Australian Basin 2016:* Likelihood of an event of this intensity occurring now is estimated to be more than 100 times higher than under pre-industrial conditions; *Marine heatwave in tropical Indian Ocean in 2015:* Event attribution analysis finds that the probability of sea surface temperature anomalies was increased at least seven-fold by anthropogenic forcing. *Marine heatwave in the tropical Atlantic in 2005:* Anthropogenic climate forcing is estimated to have increased the probability of the 2005 heatwave by at least an order of magnitude. The level of heat stress measured in the eastern Caribbean in 2005 would have been a 1-in-1,000-year event absent anthropogenic forcing.	Park et al. (2017), Laufkötter et al. (2020), Donner et al. (2007)	Moderate to major increase of occurrence probabilities of some recent major marine heatwaves induced by anthropogenic climate forcing, *low confidence* (*)	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Ocean—Changes in salinity patterns			
Global	**Observations:** Near-surface ocean salinity has changed since the 1950s, with regional enhancement of salinity contrasts: fresh regions freshening and salty regions becoming saltier.	IPCC AR6 WGI Section 9.2.2.2 (Fox-Kemper et al., 2021)	*Extremely likely*	Ocean freshening (decreased salinity) is induced by enhanced precipitation relative to evaporation and is exacerbated by sea ice melt.
	Attribution: Patterns of basin-scale salinity changes are extremely likely to result from anthropogenic forcing in the 0–700 m ocean since the mid-20th century.	IPCC AR6 WGI Section 9.2.2.2 (Fox-Kemper et al., 2021)	Strong contribution of anthropogenic climate forcing to salinity changes, *extremely likely* (***)	
	Ocean composition—Acidification			
	Observations: Over the period 1991–2011, mean ocean pH declined by 0.018 ± 0.004 units per decade in 70% of ocean biomes, with the largest declines in the Indian Ocean, eastern Equatorial Pacific and the South Pacific subtropical biomes, with slightly lower rates of change in the Atlantic and Southern Oceans. The decline is accompanied by a fall in concentration and the saturation states of various calcium carbonates. The depths at which spontaneous dissolution of calcium carbonate minerals (aragonite and calcite saturation depths) vary considerably between and within oceans. In some locations of the western and equatorial Atlantic Ocean, saturation depth has risen by ~300 m.	SROCC, Chapter 5: Lauvset et al. (2015), Sulpis et al. (2018) (rise of saturation depth); Negrete-García et al. (2019) (rise of saturation depth)	Decline in ocean pH *virtually certain*	
	Attribution: Over the last two decades, the ocean has sequestered about 25% of the CO_2 released by anthropogenic activities, which drives the decline of ocean pH.	SROCC, Chapter 5, Quéré et al. (2018)	Anthropogenic CO_2 emissions are the main driver of the observed global scale ocean acidification with only local exceptions; *high confidence* (***).	The rise in atmospheric CO_2 causes ocean acidification. Locally, surface acidification can be induced by high fertilizer inputs.
	Increased fertilizer runoff and atmospheric deposition of anthropogenic nitrogen and sulphur has enhanced surface ocean acidification as shown for the Gulf of Mexico and the East China Sea.	Doney et al. (2007), Doney et al. (2009), Cai et al. (2011)		
S08a	Coastal systems—Mean sea levels Global mean changes in sea level are measured as increase or decrease in the volume of the ocean divided by the ocean surface area. Regional attribution assessments refer to relative sea levels, i.e., relative to the land at a particular location as measured at tide gauges. There is no attribution statement provided for Figure 16.2 if attribution studies only refer to changes in absolute (eustatic) regional sea levels, i.e., the distance from the centre of the Earth to the sea surface.			
Global	**Observations:** Global mean sea level rose at a rate of 1.35 [0.78–1.92] mm yr^{-1} for the period 1901–1990 and 3.25 [2.88–3.61] mm yr^{-1} for 1993–2018.	IPCC AR6 WGI Chapter 2, Palmer et al. (2021)	The rate of global mean sea level rise since the 20th century is faster than over any preceding century in at least the last three millennia, *high confidence* (***).	
	Attribution: Today, climate change is the main driver of global mean sea level rise. At least 70% of the combined change in ice mass loss from glaciers and ice sheets, and thermal expansion since 1970 can be attributed to anthropogenic forcing. The percentage has increased over the course of the 20th century.	SROCC, IPCC AR6 WGI Chapter 3 (Eyring et al., 2021), Marcos and Amores (2014) (thermal expansion), Slangen et al. (2014), Slangen et al. (2016) (total across glaciers, Antarctic and Greenland ice sheet surface mass balance and thermal expansion)	Anthropogenic climate forcing is the dominant driver of observed increase in global mean sea level at least since 1970, *high confidence* (***).	Global mean sea level rise is driven by thermal expansion, mass loss of mountain glaciers and the Greenland and Antarctic ice sheet as well as changes in land water storage.

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	The direct anthropogenic influence on global sea level through land water storage (–0.21 mm yr^{-1}) is small compared with ice mass loss and thermal expansion (1.52 mm yr^{-1}) over the period 1900–2018. The dominance of the latter terms increases for the periods 1957–2018 and 1993–2018. Anthropogenic alteration of land water storage peaks with dam construction in the 1970s and strongly declines thereafter.	Frederikse et al. (2020)		
Africa	**Observations:** Over 1900–2018, basin mean relative sea level rose 1.3 ± 0.5 mm yr^{-1} in the Indian Ocean–South Pacific, 2.1 ± 0.7 mm yr^{-1} in the South Atlantic and 1.1 ± 0.3 mm yr^{-1} in the subpolar North Atlantic. Over 1993–2018, basin mean relative sea level rose 3.9 ± 0.6 mm yr^{-1} in the Indian Ocean–South Pacific, 3.9 ± 1.4 mm yr^{-1} in the South Atlantic and 2.7 ± 0.5 mm yr^{-1} in the subpolar North Atlantic.	Dangendorf et al. (2019), Frederikse et al. (2020) (source for basin estimates), AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence* in magnitude and direction of change on ocean basin scale (***)	
	Attribution: Ice mass loss and thermal expansion are the main contributors to relative sea level rise in the Indian Ocean–South Pacific and South Atlantic over 1957–2018 and in the subpolar North Atlantic over 1993–2018. Anthropogenic forcing is the main driver of these contributors since the 1970s. Non-climate-related drivers play a minor role. See global assessment for details.	Frederikse et al. (2020), AR6 WGI Chapter 3 (Eyring et al., 2021)	Anthropogenic climate forcing is the dominant cause of sea level rise around Africa over 1993–2018, *low confidence* (*).	Absolute local sea level changes are driven by patterns induced by changing ocean dynamics in addition to global sea level change processes. In addition to absolute local sea levels, relative ones are subject to vertical land movements induced by subsidence or changes in sedimentation.
Asia	**Observations:** Over 1900–2018, basin mean relative sea level rose 1.3 ± 0.5 mm yr^{-1} in the Indian Ocean–South Pacific and 1.7± 0.4 mm yr^{-1} in the Northwest Pacific. Over 1993–2018, basin mean relative sea level rose 3.9 ± 0.6 mm yr^{-1} in the Indian Ocean–South Pacific and 2.8 ± 0.7 mm yr^{-1} in the Northwest Pacific.	Dangendorf et al. (2019), Frederikse et al. (2020) (source for basin estimates), AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence* in magnitude and direction of change on ocean basin scale	
	Along the Bohai Sea, the Yellow Sea, the East China Sea and the South China Sea (the 'China Seas') coastline, records from 18 tide gauge stations show an average increase in relative sea levels of 2.6 ± 0.5 mm yr^{-1} (1950–2016) and 3.7 ± 0.8 mm yr^{-1} (1980–2016).	Qu et al. (2019)	*High confidence* in increasing relative sea levels along China's seas	
	In the Bay of Bengal, satellite altimetry-based absolute sea level data show a positive trend of 3.11 ± 0.44 mm yr^{-1} over the period 1993–2010 in line with the trend in global mean sea level. At four out of five available tide gauges, no significant trends in relative annual mean sea levels are detected. One gauge station shows a significant increase in annual mean relative sea level.	Ghosh et al. (2018), Antony et al. (2016)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
	Attribution: Ice mass loss and thermal expansion are the main contributors to relative sea level rise in the Indian Ocean–South Pacific and Northwest Pacific over 1957–2018. Anthropogenic forcing is the main driver of these contributors since the 1970s. Non-climate-related drivers are minor. See global assessment for details.	Frederikse et al. (2020), AR6 WGI Chapter 3 (Eyring et al., 2021)	Anthropogenic climate forcing is the dominant cause of sea level rise around Asia since the 1970s, *low confidence* (*).	Absolute local sea level changes are driven by patterns induced by changing ocean dynamics in addition to global sea level change processes. In contrast to absolute sea levels, relative ones are subject to local changes in land surface and bathymetry induced by subsidence or changes in sedimentation.
	China's seas: Tide gauge stations along the China Seas, in particular in cities, have undergone significant subsidence due to groundwater extraction. During the satellite altimetry data period 1993–2016, contributions from vertical land movement to relative sea level changes range from −4.5 ± 1.0 mm yr^{-1} to 1.4 ± 1.3 mm yr^{-1} across the stations. After removing the effect of vertical land movement (assuming that the trend due to vertical land movement found during 1993–2016 is the same over longer periods), absolute sea level is estimated to rise at a rate of 3.2 ± 1.1 mm yr^{-1} (1993–2016), 2.9 ± 0.8 mm yr^{-1} (1980–2016) and 1.8 ± 0.5 mm yr^{-1} (1950–2016) when averaging over all available tide gauge records. The contribution of thermal expansion and salinity changes is estimated to reach up to 0.9 ± 0.3 mm yr^{-1} (1950–2016). Glaciers and ice sheets are estimated to reach up to 1.1 ± 0.1 mm yr^{-1} (1950–2016). Given the dominant influence of anthropogenic climate forcing on the latter components on a global scale since 1970, anthropogenic climate forcing is considered to provide a major contribution to the observed increase in regional relative sea levels along China's seas.	Qu et al. (2019)	Major contribution of anthropogenic climate forcing to regional sea level rise along China's seas, *low confidence* (*)	
	Bay of Bengal: The 1993–2010 trend in absolute sea level is in line with the trend in global mean sea level. The missing trend in four out of five tide gauges records indicate that vertical land movements may play an important role regarding changes in relative sea levels. However, the limited number of stations does not allow for a systematic assessment.	Ghosh et al. (2018), Antony et al. (2016)		
Australasia	**Observations:** Over 1900–2018, basin mean relative sea level rose 1.3 ± 0.5 mm yr^{-1} in the Indian Ocean–South Pacific. Over 1993–2018, basin mean relative sea level rose 3.9 ± 0.6 mm yr^{-1} in the Indian Ocean–South Pacific.	Dangendorf et al. (2019), Frederikse et al. (2020) (source for basin estimates), AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence* in magnitude and direction of change on ocean basin scale	
	Australia: For the periods 1966–2009 and 1993–2009, the average trends of relative sea level around the coastline are 1.4 ± 0.3 mm yr^{-1} and 4.5 ± 1.3 mm yr^{-1}, which become 1.6 ± 0.2 mm yr^{-1} and 2.7 ± 0.6 mm yr^{-1} after removal of the signal correlated with ENSO. Relative sea level rise varied between 1.9 ± 1.6 mm yr^{-1} 2.5 ± 1.1 mm yr^{-1} for the four stations with records exceeding 75 years in length. The 1992–2019 average trend in sea surface height around Australia observed by satellites was 3.4 mm yr^{-1}.	White et al. (2014), Watson (2020)		
	New Zealand: Relative sea levels increased by 1.8 mm yr^{-1} from 1900 to 2018, 1.2 mm yr^{-1} from 1900 to 1960 and 2.4 mm yr^{-1} from 1961 to 2018. A 20th century trend of 1.7 mm yr^{-1} has been reconstructed using records at 10 tide gauges along the coast covering different periods.	Bell and Hannah (2018), Hannah and Bell (2012), Denys et al. (2020)		

Detection and attribution of observed changes in climate-related systems
('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
	Attribution: Ice mass loss and thermal expansion are the main contributors to relative sea level rise in the Indian Ocean–South Pacific over 1957–2018. Anthropogenic forcing is the main driver of these contributors since the 1970s. Non-climate-related drivers are minor. See global assessment for details.	Frederikse et al. (2020), AR6 WGI Chapter 3	Anthropogenic climate forcing is the dominant cause of sea level rise around Australasia since the 1970s, *low confidence* (*).	Absolute local sea level changes are driven by patterns induced by changing ocean dynamics in addition to global sea level change processes. In contrast to absolute sea levels, relative ones are subject to local changes in land surface and bathymetry induced by subsidence or changes in sedimentation.
	Australia: Vertical land motion contributes about 40% to relative sea level rise for the four Australian stations exceeding 75 years in length.	Watson (2020)		
	New Zealand: The contribution from vertical land movement to relative sea level rise is small but significant (0.2 mm yr^{-1}).	Denys et al. (2020)		
Central and South America	**Observations:** Over 1900–2018, basin mean relative sea level rose 1.3 ± 0.5 mm yr^{-1} in the Indian Ocean–South Pacific, 2.1 ± 0.7 mm yr^{-1} in the South Atlantic and 1.2 ± 0.4 mm yr^{-1} in the Eastern Pacific. Over 1993–2018, basin mean relative sea level rose 3.9 ± 0.6 mm yr^{-1} in the Indian Ocean–South Pacific, 3.9 ± 1.4 mm yr^{-1} in the South Atlantic and 1.8 ± 0.7 mm yr^{-1} in the Eastern Pacific.	Dangendorf et al. (2019), Frederikse et al. (2020) (source for basin estimates), AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence* in magnitude and direction of change on ocean basin scale.	
	Caribbean: Within the basin, large spatial variability in the trends is identified. In the period 1908–2009 of available tide gauge records, relative sea levels have been rising with a rate between -2.0 mm yr^{-1} and 10.7 mm yr^{-1}.	Torres and Tsimplis (2013)		
	Attribution: Ice mass loss and thermal expansion are the main contributors to relative sea level rise in the Indian Ocean–South Pacific, South Atlantic and Eastern Pacific over 1957–2018. Anthropogenic forcing is the main driver of these contributors since the 1970s. Non-climate-related drivers are minor. See global assessment for details.	Frederikse et al. (2020)	Anthropogenic climate forcing is the dominant cause of sea level rise around Central and South America rise since the 1970s, *low confidence* (*).	Absolute local sea level changes are driven by patterns induced by changing ocean dynamics in addition to global sea level change processes. In contrast to absolute sea levels, relative ones are subject to local changes in land surface and bathymetry induced by subsidence or changes in sedimentation.
	Caribbean: The influence from glacial isostatic adjustment ranges between –0.3 and 0.5 mm yr^{-1}, but the large local variability in relative sea level trends indicates that the influence from unknown vertical land movements cannot be ruled out.	Torres and Tsimplis (2013)	No individual quantification of contribution of anthropogenic climate forcing in context of other drivers	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
Europe	**Observations:** Over 1900–2018, basin mean relative sea level rose 1.1 ± 0.3 mm yr^{-1} in the subpolar North Atlantic. Over 1993–2018, basin mean relative sea level rose 2.7 ± 0.5 mm yr^{-1} in the subpolar North Atlantic.	Dangendorf et al. (2019), Frederikse et al. (2020) (source for basin estimates), IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence* in magnitude and direction of change on ocean basin scale	
	Baltic Sea: In the study period 1950–2015, relative sea level trends at tide gauge stations in the Baltic Sea range from a sinking of 7.49 mm yr^{-1} in the north (Ratan, Sweden) to a rise of sea levels of 2.04 mm yr^{-1} in the south (Klaipeda, Lithuania).	Gräwe et al. (2019)		
	Southern Europe: The five tide gauge records that span most of the 20th century show positive relative sea level trends between 1.2 and 1.5 ± 0.1 mm yr^{-1}. Trends obtained from the 21 longest records (>35 years) are smaller in the Mediterranean (0.3 to –0.7 mm yr^{-1}) than in the neighbouring Atlantic sites (1.6 to –1.9 mm yr^{-1}) for the period 1960–2000. The strongest trend is reported for Vigo, Spain (2.5 mm yr^{-1}).	Marcos and Tsimplis (2008)		
	Attribution: Ice mass loss and thermal expansion are the main contributors to relative sea level rise in the subpolar North Atlantic over 1993–2018. Anthropogenic forcing is the main driver of these contributors since the 1970s. Non-climate-related drivers are minor. See global assessment for details.	Frederikse et al. (2020)	Anthropogenic climate forcing is the dominant cause of sea level rise around Europe over 1993–2018, *low confidence* (*).	Absolute local sea level changes are driven by patterns induced by changing ocean dynamics in addition to global sea level change processes. In contrast to absolute sea levels, relative ones are subject to local changes in land surface and bathymetry induced by subsidence or changes in sedimentation.
	Baltic Sea: The contribution of vertical land movement caused by glacial isostatic adjustment ranges from –12 mm yr^{-1} in the northern Gulf of Bothnia to 1 mm yr^{-1} along the coast of Denmark. In the study period 1950–2015, absolute sea level rise contributed between 1.71 ± 0.51 mm yr^{-1} in the southwest and 2.34 ± 1.05 mm yr^{-1} in the northeast to relative sea level changes. The effect of absolute sea level rise is clearly outweighed by vertical land movements in most regions. The trends in absolute sea levels of around 2 mm yr^{-1} are in line with global mean sea level rise mainly driven by anthropogenic climate forcing. Minor regional variations in derived absolute sea level rise are due to meteorological variations of uncertain origin.	Gräwe et al. (2019)	Minor contribution of anthropogenic climate forcing to the observed decrease in the northern regions, strong contribution of anthropogenic climate forcing to the observed increase in the southern regions, *low confidence* (*)	
North America	**Observations:** Over 1900–2018, basin mean relative sea level rose 2.5 ± 0.6 mm yr^{-1} in the subtropical North Atlantic, 1.2 ± 0.3 mm yr^{-1} in the subpolar North Atlantic and 1.2 ± 0.4 mm yr^{-1} in the Eastern Pacific. Over 1993–2018, basin mean relative sea level rose 4.0 ± 1.2 mm yr^{-1} in the subtropical North Atlantic, 2.7 ± 0.5 mm yr^{-1} in the subpolar North Atlantic and 1.8 ± 0.7 mm yr^{-1} in the Eastern Pacific.	Dangendorf et al. (2019), Frederikse et al. (2020) (source for basin estimates), IPCC AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence* in magnitude and direction of change on ocean basin scale	

Detection and attribution of observed changes in climate-related systems (‘Climate Attribution’)				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Attribution: Ice mass loss and thermal expansion are the main contributors to relative sea level rise in the Eastern Pacific and subtropical North Atlantic over 1957–2018 and in the subpolar North Atlantic over 1993–2018. Anthropogenic forcing is the main driver of these contributors since the 1970s. Non-climate-related drivers are minor. See global assessment for details.	Frederikse et al. (2020)	Anthropogenic climate forcing is the dominant cause of basin mean sea level rise around North America over 1993–2018, *low confidence* (*).	Absolute local sea level changes are driven by patterns induced by changing ocean dynamics in addition to global sea level change processes. In contrast to absolute sea levels, relative ones are subject to local changes in land surface and bathymetry induced by subsidence or changes in sedimentation.
Small Islands	**Observations:** Over 1900–2018, basin mean relative sea level rose 1.3 ± 0.5 mm yr^{-1} in the Indian Ocean–South Pacific, 1.7 ± 0.4 mm yr^{-1} in the Northwest Pacific, 1.8 ± 0.7 mm yr^{-1} in the Eastern Pacific and 2.5 ± 0.6 mm yr^{-1} in the Subtropical North Atlantic. Over 1993–2018, basin mean relative sea level rose 3.9 ± 0.6 mm yr^{-1} in the Indian Ocean–South Pacific, 2.8 ± 0.7 mm yr^{-1} in the Northwest Pacific, 1.8 ± 0.7 mm yr^{-1} in the Eastern Pacific and 4.0 ± 1.2 mm yr^{-1} in the subtropical North Atlantic.	Dangendorf et al. (2019), Frederikse et al. (2020) (source for basin estimates), AR6 WGI Chapter 12 (Ranasinghe et al., 2021)	*High confidence* in magnitude and direction of change on ocean basin scale	
	For the period 1993–2017, altimetry measurements show an increase in mean absolute sea level in coastal zones (within 50 km distance from coast) of small islands. However, trends are heterogeneously distributed, with the highest increases in Oceania and lowest in North America.	Li et al. (2019a)		
	Solomon Islands: A rapid rise in sea levels in the Solomon Islands between 1994 and 2014 of about 15 cm (average of 7 mm yr^{-1} between 1994 and 2014) is indicated, which is above the longer-term trend of 3 mm yr^{-1} for the western Equatorial Pacific.	Albert et al. (2016)		
	Indian Ocean: From 1950 to 2009, relative sea level rose by 1.8 ± 0.3 mm yr^{-1} at Cocos Island and Diego Garcia, 2.8 ± 0.1 mm yr^{-1} at Malé Hulule in the Maldives and 2.6 ± 0.4 mm yr^{-1} at Le Tampon on the Reunion Island.	Palanisamy et al. (2014)		
	Attribution: Ice mass loss and thermal expansion are the main contributors to relative sea level rise in the Indian Ocean–South Pacific, the Northwest Pacific, the Eastern Pacific and the subtropical North Atlantic over 1957–2018. Anthropogenic forcing is the main driver of these contributors since the 1970s. Non-climate-related drivers are minor. See global assessment for details.	Frederikse et al. (2020)	Anthropogenic climate forcing is the dominant cause of sea level rise around Small Islands since the 1970s, *low confidence* (*).	Absolute local sea level changes are driven by patterns induced by changing ocean dynamics in addition to global sea level change processes. In contrast to absolute sea levels, relative ones are subject to local changes in land surface and bathymetry induced by subsidence or changes in sedimentation.
	Solomon Islands: Increased sea level rise since the 1990s is partly due to stronger trade winds, related to ENSO and the Pacific Decadal Oscillation (PDO).	Albert et al. (2016)	Strong contribution of anthropogenic climate forcing to observed increase in relative sea level in the considered sites on Solomon Islands, *low confidence* (*)	
	Indian Ocean: More than 50% of the relative sea level rise at Malé Hulule in the Maldives and Le Tampon in the Reunion is due to land subsidence.	Palanisamy et al. (2014)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
S08b	Coastal systems—Extreme water levels			
Global	**Observations:** Extreme water levels as observed by tide gauges have increased along most of the global coastlines with a median 165% increase in high-tide flooding between 1960–1980 and 1995–2014.	IPCC AR6 WGI 9.6.4.1 (Fox-Kemper et al., 2021)	*High confidence*	
	Attribution: Relative sea level change (as opposed to changes in tide and surge) is the primary driver of changes in extreme coastal water levels at most locations.	IPCC AR6 WGI, Chapter 9 (Fox-Kemper et al., 2021)	Major contribution of anthropogenic climate forcing to increase in extreme water levels, *medium confidence* (**)	In addition to the drivers of long-term sea levels discussed above, changes in extreme sea levels also depend on changes in storm activity, including tropical cyclones.
	Observed changes in extreme sea level can very likely be attributed to global warming, because long-term relative sea level change can be attributed to global warming.	IPCC AR6 WGI Section 9.6.4.1 (Fox-Kemper et al., 2021)		
Africa	**Observations:** Missing studies.			
	Attribution: Missing studies.		No assessment	
Asia	**Observations:** *Northwest Pacific/South China Sea:* Maximum annual sea levels as well as 90th, 99th and 99.9th percentile sea levels exhibit significant increasing trends in 12 of 15 gauges.	Feng et al. (2015), Feng et al. (2018)	*High confidence* in increasing extreme water levels along Northwest Pacific/South China Sea	
	East India/Bay of Bengal: Four out of five available tide gauges show no significant trends in the high-water percentiles. One gauge station shows a significant increasing trend in all high-water percentiles.	Antony et al. (2016)	*Low confidence*	
	Attribution: While extreme surges are driven by tropical cyclones in the Northwest Pacific and by monsoonal winds in the South China Sea, all observable trends in extreme water levels are strongly related to changes in relative sea level. As anthropogenic climate forcing is a major driver of long-term relative sea level rise (see section S08a Coastal systems – Mean sea levels), the observed trends in extreme sea level can very likely be attributed to global warming, too.	Pham et al. (2019)	Strong contribution of anthropogenic climate forcing to positive trends in extreme water levels along China's seas, *low confidence* (*); no attribution in other regions (such as Indian Ocean)	Indian ocean dipole events are a driver of Indian ocean sea level variability and thus influence extremes.
	Observed changes in extreme water levels seem to be in line with the associated changes in annual mean relative water levels. However, as the contributions of the individual drivers of annual mean water levels have not been quantified (see S08a Coastal systems – Mean sea levels), changes in extreme water levels cannot be attributed either.	Antony et al. (2016)		
Australasia	**Observations:** No assessment.			
	Attribution: No assessment.		No assessment	
Central and South America	**Observations:** *Caribbean:* Extreme water levels (at the 50th, 90th, 95th, 99th and 99.9th percentile) increase in all of the five available long-term (more than 20 years of data) gauge records at rates between 1.3 and 9.9 mm yr^{-1}.	Torres and Tsimplis (2014)		
	South America: There is no systematic assessment of changes in extreme coastal water levels but only observations of extreme absolute water levels (reanalysis and satellite altimetry) showing a positive trend over the last 5 decades.	Losada et al. (2013)	*Medium confidence*	
	Attribution: *Caribbean:* The increase in extreme water levels is consistent with the trend in mean relative sea level since the rates of the upper sea level percentiles are in line with mean sea level trends at each gauge station.	Torres and Tsimplis (2014)	No separate assessment	
	South America: Only in the Río de la Plata is the dominant driver storm surge; in all other areas along the coast of South America, it is sea level rise. As there is no quantification of mean sea level changes induced by climate forcing, there is no quantification of its contribution to extreme water levels either.			

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
Europe	**Observations:** *Mediterranean Sea*: Significant increasing linear trends of annual 99.9th percentile of hourly water levels between the mid-20th century and the year 2000 (exact years depending on data availability at each station) are observed in the Atlantic and Adriatic regions (5 out of 11 available long-term records for the Mediterranean Sea). There are no significant trends in the remaining records.	Marcos et al. (2009) (Mediterranean Sea)		
	Atlantic, North Sea: According to tide gauge records, the intensity and number of occurrences of extremes (skew surges as well as high percentiles) has increased over the last 100 years.	Dangendorf et al. (2014) (North Sea), Haigh et al. (2016) (UK), Marcos and Woodworth (2017) (Atlantic)		
	Baltic Sea: The 12 tide gauge stations in the study show varying trends in the annual 99th percentile of monthly relative sea levels ranging from –5.64 mm yr^{-1} in the north to 1.71 mm yr^{-1} in the south.	Ribeiro et al. (2014), Barbosa (2008) (Baltic Sea)		
	Attribution: *Mediterranean Sea*: No attribution assessment available.		Minor (Baltic Sea) to major (Atlantic, North Sea) contribution (increase in extreme water levels) by anthropogenic climate forcing, *low confidence* (*)	
	Atlantic, North Sea: Changes in extreme water levels are significantly correlated to both local absolute mean sea level rise and changes in the Northern Atlantic Oscillation. Most of the observed changes in extreme sea level can very likely be attributed to global warming, because long-term MSL change as well as changes to the Northern Atlantic Oscillation can be attributed to global warming.	Marcos and Woodworth (2017)		
	Baltic Sea: While the main driver of sea level change in this region is vertical land movement due to glacial isostatic adjustment (see section about mean sea level), the extreme water levels are also influenced by global mean sea level (MSL) rise and changed weather patterns. Model simulations only accounting for observed global mean sea level rise and observed changes in weather patterns indicated that both processes lead to an increase in absolute extreme water water levels (1.5–10 mm yr^{-1} over the period 1961–2005). As changes in both drivers are dominated by anthropogenic climate forcing, changes in absolute extreme water levels are dominated by anthropogenic climate forcing, too. However, in terms of coastal water levels, the effects are overcompensated by the dampening effect of the upward vertical land movement. That is why the contribution of anthropogenic climate forcing to local changes in extreme water levels are rated 'minor'.	Pindsoo and Soomere (2020)		
North America	**Observations:** In the New York harbour region, 8 of the 20 highest recorded water levels recorded since 1927 have occurred since 1990, and process-based model simulations indicate that a ~2.25-m flood height which was a 1-in-500-year event in 850–1800 in the pre-anthropogenic era has become a 1 in ~25 year event in 1970–2005 in the anthropogenic era.	Talke et al. (2014), Reed et al. (2015)		
	Upward trends in extreme water levels (annual 99th percentiles) are significant at 70% of the stations along the coasts of the North Atlantic and the Gulf of Mexico.	Marcos and Woodworth (2017)		
	The probability of nuisance-level flood events has increased at almost all 45 tide gauges along the US east and west coast between 1950 and 2012, with the only exception in the northwest, where return periods remained the same.	Sweet (2014)		
	Significant increasing trends exist in extreme sea level records (annual 99.5th percentile of hourly records) at 18 of 20 tide gauges along the Atlantic and Pacific coast for the 1929–2013 period, varying between 0 and 7 mm yr^{-1}.	Wahl and Chambers (2015)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
	Attribution: *New York:* Observed changes in extreme water levels for New York are dominated by sea level rise compared with changes in hurricane activity. However, a large part of the local relative sea level rise has been due to postglacial adjustment, i.e., a natural cause (see discussion of mean sea level changes in the section above).	Talke et al. (2014), Reed et al. (2015)	Moderate contribution of anthropogenic warming to increase in extreme water levels, *medium confidence* (**)	
	Relevance of hurricane activity along the Atlantic coast: In addition, the frequency of large surge events at tide gauges along the Atlantic coast, modelled using a threshold surge index, exhibits a statistically significant increasing trend in the period 1923–2008. This is highly correlated with most measures of TC activity. Increasing trends in TC activity can be attributed partly to anthropogenic warming (see section S07 Coastal systems – Tropical cyclone activity).	Grinsted et al. (2012)		
	Relevance of increasing mean sea levels along Atlantic and Pacific coastlines: The increasing trends in extreme sea levels along the Atlantic and Pacific coast largely follow relative sea level rise which is only in part due to anthropogenic warming (see S08a Coastal systems – Mean sea levels).	Wahl and Chambers (2015)		
Small Islands	**Observations:** *Central North Pacific/Hawaii:* The number of extreme sea level events recorded at one gauge station is increasing over the past 60 years.	Aucan et al. (2012) (for Midway, North Pacific)		
	Attribution: *Central North Pacific/Hawaii:* The increasing frequency of extreme water level events is estimated to be induced by changes in Pacific Decadal Oscillation (PDO). The observed change in the PDO has not been attributed to anthropogenic climate forcing.		Minor contribution of anthropogenic climate forcings to increasing extreme water levels in Central North Pacific/Hawaii, *low confidence* (*), no assessment elsewhere	
S07	Coastal systems—Tropical cyclone activity			
Global	**Observations:** Identifying past trends in tropical cyclone (TC) metrics remains a challenge due to the heterogeneous character of the historical instrumental data. There is substantial literature that finds positive trends in intensity-related metrics during the 'satellite period' limited to the past 40 years. For example, the likelihood that a TC will be at major TC intensity (category 3–5) and the precipitation associated with TCs have increased. However, there is evidence that the ~40-year period of highest-quality post-satellite era data is shorter than the time scale required for TC intensity trends to emerge from the noise.	AR6 WGI Section 11.7.1.2 (Seneviratne et al., 2021)	*Low* to *medium confidence*	
	North Atlantic TC activity has increased since the 1970s.	AR6 WGI Section 11.7.1.4 (Seneviratne et al., 2021)	*Virtually certain*	
	Poleward migration of the location of peak tropical cyclone intensity in the western North Pacific lies outside the range of natural variability.	AR6 WGI Section 11.7.1.4 (Seneviratne et al., 2021)	*Low* to *medium confidence*	
	Category 5 tropical cyclones have only recently emerged in the South Indian Ocean. Since 1989, their frequency of occurrence has increased. This increase poses a heightened risk of storm damage for the South Indian Ocean Island States.	Fitchett (2018)	*Low confidence*	
	TC translation speed has slowed over the USA since 1900, which is expected to increase local rainfall amounts as well as coastal and inland flooding.	AR6 WGI Section 11.7.1.2 (Seneviratne et al., 2021)		
	The frequency of rapidly intensifying TCs has increased globally over the past 40 years.	AR6 WGI Section 11.7.1.2 (Seneviratne et al., 2021)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
	Attribution: As tropical cyclone (TC) activities are affected by atmosphere–ocean coupling and associated multi-decadal modes, detection of anthropogenic effects from natural variabilities of these modes is generally difficult and particularly constrained by heterogeneity in long term observational data. In addition, SST patterns are also affected by aerosol forcing.	Lackmann (2014) (Hurricane Sandy, 2012), Takayabu et al. (2015) (Typhoon Haiyan, 2013), Patricola and Wehner (2018) (Hurricane Katrina, Maria, and Irma)	Minor influence of anthropogenic climate forcing on TC activity, *low confidence* (*), except for a moderate increase of TC activity induced by reduced aerosol forcing in the North Atlantic, *medium confidence* (**)	The genesis, development and tracks of TCs depend on conditions of the large-scale circulation of the atmosphere (e.g., wind shear) and ocean. The sea surface temperature distribution, together with the thermodynamic condition of the ocean mixed layer, directly affects TC activities.
	A reduction in aerosol forcing has contributed at least in part to the observed increase in tropical cyclone intensity in the North Pacific, in the Arabian Basin, and most prominently in the North Atlantic since the 1970s.	AR6 WGI Section 11.7.1.4 (Seneviratne et al., 2021)		
	While the slowdown of TC translation speed over the USA has contributions from anthropogenic forcing, and the poleward migration of TCs in the western North Pacific cannot be explained entirely by natural variability, there is only *limited evidence* for anthropogenic effects on rapid TC intensifications.	IPCC AR6 WGI Section 11.7.1.4 (Seneviratne et al., 2021)		
	Impacts of tropical-cyclone storm-surge flooding is exacerbated through sea level rise and intensifying rainfall. Anthropogenic climate change is the dominant driver of sea level rise (see S08a Coastal systems – Mean sea levels), and anthropogenic climate forcing is also affecting the occurrence of heavy rainfall events (see associated section of this table below).	IPCC AR6 WGI Chapter 11 (Seneviratne et al., 2021)		
S01	Cryosphere—Sea ice extent			
Polar seas	**Observations:** Arctic sea ice retreated, and seasonal area declined consistently since 1979. Arctic summer sea ice area during the last decade was the lowest since at least 1850.	IPCC AR6 WGI Chapter 9 (Fox-Kemper et al., 2021)	*Virtually certain*	
	No significant trend in overall Antarctic sea ice is observed from 1979 to 2020.	IPCC AR6 WGI Chapter 9 (Fox-Kemper et al., 2021)		
	Attribution: Anthropogenic climate forcing has very likely caused at least half of Arctic summer sea ice loss since 1979. A robust linear relationship between observed September sea ice area and cumulative carbon dioxide (CO_2) emissions implies a sustained loss of 3 ± 0.3 m^2 of September sea ice area per metric ton of CO_2 emission. The record low sea ice extent observed in 2012 has been shown to be consistent with a scenario including anthropogenic influence and to be extremely unlikely in a scenario excluding anthropogenic influence.	IPCC AR6 WGI Chapter 9 (Fox-Kemper et al., 2021), Notz and Stroeve (2016), Kirchmeier-Young et al. (2017a)	Major contribution of anthropogenic climate forcing to Arctic sea ice retreat, minor contributions to changes in Antarctic sea ice; *high confidence* (***)	
	Slight Antarctic regional increases or decreases in ice area result from regional wind forcing (*medium confidence*).			
S02	Cryosphere—Glacier mass			
Global	**Observations:** With few exceptions, glaciers have retreated since the second half of the 19th century and continued to retreat with increased rates since the 1990s (*very high confidence*); this behaviour is unprecedented in at least the last 2000 years (*medium confidence*). Global total glacier mass loss 1961–2016: 9625 Gt, 27 ± 22 mm. Approximately 30% increase of global glacier mass loss of 2006–2015 compared with 1986–2005. Glaciers are estimated to have contributed 0.027 ± 0.022 m to sea level rise between 1961 and 2016.	AR6 WGI Chapter 2 (Gulev et al. 2021), (Zemp et al. 2019), IPCC SROCC, AR6 WGI Chapter 9 (Fox-Kemper et al., 2021)	*Very high confidence* in global scale retreat (the exact numbers bear some uncertainty as indicated), *medium confidence* in unprecedentedness	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Attribution: Climate change has become the major driver of glacier retreat since the 1990s: The fraction of the total cumulative global glacier mass loss attributable to anthropogenic climate change since the pre-industrial era varies among the few available studies, between 25% and close to 100%. For the last 3 decades, there is consensus of a high contribution of anthropogenic climate change, from about 70% to 100%. Global glacier mass loss since the last decades of the 20th century cannot be explained without human induced warming (*high confidence*).	AR6 WGI Chapter 9 (Fox-Kemper et al., 2021), Marzeion et al. (2014), Slangen et al. (2016), SROCC, Roe et al. (2021)	Anthropogenic climate change has become the major driver of recent glacier mass loss, *high confidence* (***).	Increasing temperatures are clearly the main driver of global glacier loss. Locally to regionally, other climatic variables such as precipitation or humidity, or soot, can also play a role as drivers.
Africa	**Observations:** Persistent glacier mass loss since 1980. On Kilimanjaro, between 1912 and 2011 85% of the area lost, with a relatively constant retreat rate. On Mt. Kenya, glacier area has decreased from 0.6 to 0.1 km2 from the later 19th century to 2010.	Mölg et al. (2012), Pepin et al. (2014), Cullen et al. (2013), Prinz et al. (2016)		
	Attribution: While climate change clearly is the main driver of the observed losses, it is not yet fully clear how much of the observed climate change is due to anthropogenic forcing or induced by natural variability. On Kilimanjaro, land cover change is estimated to be responsible for 7–17% of glacier decline.	Mölg et al. (2012), Pepin et al. (2014), Cullen et al. (2013), Prinz et al. (2016)	Moderate to strong impact of anthropogenic climate change on observed glacier loss, *low* to *medium confidence* (*)	Precipitation and moisture increasing ablation by drying of summit climate of Kilimanjaro, lower humidity, less cloud cover and more solar radiation; in addition, there is less accumulation because of reduced precipitation.
Asia	**Observations:** Highest glacier mass loss in the eastern Himalayas (cumulative change 1960–2016: –8 m water equivalent); Karakoram is the only region in the world that has still exhibited some mass gain recently (cumulative change 1960–2016: +5 m water equivalent); Central Asia moderate mass loss since 1980, stronger mass loss in North Asia. In Caucasus and Middle East, cumulative changes from 1960 to 2016 close to –20 m water equivalent.	Zemp et al. (2019), Hock et al. (2019) (SROCC), Bolch et al. (2019)		
	Attribution: For the regions with higher losses, there is a good correlation between mass loss and increasing temperatures. In combination with current process-understanding, anthropogenic climate change provides a good explanation for the losses. However, for the Karakoram region, the relation to anthropogenic climate change is unclear.	Marzeion et al. (2014), Roe et al. (2021), Hock et al. (2019) (SROCC), Bolch et al. (2019)	Strong impact of anthropogenic climate change in regions with high mass losses, *medium confidence* (**), role of climate change for mass gain in Karakoram unresolved	Increasing (annual average) temperatures as the main driver of glacier change for most of the region. Smaller-scale and local conditions in precipitation and temperature drive spatial variability of glacier response. Length and area change of debris-covered glaciers imply slower response to climatic changes.
Australasia	**Observations:** Since 1970, consistent mass loss on New Zealand (NZ) glaciers, with an increasing negative trend. From 1978 to 2016, the area of 14 glaciers in the Southern Alps declined 21%. The end-of-summer snowline elevation for 50 glaciers rose 300 m from 1949 to 2019. Cumulative changes 1960–2016 have reached about –15 m water equivalent. From 1977 to 2018, NZ glacier ice volume decreased from 26.6 km^3 to 17.9 km^3 (a loss of 33%).	Zemp et al. (2019), Hock et al. (2019), (SROCC), Chinn and Chinn (2020), Salinger et al. (2019), Baumann et al. (2021), Salinger et al. (2021)		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Attribution: NZ glacier retreat partly attributed to climate change. The signal of anthropogenic climate change has strongly increased since the 1990s. Event attribution indicates that anthropogenic climate forcing has increased the probability of particularly high mass losses as observed in 2011 and 2018 across New Zealand's Southern Alps by a factor of 6 (2011) and a factor of 10 (2018) compared with conditions without anthropogenic climate forcing.	Vargo et al. (2020), Marzeion et al. (2014)	Strong contribution of anthropogenic climate change to today's glacier mass loss in New Zealand, *high confidence* since 2000 (***)	
Central and South America	**Observations:** Very strong glacier mass loss, especially in the Southern Andes (cumulative loss of –40 m water equivalent for 1960–2016). In the tropical Andes, cumulative loss from 1960 to 2016 has reached –30 m water equivalent. For the whole region, increasing trend of mass loss since 1980.	Zemp et al. (2019), Hock et al. (2019) (SROCC), Dussaillant et al. (2019), Reinthaler et al. (2019)		
	Palcaraju glacier, Peru: The Palcaraju glacier feeding Lake Palcacocha (Cordillera Blanca, Peru) retreated by 1.8 km since 1850.	Stuart-Smith et al. (2021)		
	Attribution: The strong, regionally consistent signal of glacier mass loss can only be explained by increasing (annual average) temperatures (the rate of temperature change is varying across the region).	Marzeion et al. (2014), Dussaillant et al. (2019), Huggel et al. (2020)	Strong reduction of glacier mass induced by anthropogenic climate change, *high confidence* (***)	Loss mainly driven by temperature increase, while precipitation changes play a minor role. Inter-annual variability strongly influenced by ENSO.
	The overall retreat of Palcaraju glacier is entirely attributable to the observed temperature trend, of which 85–105% is attributable to human greenhouse gas emissions. It is virtually certain that the observed retreat of Palcaraju glacier could not have occurred due to natural variability alone.	Stuart-Smith et al. (2021)		
Europe	**Observations:** From 2000 to 2014, a rapid glacier retreat across the European Alps (–39 km^2 yr^{-1}) with ice thickness changes of –0.5 to –0.9m yr^{-1} was observed. Strongest downwasting in the Swiss Glarus and Lepontine Alps. For the entire Alps, a mass loss of 1.3 ± 0.2 Gt yr^{1} is estimated. Since 1980, increasing mass loss. Cumulatively close to 20 m water equivalent loss for 1960–2016. In Scandinavia, glaciers gained mass in the 1980s and 1990s. Since 2000, they have lost mass (ca. –1000 kg m^{-2} yr^{-1}). Cumulative change from 1960–2016 has reached –13 m water equivalent.	Sommer et al. (2020), Zemp et al. (2019), Hock et al. (2019) SROCC		
	Attribution: Due to long-term, detailed, high-quality climate and glacier monitoring networks, *high confidence* of attribution of glacier mass loss to anthropogenic climate change. Especially for the last 3 decades, anthropogenic warming is the dominant cause of and contributor to (70–100%) glacier retreat.	Marzeion et al. (2014), Roe et al. (2021)	Strong contribution of anthropogenic climate change on glacier mass loss, *high confidence* (***)	Increasing (annual average) temperatures, including repeated hot temperature extremes, since the 2000s are the main driver of glacier loss. Precipitation variability is not a main driver across the region and decadal times scales.
North America	**Observations:** Increasing glacier mass loss since 1960, with close to –30 m water equivalent loss for 1960–2016 for western Canada and mainland USA. Alaska has also experienced strong glacier mass loss. For Arctic Canada, glacier mass loss is less strong and with more uncertainties.	Zemp et al. (2019), Hock et al. (2019) (SROCC)		
	Attribution: For Alaska and western Canada, there is *high confidence* in attribution to anthropogenic climate change, at least for the observation period from the 1990s to present.	Marzeion et al. (2014), Roe et al. (2021)	Strong contribution of anthropogenic climate change to glacier mass loss, *high confidence* (***)	

Detection and attribution of observed changes in climate-related systems (‘Climate Attribution’)				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
Small Islands	**Observations:** No studies.			
	Attribution: No studies.		No separate assessment	
S03	Cryosphere—Permafrost			
Global	**Observations:** Although permafrost persists in areas of the Northern Hemisphere where it was absent prior to 3000 years ago, increases in temperatures in the upper 30 m over the past three to four decades (start of the observational programmes) have been widespread. Since at least the early 1980s, permafrost has been warming across the Arctic. During 2007–2016, ground temperatures near the depth of zero annual amplitude increased globally by 0.29 ± 0.12°C (0.39 ± 0.15°C and 0.20 ± 0.10°C in the continuous and discontinuous permafrost zone, respectively).	AR6 WGI Section 2.3.2.5 (Gulev et al., 2021), AR6 WGI Section 9.5.2 (Fox-Kemper et al., 2021), Biskaborn et al. (2019)	*High confidence* in temperature increase in the upper 30 m over the last three to four decades.	
	Attribution: There is a clear physical link between ground temperatures (and thus permafrost) and surface air temperatures whose increase have been clearly attributed to human influence in the Arctic. The increase in ground temperatures in the continuous permafrost zone is physically consistent with surface air temperature increases (including the Arctic amplification). In the discontinuous zone, permafrost temperatures have warmed less because of latent heat effects and less strong warming.	IPCC AR6 WGI Section 9.5.2.1 (Fox-Kemper et al., 2021), Biskaborn et al. (2019)	Moderate contribution of anthropogenic climate forcing to permafrost thawing in the Arctic continuous and the discontinuous permafrost zone, *medium confidence* (**)	High Arctic: Polar amplification of global air temperature increase. Subarctic: Earlier snow season and increase of snow thickness can lead to ground warming, versus latent heat effect near 0°C. Variability in permafrost temperature trends are often related to local conditions such as snow cover, topography (especially in mountains), surface type or ice content.
Asia	**Observations:** Warming trend of mean annual ground temperatures observed in all permafrost regions, with strongest increases in Central Asia (see below).	Hock et al. (2019), SROCC, Biskaborn et al. (2019)		
	Attribution: See regional assessments below.	Hock et al. (2019), SROCC, Biskaborn et al. (2019)	Strong contribution of anthropogenic climate change to permafrost warming, *medium* to *high confidence* (***/**)	
Central Asia	**Observations:** Warming trend of mean annual ground temperatures in Tien Shan reaching 0.3–0.6°C per decade, 1974–2011. Increasing thickness of active layer (season freezing) reaching 19 cm per decade, 1992–2011.	Hock et al. (2019), SROCC		
	Attribution:	Hock et al. (2019), SROCC	Strong impact of anthropogenic climate change on permafrost warming, *medium* to *high confidence* (**)	
Tibet	**Observations:** Warming trend of mean annual ground temperatures reaching 0.08–0.24°C per decade, 2002–2012. Increasing thickness of the active layer with seasonal freezing reaching 15–67 cm per decade, 2002–2014.	Hock et al. (2019), SROCC		
	Attribution:	Hock et al. (2019), SROCC	Strong contribution of anthropogenic climate change to permafrost warming, *medium* to *high confidence* (**)	
Mongolia	**Observations:** Warming trend of mean annual ground temperatures reaching 0.2–0.3°C per decade, 2000–2009.	Hock et al. (2019), SROCC		

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')

Region	Observed change in the climate-related system + attribution to anthropogenic climate forcing	Reference	Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence	Underlying mechanism
	Attribution:	Hock et al. (2019), SROCC	Strong contribution of anthropogenic climate change to permafrost warming, *medium* to *high confidence* (**)	
Australia	**Observations:**			
	Attribution:		No assessment	
Europe	**Observations:** Positive trend in permafrost mean annual ground temperatures observed in the European Alps as well as Scandinavian permafrost regions, with stronger trends in the Alps (see below). In both regions, the thickness of the active layer (seasonal freezing) is increasing with stronger trends in the Alps, too.	Hock et al. (2019), SROCC, Dunn et al. (2020b), Biskaborn et al. (2019)		
	Attribution:	Hock et al. (2019), SROCC, Biskaborn et al. (2019)	Strong contribution of anthropogenic climate forcing to permafrost warming, *medium* to *high confidence* (**/***)	
European Alps	**Observations:** The overall statement should be adjusted to: Warming of mean annual ground temperatures of 0.2 to 0.6°C per decade for debris since 1987, depending on depth, and up to 1°C per decade for bedrock since 2008. Thickness of seasonally thawed active layer is increasing with a rate of 10–100 cm per decade (2000–2020).	Hock et al. (2019), SROCC, Dunn et al. (2020b), PERMOS (2021)		
	Attribution:	Hock et al. (2019), SROCC	Strong contribution of anthropogenic climate forcing to permafrost warming, *high confidence* (***)	
Scandinavia	**Observations:** Warming trend of mean annual ground temperatures (0.1–0.5°C per decade for 2000–2019; with up to 0.2°C per decade for debris and up to 0.5°C per decade for bedrock). Increasing thickness of active layer of seasonal freezing (7–20 cm per decade, 1978–2006).	Richter-Menge et al. (2020), Hock et al. (2019), SROCC		
	Attribution:		Strong contribution of anthropogenic climate forcing to permafrost warming, *medium* to *high confidence* (***)	
North America	**Observation:** Mean annual ground temperature increased more in Arctic regions with continuous permafrost than in those with discontinuous permafrost (ca. 0.3–0.8°C versus ca. 0.1–0.3°C per decade for the last 4 decades) Active layer thickness (ALT) increased continuously over the past 25 years in the Alaska Interior region, but for Alaska North Slope and northwest Canada ALT changes are less uniform.	Richter-Menge et al. (2020), O'Neill et al. (2019), AR6 WGI 9.5.2 (Fox-Kemper et al., 2021)		
	Attribution: Physically consistent lines of evidence between increase inground (permafrost) temperatures and surface air temperatures.	Richter-Menge et al. (2020), AR6 WGI 9.5.2 (Fox-Kemper et al., 2021)	Strong contribution of anthropogenic climate change to permafrost warming, *medium confidence* (**)	Latent heat effects related to melting ground ice influence differences between continuous and discontinuous permafrost. Observed changes in ALT relate to shorter-term fluctuations in climate and are especially sensitive to changes in summer air temperature and precipitation.

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
S04	Atmosphere—Heatwaves			
Global	**Observations:** A measure of cumulative heat shows significant increases almost everywhere since the 1950s, mainly driven by heatwave days. Trends in heatwave frequency, duration and cumulative heat have accelerated since the 1950s.	Perkins-Kirkpatrick and Lewis (2020)		
	Attribution: See assessments below.		Strong contribution of anthropogenic forcing to increase in intensity and frequency of heatwaves, *medium* to *high confidence* (**) in most regions	
Africa	**Observations:** In Africa, heatwaves, regardless of the definition, have been becoming more frequent, longer lasting and hotter over more than three decades in Africa. The reporting is still heavily constrained.	AR6 WGI Chapter 11 (Seneviratne et al., 2021), Harrington and Otto (2020)	*High confidence* that heatwaves have increased over the whole continent	
	Attribution: There are currently only attribution studies for heatwaves in North and East Africa which show a strong influence of human-induced climate change.	Bergaoui et al. (2015) (heatwave in Levante 2014), Otto et al. (2015b), Philip et al. (2017) (East Africa)	Major contribution by anthropogenic climate forcing in North and East Africa, *high confidence* (***), no assessment elsewhere	
Asia	**Observations:** Over most parts of Asia, daily high temperature extremes have increased during the last decades, including the Himalaya and Tibetan Plateau.	AR6 WGI Table 11.7 (Seneviratne et al., 2021)	*High confidence*	
	India: Historical observations show that the likelihood of heatwaves has not increased or even decreased in some parts while it has increased in others.	van Oldenborgh et al. (2018)		
	Attribution: Attribution studies focus on Japan and China and consistently find human-induced climate change plays an important role.	Lu et al. (2018), Lu et al. (2016), Yin et al. (2017a) (China), Wehner et al. (2016)	Regional mixed impacts ranging from strong contribution of anthropogenic climate forcing to increasing occurrence of heatwaves, *high confidence* (***) to regional decrease in annual maxima of daily maximum temperature in some parts of India, *low confidence* (*)	
	India: Model simulations indicate that aerosol emissions or the effects of irrigation may prevent an increase in probabilities associated with greenhouse gas emissions. Both mechanisms are considered 'anthropogenic climate forcing', too.	van Oldenborgh et al. (2018)		
Australasia	**Observations:** Temperature extremes and heatwaves have increased. *Australia*: Multi-day heatwave events have increased in frequency and duration across many regions since 1950. In 2019, the national average maximum temperature exceeded the 99th percentile on 43 d (more than triple the number in any of the years prior to 2000) and exceeded 39°C on 33 d (more than the number observed from 1960 to 2018 combined). *New Zealand*: The number of warm days (over 25°C) increased at 19 of 30 sites, and the number of heatwave days increased at 18 of 30 sites during 1972–2019. Increase in the frequency of hot February days exceeding the 90th percentile between 2010–2019 and 1980–1989, with some regions showing a more than five-fold increase.	AR6 WGI, BoM and CSIRO (2020), Perkins-Kirkpatrick and Lewis (2020), Trancoso et al. (2020), MfE (2020), Harrington (2021)	*High confidence* (***)	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
	Attribution: A large number of studies attribute recent heatwaves in Australia to anthropogenic climate change. For example, it is very likely (with 90% confidence) that anthropogenic climate change increased the likelihood of the October 2015 heatwave breaking the previous Southern Australian temperature record by at least 400%. Human influence increased the likelihood of the January 2014 heatwave in Adelaide by 186% and Melbourne by 89%. Seven-day heatwave in December 2019 was at least twice as likely due to anthropogenic climate change.	King et al. (2015a) (extreme Brisbane heat during November 2014), Dittus et al. (2014) (trends in maximum temperatures), Lewis and Karoly (2013), Lewis et al. (2017), Gallant and Lewis (2016) (record-breaking Australian spring temperatures in 2013 and 2014), Black and Karoly (2016) (record-breaking heat in southern Australia in October 2015), Black et al. (2015) (Adelaide and Melbourne heatwaves of January 2014), Perkins and Gibson (2015) (May 2014 heatwave), Hope et al. (2016) (record October heat in 2015), Perkins-Kirkpatrick and Lewis (2020), van Oldenborgh et al. (2021)	Major contribution of anthropogenic climate forcing to observed increase in temperature extremes, *high confidence* (***)	
Central and South America	**Observations:** The number of warm days and nights has increased, and the number of cold days and nights has decreased in the last decades, except over Southeast South America (SES), where hot extremes have decreased during austral summer.	AR6 WGI 11.3.2 (Seneviratne et al., 2021)	*Medium to high confidence*	
	Attribution: There is only one heatwave attribution study in Central and South America for a heatwave in Argentina. An attribution study of a cold wave in Peru showed that climate change made it less likely to occur.	Hannart et al. (2015) (heatwave), Otto et al. (2018b) (coldwave)	No assessment	
Europe	**Observations:** Maximum temperatures and the frequency of heatwaves have increased.	AR6 WGI Chapter 11 (Seneviratne et al., 2021)	*High confidence*	
	Attribution: There are few attribution studies on Scandinavia, but over Britain and Central Europe as well as the Mediterranean extreme heat in summer and decrease in cold extremes can be attributed to climate change.	Sippel et al. (2018), Sippel et al. (2017), Sippel and Otto (2014), Wilcox et al. (2018), King et al. (2015b) (England), Roth et al. (2019) (England), Kew et al. (2019) (Mediterranean), Stott et al. (2004) (European heatwave 2003), Otto et al. (2012) (European heatwave 2010), Vautard et al. (2020)	Major contribution of anthropogenic climate forcing to observed increased frequency and intensity of heatwaves, *high confidence* (***)	

Detection and attribution of observed changes in climate-related systems ('Climate Attribution')				
Region	**Observed change in the climate-related system + attribution to anthropogenic climate forcing**	**Reference**	**Synthesis statement: direction (and strength) of response to anthropogenic forcing, level of confidence**	**Underlying mechanism**
North America	**Observations:** In North America, an *increase* in the number of warm days and nights and decrease in the number of cold days and nights, also over central North America and the eastern USA, albeit with changes smaller than elsewhere in North America.	AR6 WGI Chapter 11 (Seneviratne et al., 2021)	*High confidence*	
	Attribution: Heatwave attribution studies are sparse over North America, but those that do exist find an attributable signal.	Wang et al. (2017), Shiogama et al. (2014), Philip et al. (2018) (June 2013 and 2015 heatwave in western USA)	Major contribution of anthropogenic climate forcing to increased intensity and frequency of heatwaves where studies exist, *medium confidence* (**), limited regional coverage	
Small Islands	**Observations:**			
	Attribution:		No assessment	

SM16.7.2 Details of Studies on Detection and Attribution Studies of Observed Changes in Natural, Human and Managed Systems

Table SM16.22 | Attribution of observed changes in natural, human and managed systems (orange symbols in Figure 16.2): Assessment statements relate to 'impact attribution' i.e. the identification and quantification of the contribution of long-term changes in the climate-related systems to the observed changes in the natural, human, and managed systems. The subtitles of the orange symbols in Figure 16.2 and associated numbers can be found here as titles of associated sections. Each section provides the background information (references and associated evidence) behind the ratings in the Figure (direction of change and level of confidence). The summary statements in the orange cells of the table are displayed in Figure 16.2.

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
S09	Marine ecosystems—Phenology shift			
Global	**Observations:** *Spring aggregation of plankton and fish:* Spring aggregation occurs consistently earlier. Rates of observed shifts in phenology are comparable to, or greater, than those for terrestrial systems. Based on time series of observational data/surveys:	Chapter 3: Poloczanska et al. (2013)	*High confidence*	
	High consistency (81.5%, *n* = 71) in earlier spring aggregation of phytoplankton (–5.2 d per decade, *n* = 68), albeit with *limited evidence* from the Southern Hemisphere	Chapter 3, Section 3.4.3.2	*High confidence*	
	High consistency (81.1%, *n* = 80) in earlier spring aggregation of zooplankton (–4.4 d per decade, *n* = 55).	Chapter 3, Section 3.4.3.2	*High confidence*	
	High consistency (88.0%, *n* = 64) in earlier spring aggregation of meroplankton (those species that are only temporarily in the plankton) (–5.9 d per decade, *n* = 52).	Chapter 3, Section 3.4.3.2	*High confidence*	
	Other seasonal events			
	High consistency (80.2%, *n* = 8) in phenological changes in benthic invertebrates (–6.1 d per decade, *n* = 7).	Chapter 3, Section 3.4.3.2	*Medium confidence* (*limited evidence*, *high agreement*)	
	High consistency (75.5%, *n* = 177) in earlier occurrences of seasonal events of fish (–4.5 d per decade, *n* = 71).	Chapter 3, Section 3.4.3.2	*High confidence*	
	Seasonal changes for marine mammals and seabirds are equivocal.	Chapter 3, Section 3.4.3.2	*Low confidence*, (*limited agreement)*	
	High consistency (80.1%, *n* = 8) in earlier occurrences of seasonal events for marine reptiles (–6.1 d per decade, *n* = 7)	Chapter 3, Section 3.4.3.2	*Medium confidence* (*limited evidence*, *high agreement*)	
	Attribution: There is *high confidence* that the observed changes are primarily driven by climate change (particularly earlier warming of sea waters). Attribution is largely provided by the general agreement of signals relative to expectations under climate change across multiple independent data sources/time series (as per Parmesan et al., 2013). No alternative driver is expected to induce a similarly consistent global pattern of change.	Chapter 3, Section 3.4.3.2	Strong contribution of climate change to observed changes in the phenology of ocean taxa, *high confidence* (***)	
Polar seas	**Observations:** Earlier timing of Arctic plankton blooms in spring and summer, occurrence of novel fall phytoplankton blooms in the Arctic.	Kahru et al. (2011), Kahru et al. (2016), Ardyna et al. (2014), Ardyna et al. (2017)	*High confidence*	
	Attribution: Shifts in timing in phytoplankton bloom in the Arctic are closely linked to decreasing in early summer (June) ice concentration. Secondary bloom is induced by delayed freeze-up allowing for wind-driven vertical mixing promoting primary production.	Kahru et al. (2011), Kahru et al. (2016), Ardyna et al. (2014), Ardyna et al. (2017)	Strong impact of climate change on changes in the timing of phytoplankton bloom (expansion of vegetation period), *high confidence* in causal link between sea ice retreat and timing of plankton blooms (***)	Biomass events mainly occur in response to changes in light and nutrients driven by the seasonal cycles of radiation, temperature and water column stability.

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
Temperate ocean	**Observations:** *Zooplankton:* Earlier occurrence of peaks in zooplankton abundance in temperate zones. Evidence of shifts in phenology of zooplankton is strongest in the Northeast Atlantic. *Phytoplankton:* Based on time series from surveys, evidence of changes in phenology of phytoplankton is strongest in the North Atlantic and the Baltic Sea.	Chapter 3 Edwards and Richardson (2004) (North Sea), McGinty et al. (2011), Persson et al. (2012), Chevillot et al. (2017) (zooplankton, Northeast Atlantic), Chivers et al. (2020) (phytoplankton, North Atlantic), Scharfe and Wiltshire (2019), Wasmund et al. (2019) (phytoplankton, Baltic Sea)	*High confidence*	
	Attribution: *Zooplankton + phytoplankton:* Attribution is provided by the general agreement of signals relative to expectations under climate change across multiple independent data sources/time series (as per Parmesan et al. 2013). *Zooplankton:* Changes in the timing of summer plankton maxima could be largely explained by SSTs in the North Sea, in particular for dinoflagellates and meroplankton. Fluctuations in zooplankton phenology and age structure in the White Sea are partly driven by temperature changes.	Edwards and Richardson (2004) (North Sea), McGinty et al. (2011) Persson et al. (2012)	Strong to moderate impact of climate change on changes in timing of seasonal events in phytoplankton and zooplankton, respectively; *high confidence* (***)	
Tropical oceans	**Observations:** In the northern Red Sea, winter phytoplankton blooms have shorter duration during warm conditions as they start later and end earlier. Published reports documenting phenological changes are predominately for the temperate or polar oceans, with 96% of reports since SROCC from the Northern Hemisphere.	Gittings et al. (2018) Chapter 3, Section 3.4.3.2		
	Attribution: Changes in winter phytoplankton bloom in northern Red Sea directly linked to thermal stratification and changes in air–sea heat fluxes.	Gittings et al. (2018)	Major contribution of climate change to the observed change in phytoplankton phenology, *low confidence* (*), no assessment elsewhere	
S10	Marine ecosystems—Range reduction or shift			
Global	**Observations:** Poleward range shifts of marine taxa. Marine taxa shifting at higher velocities than terrestrial species (expansion of cold limit by 72 km per decade versus 6 km per decade, respectively).	Poloczanska et al. (2016), Poloczanska et al. (2013)	*High confidence*	
	Evidence from deep-sea sediment records of zooplankton indicate community-level poleward shifts at an average rate of 40 km per decade (range, 3–170 km per decade).	Jonkers et al. (2019)	*High confidence*	
	Evidence for vertical range shifts into deeper waters is also present, typically at rates slower than 10 m per decade; however, this may be possible for only a limited number of taxa because of oxygen limitation and associated effect on suitable habitat.	Section 3.4.3.1, Dulvy et al. (2008), Currey et al. (2015), Brown and Thatje (2015)	*Medium confidence* (*limited evidence*, *high agreement*)	
	Attribution: Of the species responding to climate change, rates of distribution shifts were, on average, consistent with those required to track ocean surface temperature changes.	Poloczanska et al. (2016), Molinos et al. (2017)	Strong impact of climate change on range expansion of warm-affiliated species, *high confidence* (***) Strong contribution of climate change to the observed contraction of ranges of polar fish species, *high confidence* (***) (see polar seas) Strong impact of climate change on development of novel species assemblages, with increasing representation by warm-affiliated species, *high confidence* (***)	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
Polar seas	**Observations:** Ranges of Arctic fish species are declining and contracting, while those of arcto-boreal or boreal fish species are expanding and increasing.	Frainer et al. (2017), Kjesbu et al. (2014), Fossheim et al. (2015), Hedges et al. (2017)	*High confidence*	Temperature, sea ice melt
	Attribution: Functional trait distribution changed rapidly, especially in the Arctic, concurrent with the observed increase in sea bottom temperature and reduction in sea ice coverage. Boreal communities have expanded northwards at a pace reflecting the local climate velocities.	Frainer et al. (2017), Kjesbu et al. (2014), Fossheim et al. (2015), Hedges et al. (2017)	Strong contribution of climate change to the observed contraction of ranges of polar fish species and strong expansion of ranges of arcto-boreal or boreal fish, *high confidence* (***)	
Temperate ocean	**Observations:** The observed expansion of marine communities from warmer regions into colder ones (thermophilisation) effectively leads to novel communities and biotic interactions, with concomitant changes in ecosystem functioning and servicing. Observed expansion of the range of tropical fish into subtropical and temperate regions for tuna and tropical herbivores (tropicalisation).	WGII Chapter 3, Section 3.4.4.1.3, Burrows et al. (2019), Kumagai et al. (2018), Fossheim et al. (2015) (thermophilisation), Zarco-Perello et al. (2017), Pecuchet et al. (2020), Vergés et al. (2019), Peleg et al. (2020), Nagelkerken et al. (2020), Erauskin-Extramiana et al. (2019) (tuna), Vergés et al. (2019) (tropical herbivores)	*High confidence*	
	Shift in mackerel stocks: Rapid change in the distribution of the northeast Atlantic mackerel stock after 2007. Atlantic mackerel became more abundant in northern Atlantic waters, with ranges progressively expanding as far as Icelandic and south Greenlandic waters in the west, and Spitzbergen in the north.	ICES (2013), Nøttestad et al. (2015)		
	Attribution: Poleward range shift of many species, including zooplankton (eastern North Atlantic, Mediterranean Sea), tuna (all temperate oceans), tropical herbivores (Australian coast) and bony and cartilaginous species (northwest Atlantic), have tracked changes in temperature. In some cases, competitive interactions between species have been influenced by warming (cod and haddock in the North Atlantic).	Section 3.4.3.1, Fredston-Hermann et al. (2020), Erauskin-Extramiana et al. (2019) (tuna), Villarino et al. (2020), Durant et al. (2020), Vergés et al. (2019) (tropical herbivores), Monllor-Hurtado et al. (2017), Mach et al. (2019) (tuna)	Strong contribution of climate change to the observed expansion of ranges of warm-affiliated species into colder regions, *high confidence* (***) Strong impact of climate change on development of novel species assemblages, with increasing representation by warm-affiliated species in colder regions, *high confidence* (***)	
Tropical ocean	**Observations:** Decline in species richness around the equator since the 1970s, especially pelagic fish.	Chaudhary et al. (2021) (pelagic fish)	*Medium confidence* in loss of marine species diversity around the equator	
	Loss of living coral from mass coral bleaching events has led to changes in reef fish species assemblages, including loss of specialist species, e.g., in the Great Barrier Reef (Australia) and the Seychelles.	Section 3.4.2.1, Richardson et al. (2018), Robinson et al. (2019)	*High confidence*	
	Attribution: Decline in species richness around the equator followed the climate-induced shift of climatically suitable range of sea surface temperature.	Chaudhary et al. (2021)	Moderate loss of species richness induced by climate change, *low confidence* (*)	
	Change in reef fish species assemblages occur within 1–3 years of coral bleaching events, which can be attributed to marine heatwaves.	Section 3.4.2.1, Richardson et al. (2018), Robinson et al. (2019)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
S11	Marine ecosystems—Coral bleaching and associated effects			
Global	**Observations:** No global assessment as warm-water corals are mainly located in the tropical ocean.			
	Attribution: No global assessment as warm-water corals are mainly located in the tropical ocean.		No assessment	
Tropical oceans	**Observations:** First mass coral bleaching events were observed in the 1980s. Since then, the frequency of mass coral bleaching and mortality events has increased in concert with anomalous ocean temperatures such that the return time between events has been reduced to less than the time needed for full recovery.	Donner et al. (2017), Hughes et al. (2018), Sully et al. (2019), Section 3.4.2.1	*Very high confidence*	
	Attribution: Process-understanding, experiments and observations show that coral bleaching is induced by unusually high water temperatures. Mass bleaching events follow the trend in the occurrence of marine heatwaves.	Hoegh-Guldberg et al. (2014), AR5 regarding temperature sensitivity of corals (Chapter 6), IPCC Working Group 2 Section 3.4.2.1	Strong contribution of climate change to observed bleaching-induced loss of warm-water corals, *virtually certain* (***)	Bleaching occurs when the density of algal symbionts, or zooxanthellae (*Symbiodinium* spp.), is lost due to changes in the environmental conditions, including increases in temperature.
Tropical Atlantic	**Observations:** The Caribbean and western tropical Atlantic have reported more bleaching events since the 1980s at two to three times the rate of any other region. Widespread bleaching was observed in 2005, 2010 and 2016, with 50–90% of locations surveyed each year experiencing at least moderate bleaching. Most Mexican Caribbean coral reefs are no longer dominated by hard corals, as coral cover declined from 26% to 16% from 1978 to 2016.	Donner et al. (2017), Hughes et al. (2018), Contreras-Silva et al. (2020) (Mexican Caribbean, 1978–2016)	*Very high confidence*	
	Attribution: Periods of locally anomalous warm temperatures are well understood as a trigger for mass coral bleaching. The spatial extent and the timing of available bleaching observations match the occurrence of heat stress in the historical record, including the 2005, 2010 and 2016 events. Other drivers of bleaching (cold water, freshwater, tidal exposure) or non-climate hazards cannot explain the increase in bleaching observations or the timing or broad spatial extent of those observations. At minimum, the event in 2005 can be attributed to anthropogenic climate change as the underlying marine heatwave has been attributed (see section on marine heatwaves in Table SM16.21).	Donner et al. (2017), Eakin et al. (2010), Hughes et al. (2017)	Major contribution of climate change to increased frequency of bleaching and associated mortality, *high confidence* (***)	
Tropical Indian Ocean	**Observations:** Mass bleaching was observed in 1998, 2010 and 2015/2016. In 2016, bleaching intensity exceeded 20% in surveyed locations in the western Indian Ocean, eastern Indian Ocean and western Indonesia. In Huvadhoo Atoll in southern Maldives, the 2016 event contributed to a decline in reef complexity and exceptionally low juvenile coral densities, below recovery thresholds identified for other reefs in the region.	McClanahan et al. (2019), Chapter 15, Perry and Morgan (2017) (Maldives)	*Very high confidence*	
	Attribution: As in other regions, the seasonal timing and spatial extent of bleaching matches with periods of warm season heat stress. Peak temperature values and timing of hot and cold peaks best explain the spatial pattern of bleaching in the 2015 event (in the Indian Ocean and southwest Pacific). At least the 2015 event can be attributed to anthropogenic climate change as the underlying marine heatwave has been attributed (see section on marine heatwaves in Table SM16.21).	Park et al. (2017), McClanahan et al. (2019)	Major contribution of climate change to increased frequency of bleaching, *high confidence* (***)	
Tropical Pacific	**Observations:** Climate-driven mass bleaching has been reported in all countries in the region, with the most bleaching reports coinciding with 2014 through 2017 marine heatwaves. Fifty percent of coral within shallow-water reefs of the northern and central two-thirds of the Great Barrier Reef (GBR) was killed in 2015/16. Subsequent coral recruitment in 2018 was reduced to only 11% of the long-term average, representing an unprecedented shift in the ecology of the northern and middle sections of the reef system to a highly degraded state.	Chapter 3, Chapter 11, Chapter 15, Hughes et al. (2018), Hughes et al. (2019)	*Very high confidence*	

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Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: As in other regions, observed mass warm season bleaching events are correlated with periods of warm-season heat stress. For example, the spatial pattern and severity of mass bleaching on the GBR in 1998, 2002 and 2016 were determined by marine heatwaves. The likelihood of 2016 heat stress has been strongly increased by climate change (see marine heatwave attribution section in Table SM16.21).	Chapters 3, 11, 15, Hughes et al. (2017)	Strong adverse impact of climate change, *high confidence* (***)	
S12	Marine ecosystems—Kelp forest distribution			
Global	**Observations:** Kelp populations have declined in 38% of the ecoregions examined and increased or remained stable in 68% of ecoregions.	Krumhansl et al. (2016), Smale et al. (2019)	*Very high confidence*	
	Attribution: Warming is driving range contraction and local extinction at the warm end of species ranges, and range expansions at the cold end of species ranges. Kelp forests have decreased due to the direct effects of increased temperature associated with both chronic gradual warming and acute extreme warming events exceeding species' thermal limits.		Major gains (at the cold end of the species range) and moderate losses (at the warm end) leading to an overall gain in kelp forests induced by climate change, *medium confidence* (**)	Temperatures outside species' thermal limits cause physiological stress, leading to tissue damage, reduced growth and reduced productivity. Chronic gradual warming generally leads to range shifts, whereas acute heat stress can lead to mortality, decreases in size, decreases in abundance, and local extinction.
Polar seas	**Observations:** Although observations to date are rare, available data from Greenland and Kongsfjorden, Svalbard report increased kelp abundance and productivity.		*Medium confidence*	
	Attribution: Increasing abundances can be explained by decreased ice cover leading to increased light and substrate availability: Seasonal sea ice cover has been identified as principal driver of spatial and temporal variation in depth extension and annual production of kelp in Greenland and a combination of melting landfast sea ice, increased open-water light period and increased sedimentation can explain the observed changes in kelp distributions in Kongsfjorden, Svalbard.	Krause-Jensen et al. (2012) (Greenland), Bartsch et al. (2016) (Svalbard)	Major contribution of climate change to minor gains in kelp abundance; *medium confidence* (**)	
Temperate oceans	**Observations:** Long-term declines in kelp area and acute kelp loss have been observed across temperate oceans, particularly at the warm edge of species. Local declines in kelp and other canopy-forming seaweeds have caused shifts to systems dominated by turf, urchins or tropical species like corals.	Filbee-Dexter and Wernberg (2018), Smale (2019)	*Very high confidence*	
	Attribution: The timing and spatial extent of both long-term and acute kelp losses correspond with warming trends reducing species' thermal habitat and marine heatwaves (MHWs) exceeding species' thermal thresholds. A well-documented abrupt loss event was triggered by the marine heatwave in Western Australia in 2011, which may be attributed to anthropogenic climate change (fraction of attributable risk ~0.8 but not significantly greater than zero, see Table SM16.21). Even independent of the attribution to anthropogenic climate forcing, the event clearly documents the sensitivity of the system to heat.	See below	Major contribution of anthropogenic climate change to kelp forest decline and shifts in species' ranges, including minor gains and major losses, *high confidence* (***)	
North Atlantic	**Observations:** Northwest Atlantic: Decline in mean kelp biomass by 85–99% over the past 4–6 decades in Nova Scotia, Canada, and in sugar kelp cover (*Saccharina latissima*) by 80% since 1972 in Rhode Island, USA.	Filbee-Dexter et al. (2016) (Canada), Filbee-Dexter et al. (2020) (USA)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: The timing of kelp decline in Nova Scotia and Rhode Island correlates with gradual warming and the timing of MHWs, including the 2012 Northwest Atlantic heatwave which has been attributed to anthropogenic climate change (Table SM16.21).	Filbee-Dexter et al. (2016) (Canada), Filbee-Dexter et al. (2020) (USA), Laufkötter et al. (2020)	Major contribution of ocean warming to the observed loss of kelp forests along the North American east coast, *medium confidence* (**)	
North Atlantic	**Observations:** Poleward expansion of kelp forests, loss of species along the Iberian Peninsula; and loss of cold-water species along Ireland and Norway.	Smale et al. (2015) (southwest UK), Schoenrock et al. (2019) (western Ireland), Rinde et al. (2014) (Norway), Simkanin et al. (2005) (Ireland), Casado-Amezúa et al. (2019) (Spain, Portugal), Piñeiro-Corbeira et al. (2016) (Spain), Díez et al. (2012) (Spain), Fernández (2011) (Spain), Voerman et al. (2013) (Spain)		
	Attribution: Poleward expansion of kelp forests follows poleward expansion of the thermal niche, i.e., abundance rapidly increased at the poleward leading range edge.	Smale et al. (2015) (southwest UK); Schoenrock et al. (2019) (western Ireland)	The impact of climate change ranges from major gain to major losses, *high confidence* (***)	
	Observed long-term declines are induced by gradual warming: Loss of species at their thermal maximum.	Rinde et al. (2014) (Norway), Simkanin et al. (2005) (Ireland), Casado-Amezúa et al. (2019) (Spain, Portugal), Piñeiro-Corbeira et al. (2016) (Spain), Díez et al. (2012) (Spain), Fernández (2011) (Spain), Voerman et al. (2013) (Spain)		
North Pacific	**Observations:** *Japan:* Long-term decline in species abundances. *North America:* Long-term decline in species abundance at sites in British Columbia, California and northern Mexico since the early 1990s, including a 90% decline in bull kelp (*Nereocystis luetkeana*) in northern California and accompanying phase shift to urchin-dominated systems, and loss of giant kelp (*Macrocystis pyrifera*) at the warm edge of the species range in Mexico.	Tanaka et al. (2012) (Japan), Rogers-Bennett and Catton (2019) (California), Starko et al. (2019), (Canada), Arafeh-Dalmau et al. (2019) (Mexico) McPherson et al. (2021)		
	Attribution: *Japan:* Declines are induced by gradual warming: loss of species occurs at their thermal maximum. *North America:* Timing of decline in abundance of multiple species (British Columbia), bull kelp decline and ecological phase shifts (California), and giant kelp loss (Mexico) are linked with 2013–2015 MHW (‘the Blob’), chronic warming and local ecological stressors (California). The 2013–2015 MHW has been attributed to anthropogenic climate change (Table SM16.21).	Tanaka et al. (2012) (Japan), Rogers-Bennett and Catton (2019) (California), Starko et al. (2019) (Canada), Arafeh-Dalmau et al. (2019)	Major to moderate contribution of climate change to observed reduction of kelp forests, *medium confidence* (**)	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
Australasia seas	**Observations:** Long-term decline in kelp species observed in southeast Australia and South Island of New Zealand, including localised extinction of bull kelp (*Durvillaea* spp.) in New Zealand.	Babcock et al. (2019) (Australia), Carnell and Keough (2019) (Australia), Thomsen et al. (2019) (New Zealand)	*High confidence*	
	Attribution: Decline in common kelp species (*Ecklonia radiata*) in southeast Australia at the warm edge of species range since 1997, and increase in urchin abundance and distribution, corresponding with ocean warming and marine heatwaves. Extent and timing of loss and local extinction of bull kelp in New Zealand correlated with a 2017–2018 MHW demonstrating the sensitivity of the system to high temperatures.	Babcock et al. (2019) (Australia), Carnell and Keough (2019) (Australia), Thomsen et al. (2019) (New Zealand)	Moderate to major impact contribution of climate change to observed loss of kelp forest, *medium confidence* (**)	
Temperate Indian Ocean	**Observations:** Loss of 43% of kelp forests in southwest Australia and abrupt decline (>90%) of a common kelp species (*Ecklonia radiata*) during 2011 Western Australia MHW. Localised extinction and tropicalisation of kelp ecosystems observed at the warm edge of species' range.	Babcock et al. (2019), Wernberg et al. (2016)	*Very high confidence*	
	Attribution: Timing and spatial pattern of kelp loss, local extinction and tropicalisation correspond with 2011 Western Australia MHW, which has been attributed to anthropogenic climate change (Table SM16.21).	Babcock et al. (2019), Wernberg et al. (2016), Laufkötter et al. (2020)	Major impact of climate change on kelp loss and local extinction, *high confidence* (***)	
Tropical oceans	**Observations:** Kelp forests are extremely rare in the tropics.			
	Attribution:		No assessment	
S13	Marine ecosystems—Seagrass distribution			
Global	**Observations:** In areas with available data, 29% of seagrass meadows were lost between 1879 and 2006, with rates of loss accelerating from 0.9% yr^{-1} before 1980 to 7% yr^{-1} after 1990.	Waycott et al. (2009)	*Medium confidence*	
	Attribution: Historically, non-climate hazards, including coastal development and reduced water quality, have been primary drivers of seagrass loss. Since 1990, warming and marine heatwaves, together with storm-driven turbidity and structural damage, have contributed to seagrass die-off and shift in species assemblages.	Section 3.2.4.5, Waycott et al. (2009), Nowicki et al. (2017)	Moderate decline in seagrass induced by climate change, *low confidence* (*)	
Polar seas	**Observations:** Very rare in polar regions.			
	Attribution:		No assessment	
Temperate ocean	**Observations:** Specific cases of seagrass loss in the temperate ocean include 38% loss of seagrass cover in Langebaan Lagoon, South Africa between 1960 and 2007.	Pillay et al. (2010), Mvungi and Pillay (2019)		
	Loss of one-third of dense seagrass cover in Shark Bay, Western Australia from 2010 through 2016.	Strydom et al. (2020), Serrano et al. (2021)		
	Attribution: Mainly attributed to direct human impact, eutrophication impacts exacerbated by warming.	Mvungi and Pillay (2019)	Moderate contribution of climate change to observed loss of seagrass in South Africa, *low confidence* (*), major impact of climate change on seagrass loss in Western Australia, *high confidence* (***)	Warming due to climate change exacerbates eutrophication, and fouling by microalgae
	Timing of Western Australia seagrass decline corresponds with 2011 Western Australia MHW, during which sea surface temperatures exceeded the thermal optima for key species. The MHW has been attributed to anthropogenic climate change (Table SM16.21), and the decline of seagrass appears as part of a long-term change of the ecosystem from a dominance of temperate species to a dominance of tropical species.	Laufkötter et al. (2020), Strydom et al. (2020), Serrano et al. (2021)		Marine heatwaves lead to direct warming-induced loss.
Tropical ocean	**Observations:** For the large majority of sites, a decline in seagrass communities has been documented (e.g., tropical USA and Australia, Bermuda and Colombia), while for some sites an increase has been reported (e.g., USA, Australia, Cayman Islands, US Virgin Islands); large data gap for tropical Indo-Pacific region.	Chapter 15, Waycott et al. (2009) (review of sites across globe)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: As in other regions, attribution to climate change is complicated by increasing non-climate hazards, including direct physical damage, coastal erosion linked to development, and decline in local water quality.	Section 3.4.2.5, Short et al. (2016), Mach et al. (2019)	Minor contribution of climate change to observed loss of seagrass at several Small Islands' coasts, *low confidence* (*); no assessments elsewhere	
S21	Terrestrial ecosystems—Range reduction or shift			
Global	**Observations:** Poleward and up-elevation range shifts tend to lead ultimately to reduced range sizes. Shifts observed in about 50% of terrestrial taxa. Of 976 species examined, 47% showed local extinctions at warm boundaries, higher in tropics (55%) than temperate (39%) latitudes, higher for animals (50%) than plants (39%), highest in freshwater (74%), then marine (51%), then terrestrial (46%) realms. Observed range shifts for temperate zone species typically lag far behind those predicted by recent warming (1). In contrast, observed shifts among tropical species roughly match those predicted by climate shifts (12).	Chapter 2, Wiens (2016) Sheldon (2019), Scheffers et al. (2016), Parmesan and Yohe (2003) (50%, 460 of 920 species) Root et al. (2003) (52%, 483 of 926 species), Wiens (2016) (47%, 460 of 976 species)		
	Attribution: Poleward and up-elevation range shifts mainly due to local extinction at warm boundaries with some colonisation beyond previously cold temperature limited boundaries. Global warming trends can be linked quantitatively to observed range shifts, elevational shifts parallel latitudinal shifts.	Wiens (2016), Parmesan and Yohe (2003), Root et al. (2003), Rosenzweig et al. (2008), Anderegg et al. (2019)	Major contribution of climate change to the observed large-scale shifts to higher altitudes and colder latitudes, *high confidence* (***) It is to be noted that there exists very wide variation and idiosyncrasy in range of individual species' responses to climate change, and this discounts the likelihood that ecological communities would shift range as coherent entities.	Warming exceeds tolerance limits of species at warm range edges, and increases habitability of cold range edges, thus prompting local extinction and colonisation in each habitat respectively; extinction rate at 'trailing edges' may lag behind colonisation rate at 'leading edges'.
Africa	**Observation:** *Ethiopian wolf:* Reduction and upward shift (2500 metres above sea level [m.a.s. l.] in early 20th century, to 3000 m.a.s. l. currently) of the range of the rare and Africa's most endangered Ethiopian wolf (*Canis simensis*).	Gottelli et al. (2013)		
	Afro-palaearctic species: Population declines in migratory Afro-palaearctic species (1981–2012), species wintering in southern Africa and some in the northern Sahel had the greatest mean declines per species.	Beresford et al. (2019)		
	Attribution: *Ethiopian wolf:* Numbers of Ethiopian wolves declined naturally with natural global warming 18,000 years ago, as Afroalpine habitats contracted at higher elevations; since the 20th century, unique habitats that supported this species are becoming both more desiccated and prone to human disturbance. Direct human influences on the habitat appear to be the dominant driver in contrast to climate change.	Gottelli et al. (2013) (Ethiopian wolf)	Minor contribution of climate change to the observed contraction of range and populations assessed so far, *low confidence* (*), No assessment elsewhere	
	Afro-palaearctic species: For Afro-palaearctic birds, impacts appear to occur via climate effects on vegetation activity, with senescence (ageing and dying of leaves) more important in Sahel, and green-up more so in southern Africa. The observed changes in population patterns suggest that species' populations increased more (or decreased less) where senescence is delayed.	Beresford et al. (2019)		
Asia	**Observations:** Range expansions and neutral range shifts observed in *Larix* species. In Russia, on average, 83% of tree lines advanced northward, mainly *L. cajanderi* (92% of sites). In China, range reduction of *L. olgensis* was concentrated in northeastern China (67% of sites). In Mongolia, *L. sibirica* range shifts were evenly split between advance (45%) and recessions (45% of sites).	Mamet et al. (2019)		
	Species range of black-billed Capercaille declined by 35.50% between 1970 and 2000.	Zhang et al. (2020a), Yang et al. (2018)		

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	Attribution: Using *Larix* species bioclimatic niches of ~5–16°C and ~100–390 mm for mean growing season temperature (GST) and precipitation (GSP), the direction that niche centroids moved between observation periods (1944–1979 and 1980–2015) was evaluated. Siberian species tracked temperature increases, while increased trends in precipitation were also significant. *L. potaninii* tracked drier and *L. griffithiana* tracked wetter conditions, but tracking of changes in precipitation and temperature trends was variable among many species.	Mamet et al. (2019)	Moderate contribution of climate change to range reduction, *medium confidence* (**)	*Larix* (larch) distributions may be particularly sensitive to climatic change because of deciduous habit, fast growth and maturation.
	Black-billed capercaillie: Ensemble range simulations using historical observed data to assess the relative impact of climate change and anthropogenic disturbance between 1970s and 2000s show that *Tetrao urogalloides* is sensitive to climate change. The observed decline in species range between 1970 and 2000 is dominated by human disturbances other than climate change (29%), while climate change has contributed, too (6.5%).	Zhang et al. (2020a), Yang et al. (2018)		
Australasia	**Observations:**			
	Australia, Bramble Cay melomys (rodent): 100% range loss (global extinction) in 2014.	Waller et al. (2017) (Bramble Cay Melomys)		
	Australia, canopy tree species in Australian Alps: Local extirpations and replacement of dominant canopy tree species and replacement by woody shrubs due to seeders having insufficient time to reach reproductive age (Alpine Ash) or vegetative regeneration capacity being exhausted (Snow Gum woodlands) in southern and southwestern Australia.	Bowman et al. (2014), Fairman et al. (2016), Harris et al. (2018), Zylstra (2018)		
	Australia, vertebrate species: Decline in distribution area of the koala in southeastern New South Wales; population decline and range contraction of the tawny dragon lizard, mass mortality of wildlife species (flying foxes, freshwater fish), and decline in distribution area and population size of possums and birds in the Australian Wet Tropics rainforests.	Lunney et al. (2014) (koala), Walker et al. (2015) (lizard), Ratnayake et al. (2019) (flying fox), Vertessy et al. (2019) (freshwater fish), Hoffmann et al. (2019) (possum, bird)		
	Australia, alpine vegetation: Shifts in dominant vegetation with a decline in grasses and other graminoids and an increase in forb and shrub cover in Bogong High Plains, Victoria, Australia.	Wahren et al. (2013)		
	New Zealand, endemic forest birds: Range contraction and population decline in bird species with large body size, those nesting in tree cavities and/or having poor dispersal capabilities due to increased predation pressure by invasive species.	Walker et al. (2019)		
	Attribution: See individual assessments below.		Strong reduction in ranges caused by climate change, *high confidence* (***)	
Australia	*Extinction of Bramble Cay melomys:* Sea level rise and storm surges in Torres Strait resulted in habitat loss and direct mortality of this rodent species.	Waller et al. (2017)		
	Canopy tree species in Australian Alps: Multiple wildfires in short succession resulting from increased fire risk conditions induced by declining winter rainfall and increasing hot days.	Fairman et al. (2016), Harris et al. (2018), Zylstra (2018)		
	Vertebrate species: Droughts and increase in temperatures as a major driver of the decline in distribution area of the koala in southeastern New South Wales. Higher body temperatures and declining rainfall led to population decline and range contraction of the tawny dragon lizard. Extreme heat caused mass die-offs of flying foxes. Extreme hot and dry climate conditions caused fish deaths. In the wet tropics rainforest, warming and increasing length of dry season led to decline in possum and bird populations.	Lunney et al. (2014) (koala), Walker et al. (2015) (lizard), Ratnayake et al. (2019) (flying fox), Vertessy et al. (2019) (freshwater fish), Hoffmann et al. (2019) (possum, bird)		

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Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
New Zealand	*Alpine vegetation*: Severe drought, warming and climate-induced biotic interactions led to shifts in dominant vegetation.	Wahren et al. (2013)		
	Endemic forest birds: Climate warming leads to range expansion of invasive species and increase in predation pressure on endemic forest birds that retreat to higher elevations of forested mountains.	Walker et al. (2019)		
Central and South America	**Observations:** *Andean tree genera:* A study of 38 Andean tree genera monitored in repeated (2003/2004–2007/2008) censuses of 14 1-ha forest inventory plots spanning an elevational gradient from 950 to 3400 m in Manu National Park in southeastern Peru show an upward shift of the mean distributions of most species upslope (2.5–3.5 vertical metres upslope per year). Abundances of tree genera previously distributed at lower elevations increased in the majority of study plots.	Feeley et al. (2011)		
	Mountaintop extirpations in tropical bird community, Peru: Comparison of survey data from 1985 and 2017 on bird species shows significant upward shifts of most species. The low elevation limit of mountaintop species (historically found only above 1300 m) has generally shifted upslope and squeezed high-elevation populations into smaller total areas. Nearly all mountaintop species have declined in abundance, and 8 of the 16 species could not be found anymore. In contrast, low-elevation species seem to be benefitting from temperature increases. The upper elevational limits of species found at the lowest elevations (i.e., at the Palatoa River) during the historic survey have shifted upward even as these species continue to exist at the bottom of the transect. As a consequence, lowland species have increased in elevational distribution by an average of 71 m and also increased in available area.	Freeman et al. (2018)		
	Attribution: *Andean tree genera:* The observed changes support the hypothesis that rising temperatures are one important driver of upward movement where the movement is slower than expected based on observed temperature change. However, overall, the study period (4 years) is still too short to consider the observed changes an 'observed impact of long-term climate change', but rather a hint how sensitive the system may be to changing climate. So far, it cannot be excluded that the observed changes may be in response to an isolated climatic event.	Feeley et al. (2011)	Strong reduction of the range and abundance of mountaintop bird species and range expansion of low-elevation birds induced by warming, *low confidence* (*) as only based on one study (summarised in Figure 16.2 as range reduction in mountaintop birds) No broader assessment	
	Mountaintop extirpations in tropical bird community, Peru: The observed reduction in range and abundances matches the expected shifts induced by warming; the area is not affected by other direct influences such as land use changes.	Freeman et al. (2018)		
Europe	**Observation:** Systematic shifts towards higher elevation and upstream were found for 32 stream fish species in France.	Comte et al. (2013)		
	For British taxa, mean northwards range margin change 1966–1975 to 1986–1995 was 23 km per decade (N = 13 taxonomic groups) and from 1986–1995 to 2001–2010 was 18 km per decade (N = 16 taxonomic groups).	Mason et al. (2015)		
	In Finland, 37 of 48 sampled butterfly species shifted range margins northward (average of 59.9 km, 1992–1996 compared with 2000–2004), 9 species' ranges retracted southward, and 2 species' ranges did not change.	Pöyry et al. (2009)		
	Mountain butterflies (37 species), eastern Alps: Significant shifts of distributions towards higher elevations (1965–2015). While the highest altitudinal maxima were observed mostly in more recent years, observations at the respective lowest altitudes are restricted to the period prior to 1980. Average altitudinal distributional shift of more than 300 m uphill across six decades.	Rödder et al. (2021)		
	Increase in plant species richness on 87% of the 302 sampled mountain tops over 145 years. This trend was consistent across all nine geographical regions that were sampled. Rate of species increase was 1.1 species per decade in 1957–1966, and increased to 5.4 species per decade in 2007–2016.	Steinbauer et al. (2018)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: The shifts follow geographic variation in climate change. For British data, range shifts were associated with warming of 0.21°C and 0.28°C per decade. For the data from Finland, mean temperature of the summer months increased by 0.45–1.8°C during the study period, and isotherms of growing degree days shifted by 200–300 km northward. Increase in plant species richness on mountain tops was positively related to temperature increase across all 302 time series. *Mountain butterflies (37 species), eastern Alps:* Climate change is identified as a main driver of the shifts as observations are basically in line with species distribution models accounting for temperature and precipitation changes in addition to topographic variables.	Comte et al. (2013) Mason et al. (2015), PÖYRY et al. (2009), Steinbauer et al. (2018), Rödder et al. (2021)	Strong shifts to higher elevation and reduction of ranges of different plant and animal taxa induced by climate change; *high confidence* (***)	
North America	**Observation:** *Bull trout*: For the bull trout (*Salvelinus confluentus*), 11–20% (8–16% per decade) of headwater stream breeding habitat was lost in Idaho, and a reduction in the number of occupied sites was documented in a watershed in Montana (site abandonment probabilities [0.36] higher than colonisation probabilities [0.13]).	Isaak et al. (2010), Eby et al. (2014) (bull trout in Montana)		
	Stonefly: Range of stonefly (Zapada glacier) retreated upstream to higher and cooler sites in alpine streams in Montana. Of the six streams sampled in 1963–1979, the stonefly was detected in only one stream in 2011–2013 and at two new sites.	Giersch et al. (2015)		
	Breeding ranges of birds: 84% of species shifted their elevational distribution in the Sierra Nevada Mountains, USA (n = 77 sites, 223 bird species) over 80–100 years. Of those, 51% shifted upslope (161 to 1320 m for lower limits, 218 to 2503 m for upper limits), the others downslope (shifts ranged from 113 to 1557 m for lower limits and 127 to 1567 m for upper limits).	Tingley et al. (2012)		
	Populations of the endemic Eastern Massasauga snake (*Sistrurus catenatus*) are declining.	Pomara et al. (2014)		
	Attribution: *Bull trout:* Largest losses are occurring in coldest habitats and have been attributed to increasing temperatures induced by anthropogenic climate forcing and to increased wildfire that reduced vegetation shading streams.	Isaak et al. (2010) (bull trout in Idaho), Eby et al. (2014) (bull trout in Montana)	Moderate contribution of climate change to observed shifts in species ranges, *medium confidence* (**) No broad assessment	Spawning and early juvenile rearing appear to be adversely affected by warming water, but study calls for further work to understand mechanisms better.
	Stonefly: Upstream retreat of the stonefly was attributed to increase of water temperature (0.67–1.00°C from 1960 to 2012) and decrease in glacial surface area (35% reduction from 1966 to 2005).	Giersch et al. (2015)		
	Breeding ranges of birds: Upslope shifts of bird ranges associated with increase in temperatures, downslope shift with increase in precipitation.	Tingley et al. (2012)		
	Demographic models for 189 population locations based on observational data for 1950 to 2008 predicted known extant and extirpated populations well (area under the curve [AUC] = 0.75), and allowed association of population declines to increasing extreme event frequency and severity (note that models combining climate change and land use change factors performed better than models incorporating these drivers independently).	Pomara et al. (2014)		
Small Islands	**Observations:** *Birds:* Island extinction rates are two to three orders of magnitude higher than continental rates for birds and mammals. In Papua New Guinea, upslope shifts of bird ranges averaged 113 m (Mt Karimui) and 152 m (Karkar Island) for upper limits and 95 m (Mt Karimui) and 123 m (Karkar Island) for lower limits over 47 (Mt Karimui) and 44 (Karkar Island) years, respectively.	Freeman and Freeman (2014) (birds and other species, New Guinean birds), Koide et al. (2017) (vascular plants, Hawaii), Taylor (2016) (review across different species, Pacific region), Taylor (2016), Loehle and Eschenbach (2012) (bird island extinction rate)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Puerto Rico: Eight of 20 forest bird species (38%) changed elevational distribution significantly; of those, distribution expanded for six species (upslope for five of those), and distribution contracted for two species.	Campos-Cerqueira et al. (2017)		
	Reptiles and amphibians: Upslope distribution movement of 30 species, representing five families of reptiles and amphibians in the Tsaratanana Massif, Madagascar (overall mean shifts in elevational midpoint from 1993 to 2003 of 19–51 m upslope; mean lower elevation limit 29–114 m; mean upper elevation limit 8–53 m).	Raxworthy et al. (2008) (reptiles and amphibians, Madagascar)		
	Vascular plants: Significant mean upward range shift across 69 vascular plant species on island of Hawaii (65.2 m from 1970 to 2010). In the sub-group of native species, the upper elevation limit did not change, but the lower elevation limit shifted significantly upward by 94.1 m (insignificant range contraction). In contrast, the sub-group of non-native species displayed a different pattern of a significant upward shift in both their upper and lower elevation limits, by 126.4 and 81.6 m, respectively (no range contraction).	Koide et al. (2017) (vascular plants, Hawaii)		
	Marion Island: Earlier breeding increased the number of invasive mice on Marion Island by 430.0% between 1979–1980 and 2008–2011.	McClelland et al. (2018)		
	Attribution: While, generally, reductions in species ranges have often been dominated by direct human interventions (land use changes, pollution, distribution of invasive species), the observed upward range shifts appear to be dominated by climate trends. Bird ranges in Papua New Guinea shifted upward by 32 and 27.5 m per 0.1°C while regions were not disturbed by other direct human influences. Observed range shifts were linked to local temperature trends, including a high warming rate of 2.2°C in 17 years in Puerto Rico. Observed shifts in tropical montane species across very different taxa (e.g., trees, plants, birds, lizards and moths) seem to match observed shifts in temperature ranges more closely than the range shifts of temperate montane species whose response may lag behind for a longer time. Climate change also at least appears as a very plausible explanation for the upward shift of vascular plants. Range shifts of reptiles and amphibians in Madagascar are well in line with the shift of temperature ranges from 1993 to 2003.	Taylor and Kumar (2016), Freeman and Freeman (2014) (New Guinean birds and re-evaluation of surveys across other taxa), Campos-Cerqueira et al. (2017) (Puerto Rico), Koide et al. (2017) (vascular plants, Hawaii), Raxworthy et al. (2008) (reptiles and amphibians, Madagascar), McClelland et al. (2018) (invasive mice in Marion Island)	Climate change is a dominant driver of the observed upward range shifts in mountain regions, *medium confidence* (**).	Warming directly affects the thermal performance of sensitive species. Warming trends reduce habitat suitability within small, limited terrain at low elevation and increase suitability at higher elevations, and range sizes become further restricted at higher elevations owing to decreasing availability of land area with altitude.
S22	Terrestrial ecosystems—Net primary production (NPP) NPP = amount of atmospheric carbon fixed by plants and accumulated as biomass = photosynthesis by plants – plant energy use through respiration Note: The synthesis in Figure 16.2 refers to the effects of climate change, not CO_2 fertilisation.			
Global	**Observations:** Global terrestrial NPP has exceeded land use emissions since the early 2000s, making terrestrial ecosystems a net carbon sink. Global terrestrial NPP increased 6% from 1982 to 1999, then decreased 1% from 2000 to 2009. From 1999 to 2015, Normalised Difference Vegetation Index (NDVI) declined globally, particularly in semiarid ecosystems, indicating widespread decreases in NPP and expansion of browning areas. Between 2000 and 2009, NPP increased on 65% of vegetated land area in the Northern Hemisphere, while it decreased on 70% of vegetated land in the Southern Hemisphere (based on remotely sensed vegetation properties).	Friedlingstein et al. (2020) (terrestrial carbon sink), Nemani et al. (2003) (NPP changes), Zhao and Running (2010) (drought impacts), Huang et al., 2016 (NDVI), Yuan et al. (2019) (NPP decrease since 1999); Pan et al. (2018) (expansion of browning areas, 1982–2013), Zhang et al. (2021) (reversal of greening trend, NDVI, 1981–2015) Chapter 2 (Section 2.4.4.5.1) Zhao and Running (2010)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	From 2000 to 2014, 29 of 53 countries together representing 90% of global NPP showed increasing NPP trends. Russia, Argentina, Peru and several countries in Southeast Asia showed a marked decrease in NPP (~15 g C m^{-2} yr^{-1}).	Peng et al. (2017)		
	Spatially varying trends in satellite-derived biomass (vegetation optical depth, VOD) and nine site-based NPP measurements.	Murray-Tortarolo et al. (2016)		
	Structurally intact tropical forests: The carbon gains through tree growth and newly recruited trees (here considered the NPP component) have increased (1983–2011).	Hubau et al. (2020) (Africa and Amazonian), Brienen et al. (2015) (Amazon), Qie et al. (2017) (Southeast Asia)		
	Grassland ecosystems: Globally, 49.25% of grassland ecosystems experienced degradation (2000–2010). Slight increase in NPP in Asia and North America; slight decrease in NPP in Africa, Oceania, South America and Europe.	Gang et al. (2014)		
	Arid regions: Of 44.5 million km^2 global area of dryland vegetation, 2.70 million km^2 (6%) showed a significant negative NPP trend (desertification), 41% showed significant positive NPP trend (greening) and 53% showed no significant change between 1982 and 2015.	Burrell et al. (2020) Murray-Tortarolo et al. (2016)		
	Attribution: Global terrestrial NPP increase from 1982 to 1999 is attributed to increasing temperature and increased solar radiation in the Amazon from decreased cloud cover. The decrease of global NPP from 2000 to 2009 has been shown to be induced by droughts in the Southern Hemisphere. The observed decline in NPP (derived from NDVI) from 1999 to 2015 is induced by increased aridity.	Nemani et al. (2003) (climate-related increase); Zhao and Running (2010) (drought-induced reduction 2000–2009); Yuan et al. (2019) (both on declines from 1999 to 2015), Zhang et al. (2021) (water availability controlling vegetation trends, NDVI, 1981–2015), Peng et al. (2017) Chapter 2 (Section 2.4.4.5.1)	Climate change increased NPP in the observational period into the 2000s, *medium confidence* (**), findings for later period still inconclusive. Increasing CO_2 concentrations have been an overarching factor facilitating increased NPP, and have partly compensated for some climate-change-related adverse impacts on NPP.	
	Structurally intact tropical forests: The increase in NPP is linked to CO_2 increase (effect about equally strong in Africa as in Amazonia) which has compensated for negative effects of droughts and temperature increase. A weaker climate-induced reduction in Africa seems to be driven by slower warming, fewer or less extreme droughts, lower forest sensitivity to droughts, and overall lower temperatures (African forests are on average ~1.1°C cooler than Amazonian forests, because they typically grow at higher elevations of ~200 m above sea level).	Hubau et al. (2020) (Africa and Amazonian)		
	Arid regions: Globally, CO_2 fertilisation was the largest absolute driver of NPP change in 44.1% of areas, followed by land use practices (28.2%), climate variability (14.6%) and then climate change (13.1%). The main driver of significant NPP decline (desertification) was land use (79.9%), followed by climate change and climate variability.	Burrell et al. (2020), Donohue et al. (2013)		
	Using a combination of statistical and modelling approaches, variations in temporal trends in NPP were attributed to variations in temporal trends in dry season intensity and length in dry regions when the opposing positive effect of CO_2 fertilisation was removed.	Murray-Tortarolo et al. (2016)		
	Modelling studies have identified a consistent overarching positive effect of fertilisation by increased atmospheric CO_2 in enhancing NPP (1961–2010).	Li et al. (2017b), Martínez Martínez et al. (2019), Liu et al. (2019)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
Africa	**Observations:** Positive NPP trends observed in tropical Africa, and negative trends observed in subtropical southern Africa 2000–2009.	Zhao and Running (2010)		
	The Central African Republic is observed to have the highest positive NPP trend globally (23 g C m^{-2} yr^{-1}) between 2000 and 2014.	Peng et al. (2017)		
	Intact African tropical forests: Analysis of live aboveground biomass of 244 plots spanning 11 countries shows a stable carbon sink (no trend) in live aboveground biomass for the three decades to 2015. The NPP term (tree growth and newly recruited trees) shows a positive trend (0.008 Mg C ha^{-1} yr –2, 1983–2011).	Hubau et al. (2020) (244 plots)		
	Sahel greening: Major increase in NPP (greening) observed across the Sahel between 1981 and 2015. Homogeneous greening in Northern Sub-Saharan Africa is the major contribution to the zonally averaged greening in the region of 5°N–15°N, which is strongest and long-lasting in comparison with other latitudes.	Burrell et al. (2020), Zhang et al. (2021) (NDVI, 1981–2015)		
	Attribution: Increase in net primary productivity in Africa was attributed to decrease in vapour pressure deficit and increase in rainfall. Model simulations indicate that the positive trend from 1980 to 2009 can be explained by an increase in precipitation, increasing CO_2 (accounts for 29% of NPP variation) and increasing nitrogen deposition (accounts for 28% of NPP variation).	Zhao and Running (2010), Hoscilo et al. (2015), Pan et al. (2018)	Recent climate change has reduced NPP (tropical forests), *medium confidence* (**) and strongly increased NPP (in the Sahel zone), *high confidence* (***). Increasing CO_2 concentrations partly compensated for the climate-induced decline in NPP (e.g., in the tropical forests) and contributed for the increase in the Sahel zone.	Warmer and wetter climatic conditions, together with elevated atmospheric CO_2 concentration and nitrogen deposition, have resulted in a significant increase in African terrestrial NPP during 1980–2009.
	African tropical forests: The long-term positive trend in carbon gains from tree growth and newly recruited trees (NPP) derived from census data of intact forests, is mainly induced by CO_2 fertilisation that has compensated for negative effects induced by droughts and rising temperatures (3.7% increase due to CO_2 fertilisation, 0.5% reduction due to droughts, 0.1% reduction due to temperature increase, 2000–2015). Another study of satellite measurements (2000–2009) indicates that the identified increase in NPP is mainly induced by decreased vapour pressure deficit (VPD) in line with the model simulations mentioned above.	Hubau et al. (2020) (census data), Zhao and Running (2010) (satellite measurements)		
	Sahel greening: Greening in the Sahel zone is related to recovery from severe droughts in the 1970s and early 1980s causing a low baseline for vegetation productivity; and an increase in precipitation from later 1980s onwards allowing for strong vegetation growth in the water-limited ecosystem. CO_2 fertilisation additionally increases NPP.	Burrell et al. (2020), Zhang et al. (2021) (NDVI, 1981–2015), Kaptué et al. (2015), Piao et al. (2020) (review of characteristics, drivers and feedbacks of global greening)		
Asia	**Observations:** *Asian rainforest:* Between 2000 and 2009, NPP decreased at –0.562 Pg C per decade across Asian rainforests. Across Borneo, intact forests gained 0.43 Mg C ha^{-1} yr^{-1} between 1988 and 2010 (*n* = 49 plots), and edge forests lost 0.28 Mg ha^{-1} yr^{-1} (*n* = 22 plots).	Zhao and Running (2010) (Asia), Qie et al. (2017) (Borneo)		
	Grasslands: Compared globally, Asia had the largest areas of both, grassland degradation and restoration, and 41.31% of grassland showed an increase in NPP.	Gang et al. (2014)		
	Case studies: In the source region of Yangtze River, total NPP increased by 0.18 Tg C yr^{-1} (2000–2014). NPP (aboveground) also increased at four sites of ungrazed grassland of the Tianshan Mountains in central Asia (1985–2016).	Yuan et al. (2021) (source region of Yangtze River, 2000–2014), Li et al. (2020a) (Tianshan Mountains, 1985–2016)		

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	India and China: Overall strong positive contribution of India and (eastern) China to global average greening (NPP increase). China accounts for 25% of the global net increase in leaf area with only 6.6% of global vegetated area (2000–2017). In India, the contribution to overall greening comes from forests (42%) and croplands (32%), while in India it is mainly induced through croplands (82%).	Zhang et al. (2021) (NDVI, 1981–2015), Chen et al. (2019a)		
	Attribution: *Arid and semiarid China:* Model simulations for NPP across arid + semiarid China showed that NPP was positively correlated with precipitation. The reduction in NPP due to reduction in precipitation was compensated by the CO_2 fertilisation effect, resulting in a slight increase of NPP.	Fang et al. (2017b)	Climate change seems to play a minor role in the region's overall contribution to global NPP (greening), which seems to be dominated by direct human influences in India and China. Regionally varying positive and negative effect of climate change on NPP, *low confidence* (*) CO_2 fertilisation partly compensated for climate-induced declines.	
	Asian grassland: Observational data from 2000 to 2010 showed that 38.94% of grassland degradation across Asia was caused by human activities, 30.67% by climate change and 30.38% by combined effect of human activity and climate change, while 36.12% of grassland restoration was caused by human activities, 35.12% by combined effects and 28.76% by climate change. Model simulation of NPP across Central Asia identified climate change (especially decrease in precipitation) as the main driver of NPP decline between 1982 and 1999. After 1999, human activities were mostly responsible for NPP decline. In both time periods, climate change led to an increase in NPP in certain regions (e.g., in Tajikistan).	Gang et al. (2014) (observational data), Chen et al. (2019b) (model simulation)		
	Asian rainforest: Decreased NPP across 2000–2009 caused by decrease in solar radiation.	Zhao and Running (2010)		Growth of rainforests constrained by solar radiation due to strong cloudiness.
	Arid regions: Decrease in NPP (desertification) across central and western Asia caused mostly by land use change, and to a lesser extent by climate change. Greening in India caused by land use change, CO_2 and climate variability; and greening in China caused by land use change.	Burrell et al. (2020)		
	India and China: The greening in China and India is mainly due to land management (conservation and expansion of forests in China, intensification of agriculture).	Chen et al. (2019a), Piao et al. (2020) (review), Burrell et al. (2020)		
	Case studies: Temperature and precipitation increase seem to be the main drivers of NPP increase in most of the Source Region of Yangtze River and the high elevation grassland sites in Tianshan mountains in central Asia. Direct human influences have played a more important role in the downstream region where they have induced a decline in NPP.	Yuan et al. (2021) (2000–2014), Li et al. (2020a)		
Australasia	**Observations:** Increase in NPP (greening) between 1981 and 2015, with southern Australia contributing strongly to total greening, while NPP decreased in northern Australia.	Zhang et al. (2021) (1981–2015)		
	Arid regions: Increase in NPP (greening) across arid regions in Australia from 1982 to 2015, especially southern and northeastern Australia.	Burrell et al. (2020)		
	Grassland: Between 2000 and 2010, significant decline in grassland NPP across central and eastern part of the state Western Australia.	Gang et al. (2014)		
	Attribution: Increase in precipitation identified as driver of NPP increase across Australia.	Zhang et al. (2021) (1981–2015)	Increasing in rainfall has increased NPP in parts of Australia, *low confidence* (*) Increasing CO_2 has had a mainly positive effect.	
	Arid regions: NPP increase driven by CO_2, land use and climate variability. Model simulation driven by observational climate data estimated for Australian grazing land that increased rainfall from 1931–1970 to 1971–2010 led to an increase in NPP.	Burrell et al. (2020) (arid regions, 1982–2015), Liu et al. (2017) (model simulation)		
Central and South America	**Observations:** *Tropical forests:* Average NPP across the forest area decreased by 2 g C m^{-2} yr^{-1} in Central and South America (2001–2013) and spatially aggregated NPP has declined by 0.424 Pg C per decade in the Amazon rainforest (2000–2009).	Yin et al. (2017b) (satellite data, 2001–2013), Zhao and Running (2010) (satellite data, 2000–2009)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
	Analysis of live aboveground biomass of 321 plots of intact tropical forest shows a decline of the overall carbon sink in live above ground biomass. However, the loss is dominated by tree mortality, while the NPP term (tree growth and newly recruited trees) shows a slight positive trend (0.014 Mg C ha^{-1} yr –2, 1983–2011).	Hubau et al. (2020) (analysis of 321 plots, 1983–2011), Brienen et al. (2015) (census data)		
	Arid regions: Significant NPP decline in Caatinga Forest in Brazil.	Burrell et al. (2020) (1982–2015)		
	Southern South America: Widespread browning in Southern South America.	Zhang et al. (2021) (NDVI, 1981–2015)		
	Attribution: A weak positive trend in carbon gains from tree growth and newly recruited trees (NPP) derived from census data of intact forests, is mainly induced by CO_2 fertilisation (3.7%), while drought effects reduced carbon gains by 2.7% and temperature increase further reduced gains by 1.1% (2000–2015). The estimated negative effect of climate change aligns with the analysis of satellite data indicating that the identified reduction in NPP from 2000 to 2009 was caused by increasing air temperature, which greatly increased autotrophic respiration, and by a slight drying trend, especially a severe drought in 2005.	Hubau et al. (2020) (analysis of 321 plots), Brienen et al. (2015) (census data)	Climate change has induced reductions in NPP in tropical forests, *medium confidence* (**) No assessment elsewhere Increasing CO_2 has had a positive effect with no identifiable CO_2 saturation (2000–2015).	
	Arid regions: NPP decline in northeastern Brazil caused by both climate change and land use change. Negative impacts of decreased rainfall over semiarid Caatinga Forest of Brazil has amplified the effects of widespread deforestation and grazing intensification.	Burrell et al. (2020)		
Europe	**Observations:** Overall strong positive contribution of Europe to global trend in greening (1981–2015).	Zhang et al. (2021) (NDVI)		
	Forest stands in Central Europe: Analysis of oldest existing experimental forest plots in Central Europe indicate that the dominant tree species Norway spruce (36 plots) and European beech (22 plots) exhibit significantly faster tree growth (32–77%) and stand volume growth (10–30%) than in 1960. The increase in growth rates means that stands achieved defined sizes, standing stock and stand development stages significantly earlier under recent conditions than in the past.	Pretzsch et al. (2014)		
	Summer 2003 and 2010: Particularly low average NPP across Europe (e.g., annual total NPP deviation of up to –100 Tg C yr-1 in 2010 doe western Europe relative to the 2000 to 2011 average, excluding anomalous years).	Ciais et al. (2005), Bastos et al. (2014)		
	Grassland: Compared globally, the least grassland degradation was observed for Europe, but the NPP trend was still negative.	Gang et al. (2014)		
	Attribution: Agricultural intensification may have contributed considerably to greening over agricultural lands in Eastern Europe. In addition, model simulations indicate that the afforestation and forest regrowth have contributed to the greening in parts of Europe.	Piao et al. (2020) (review), Kondo et al. (2018)	Climate change has increased NPP in some sites (forest stands in Central Europe), *low confidence* (*), but has decreased NPP in individual events attributable to anthropogenic climate forcing, *medium confidence* (**).	
	Rising atmospheric CO_2 concentrations have contributed to the overall greening (increase in NPP).	Burrell et al. (2020) (on arid land)		
	Forest stands in Central Europe: Observed acceleration in growth is primarily due to rises in temperature and expansion of growing seasons. The impacts are particularly strong on sites that are not constrained by the nutrient supply.	Pretzsch et al. (2014)		
	Summer 2003 and 2010: Observed strong reductions in NPP were induced by the 2003 and 2010 heatwaves in Europe that have been attributed to anthropogenic climate forcing (Table SM16.21). In the 2003 heatwave, both moisture deficits and high temperatures drove the extreme response of vegetation, while for the 2010 event very high temperatures appear to be the sole driver of very low productivity.	Ciais et al. (2005), Bastos et al. (2014)		
	Grassland: NPP decline in 47.5% of grasslands caused by combined effect of climate and land use change. NPP increase of 51.8% in restored grasslands caused by human activities.	Gang et al. (2014)		

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Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
North America	**Observations:** Strong greening in southeastern North America (1981–2015).	Zhang et al. (2021) (NDVI)		
	Temperate forest plots, Maryland, USA: Tree biomass data collected over the past 22 years from 55 temperate forest plots with known land use histories and stand ages ranging from 5 to 250 years show that recent biomass accumulation greatly exceeded the expected growth caused by natural recovery.	McMahon et al. (2010)		
	Attribution: The observed greening in southeastern North America seems to be mainly driven by plant regrowth due to land use change and CO_2 fertilisation; the relative quantification of these effects is uncertain.	Burrell et al. (2020) (western part, CO_2 effect), Kondo et al. (2018) (1960–2010)	Strong increase in NPP due to extended growing season and warming trends in individual forest plots, *low confidence* (*) No assessment elsewhere CO_2 fertilisation and land use change have contributed to observed greening, *medium confidence* (**)	Extended growing season and warming trends, together with CO_2 fertilisation, enhance photosynthetic activity and net primary production.
	Temperate forest plots, Maryland, USA: Ruling out other explanations, long-term temperature increase, longer growing seasons, and CO_2 fertilisation are the most likely drivers of the observed increase in recent rates of biomass gain above their long-term trend.	McMahon et al. (2010)		
Small Islands	**Observations:** Negative trends in NPP on Java island (2001–2011), the Philippines (–9 g C m^{-2} yr^{-1}, 2000–2014), Papua New Guinea (large areas with trends below –30 g C m^{-2} yr^{-1} 2000–2014), and Indonesia (–14 g C m^{-2} yr^{-1} 2000–2014).	Indiarto and Sulistyawati (2014) (Java), Peng et al. (2017) (Philippines, Papua New Guinea, and Indonesia)		
	Island of Cephalonia in western Greece: A study of the endemic Greek fir (*Abies cephalonica*) from Ainos Mountain shows a decline in productivity of *A. cephalonica* which was replaced by a positive productivity trend after 1988. The conifer *Pinus halipensis* has shown declining productivity from the early 1900s to early 2000s.	Koutavas (2013), Sarris et al. (2011)		
	Attribution: *Java Island*: Statistical analysis concluded strong relationship between NPP and climatic parameters, but not between NPP and land-cover-related parameters.	Indiarto and Sulistyawati (2014)	Minor to moderate contribution of climate change to observed reduction in NPP, *low confidence* (*) One case of an apparent ameliorating effect of CO_2 fertilisation	*Java Island*: High precipitation values decreased solar radiation and photosynthesis.
	Indonesian islands: NPP and drought (Standardized Precipitation Evaporation Index [SPEI]) linked statistically, distinctly from the contribution of land cover change to NPP change.	Peng et al. (2017)		
	Island of Cephalonia in western Greece: Statistical analysis and inference suggest that the limiting effect of drought on productivity of *A. cephalonica* has been replaced by a positive productivity trend due to CO_2 fertilisation since the late 1980s. Linear regression was used to attribute declining productivity in *P. halipensis* to declining rainfall.	Koutavas (2013) (Greek fir), Sarris et al. (2011) (*P. halipensis*)		
S23	Terrestrial ecosystems—Structural change			
Global	**Observations:** *Biome shifts:* Latitudinal and elevational biome shifts recorded at 19 locations including boreal, temperate and tropical ecosystems, further upslope or latitudinal biome shifts over periods of 24–210 years have been recorded at numerous sites.	AR5 Chapter 4 Settele et al. (2014); Gonzalez et al. (2010) Chapter 2		
	Between 1981 and 2012, 13–14% of the spatial extent of all natural and semi-natural vegetation assessed (representing all African biomes) changed biome state (as defined by biome structure and function).	Higgins et al. (2016)		
	Woody encroachment: Global trend of woody encroachment established prior to the 1980s; woody encroachment recorded widely in tropical and temperate grasslands.	Chapter 2, Stevens et al. (2017)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Satellite observations, analysed to remove the effect of variations in precipitation, show that shrub cover across environments where water is the dominant limit to vegetation growth has increased by 11%.	Donohue et al. (2013)		
	Widespread increase of shrub cover in arid ecosystems globally, with some areas showing increased grass dominance.	Chapter 2		
	Attribution: Upslope and latitudinal shifts have been attributed to, or found to be consistent with, observed warming trends.	AR5 Chapter 2, Gonzalez et al. (2010), Chapter 2	Moderate global shifts in vegetation structure overall, due to warming, moisture and growing season changes, *high confidence* (***) Additional moderate contribution of rising CO_2 concentrations to observed thickening of shrublands and woodlands and expansion of woodlands and forests, *high confidence* (***)	Warming, moisture and growing season changes induce shifts in vegetation height and activity, with rising atmospheric CO_2 increasing water use efficiency, permitting greater leaf area development in arid systems, and faster recovery from wildfire disturbance converting grass-dominated to woodland systems.
	Global analysis of biome state shifts based on remotely sensed data for vegetation productivity and height identified temperature, moisture, growing season duration and seasonality changes as consistent with observed biome shifts.	Higgins et al. (2016)		
	Arid ecosystem grass dominance changes attributed to changing rainfall amounts and seasonality, with shrub cover increase also attributed to CO_2 fertilisation, and woody encroachment of temperate grasslands attributed to warming.	Chapter 2		
	Mechanisms incorporated into modelling approaches link a substantive fraction of the observed woody encroachment and increase in leaf area index to rising atmospheric CO_2 concentration.	Chapter 2		
Africa	**Observations:** When accounting for land use, African savannas have a mean rate of annual woody cover increase 2.5 times that of Australian savannas. In Africa, encroachment occurs across multiple land uses and is accelerating over time.	Chapter 9, Stevens et al. (2017)		
	Woody vegetation cover over Sub-Saharan Africa increased by 8% over the past three decades. Woody cover loss was prevalent in parts of the Sahel, East Africa and much of Madagascar, but woody plant encroachment dominated the central interior of Africa. Countries exhibiting a mean fractional increase >30% were Cameroon, Central African Republic, South Sudan and Uganda.	Venter et al. (2018)		
	African Sahel has experienced widespread increases in vegetation cover and above-ground biomass.	Zhu et al. (2016), Liu et al. (2016a), Brandt et al. (2017)		
	Woody cover increase and shift of mesic species into arid areas in Namib Desert over 97 years.	Rohde et al. (2019)		
	Central inland arid Nama-Karoo shrub–grasslands have increased in grass cover, shifting grass/shrub balance over tens to hundreds of kilometres westwards.	Masubelele et al. (2015), du Toit and O'Connor (2014)		
	Woody encroachment in Nama-Karoo valley bottoms.	Masubelele et al. (2015), Ward et al. (2014a), Hoffman et al. (2018)		

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	Attribution: Namib woody increase associated with increased fog days and westward expansion of convective rainfall, increase in number of extreme rainfall events and ~30% rise in atmospheric CO_2 in the last 97 years.	Rohde et al. (2019)	Moderate contribution to expansion and thickening of woodlands, roughly equally due to climate and CO_2 change, *high confidence* (***)	Rising atmospheric CO_2 increases water use efficiency, permitting greater leaf area development in arid systems, and increases carbon storage in woody plants that permits faster recovery from disturbance; however, this effect is likely to interact with multiple drivers.
	Nama-Karoo grass increase associated with warming and rainfall trends, enhanced by fire regime.	du Toit and O'Connor (2014), du Toit et al. (2015), du Toit and O'Connor (2017)		
	Boosted regression tree approach used to attribute Sub-Saharan African woody vegetation cover increase of 8% over the past three decades, with 18% and 19% of these trends attributable to rainfall and temperature changes, respectively (together with warming and rainfall trends, land use and disturbance trends explained up to 78% of the spatial variation in the overall woody cover increasing trend).	Venter et al. (2018)		
Asia	**Observations:** *Woodland and forest spatial shifts*: In Central Siberia, structural shifts to woodland vegetation associated with poleward shift of southern taiga biome ecotone.	Brazhnik et al. (2017)		
	Low montane vegetation (tundra and steppe) replaced by woodland and forest as treeline position in Asian mountains has shifted broadly in central and northern Asia.	Chapter 10, Shiyatov and Mazepa (2015), Zolotareva and Zolotarev (2017), Moiseev et al. (2018), Sannikov et al. (2018), Gaisin et al. (2020), Schickhoff et al. (2014)		
	Attribution: Site-specific interaction of a positive effect of warming on tree growth, which offsets drought stress. Part of the change can also be attributed to land use change, especially grazing.	Chapter 2, Liang et al. (2014), Tiwari et al. (2017), Tiwari and Jha (2018)	Moderate impact of warming on structural shifts from low tundra and steppe vegetation to woodland vegetation in montane regions of central and northern Asia, *high confidence* (***)	
Australasia	**Observations:** Low rates of woody plant encroachment in savanna systems.	Stevens et al. (2017)		
	Declines in grass and graminoid cover, and replacement by shrubs and forbs in Bogon High Plains, Victoria.	Hoffmann et al. (2019)		
	Canopy dieback across a range of forest and woodland types.	Hoffmann et al. (2019)		
	Replacement of dominant canopy tree species by woody shrubs.	Bowman et al. (2014), Fairman et al. (2016), Harris et al. (2018) Zylstra (2018)		
	Widespread mortality of fire-sensitive trees species.	Hoffmann et al. (2019)		

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	Attribution: In Australia, changes in rainfall and warming trends are linked to drought stress and enhanced wildfire regime; the observed increase in foliage cover in warm arid environments is in line with predictions of direct responses to rising CO_2.	Stevens et al. (2017), Donohue et al. (2013)	Moderate changes in vegetation structure due to warming, drought and related impacts via wildfire, comprising decline of fire- and drought-sensitive woodland and forest species, and encroachment of woody shrubs and forbs, *medium confidence* (**)	
Central and South America	**Observations:** Woody cover is increasing rapidly in the remaining uncleared savannas of South America.	Stevens et al. (2017)		
	Structural change due to losses of standing biomass observed in tropical forest (Amazon).	Brienen et al. (2015), Feldpausch et al. (2016), Phillips et al. (2009), Zuleta et al. (2017)		
	Alpine paramo vegetation increased vegetation cover and height at its upward election limit in the Chimborazo, while structural change above the upper forest limit is occurring at a lower rate, or not observed yet.	Morueta-Holme et al. (2015), Harsch et al. (2009), Rehm and Feeley (2015)		
	Extensive dieback in several *Nothofagus* species, with evidence of one species decline beginning from the 1940s.	Suarez et al. (2004), Rodríguez-Catón et al. (2016)		
	Attribution: In South America, woody encroachment is most likely due to fire suppression and land fragmentation.	Stevens et al. (2017), Donohue et al. (2013)	Moderate impacts due to warming and rainfall change on structural changes in multiple ecosystems in locations ranging from tropical forest to temperate low-stature vegetation (from arid lowlands to high elevations), *medium confidence* (**) Some evidence of CO_2 fertilisation-linked woody encroachment in savanna	Land use and fire suppression effects may overwhelm effect of increases in atmospheric CO_2; these systems have been subjected to significant human land use.
	Biomass loss attributed to drought events causing at least temporary losses and structural change.	Brienen et al. (2015), Feldpausch et al. (2016), Zuleta et al. (2017), Phillips et al. (2009)		
	Nothofagus decline attributed to impacts of several droughts after the 1940s.	Rodríguez-Catón et al. (2016)		
Europe	**Observations:** 867 vegetation samples (764 vascular plant species) above the treeline from 60 summit sites in all major European mountain systems show that generally more cold-adapted species decline while warm-adapted species increase (covered time period: 2001–2008).	Gottfried et al. (2012)		
	Attribution: The general pattern of change in mountain plant communities mirrors the degree of recent warming and is more pronounced in areas where the temperature increase has been higher. This general pattern indicates that climate change is an important driver of the observed changes.	Gottfried et al. (2012)	Strong contribution of climate change to the observed change in mountain vegetation structure, *low confidence* (*) given the relatively short observational time series No assessment elsewhere	

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Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
North America	**Observations:** *Boreal, sub-alpine and arctic vegetation*: Structural changes with decreases in evergreen forest area (–14.7 ± 3.0% relative to 1984) and increases in deciduous forest area (+14.8 ± 5.2%) in the boreal biome, and structural switch of tundra to herbaceous and shrub vegetation (+7.4 ± 2.0%) in the Arctic biome.	Wang et al. (2020)		
	Alpine meadows structural change to conifer forest.	Lubetkin et al. (2017)		
	Alaska: Boreal forest biome shifting into tundra grassland at poleward edge and undergoing replacement by grassland and temperate forest at equatorward edge.	Beck et al. (2011) (Alaska), Myers-Smith et al. (2019)		
	Western USA arid lands: Dominant Chihuahuan Desert grasses expanding into Great Plains. Woody encroachment of Chihuahuan and Sonoran Deserts by *Prosopis* spp. with increased cover of 3% per decade, woody encroachment of great plains grasslands, at 8% per decade, by *Prosopis* and juniper species. Invasive alien grasses expanding in sagebrush steppes.	Collins and Xia (2015), Rudgers et al. (2018), Chambers et al. (2014), Archer S.R. et al. (2017)		
	Western USA: Limited tree regeneration following fires in recent decades particularly acute in low-elevation forests.	Roccaforte et al. (2012), Rother and Veblen (2016)		
	Vegetation type conversions: Oak forest decline in south-central USA; oak forest structural shifts in Californian oak woodlands; forest conversion in western North America (wildfire driven).	Bendixsen et al. (2015), McIntyre et al. (2015), Coop et al. (2020), O'Connor et al. (2020)		
	Attribution: *Western USA arid lands:* Chihuahuan grass expansion into Great Plains associated with increased aridity and inter-annual rainfall variation. Great Plains encroachment is multifaceted, but includes elements of climate and atmospheric CO_2. Invasive grass expansion in sage steppes associated with warmer growing-season temperatures.	Rudgers et al. (2018), Chambers et al. (2014), Hufft and Zelikova (2016), Reviews by Archer S.R. et al. (2017)	Moderate contribution of climate change (warming and rainfall change) to vegetation type conversions occurring from temperate and Mediterranean to boreal, sub-alpine and tundra vegetation types; *medium confidence* (**) CO_2 effects enhancing arid land conversion to grasslands and woody cover increase elsewhere, *medium confidence* (**)	Invasive release from natural enemies, combined with CO_2 effects, are likely interacting to support grass encroachment.
	Western USA: Wildfires act like a trigger of abrupt vegetation changes enabled by long-term climate change: after-fire regeneration of low-elevation ponderosa pine and Douglas fir forests shows a distinct threshold for recruitment based on vapour pressure deficit, soil moisture and maximum surface temperature. At dry sites, seasonal to annual climate conditions over the past 20 years have crossed these thresholds.	Davis et al. (2019), Tepley et al. (2017)		Wildfire can catalyse vegetation change by killing adult trees that could otherwise persist in climate conditions no longer suitable for seedling establishment and survival.
	Alaska: Boreal forest biome shift attributable via trends in satellite estimates of primary productivity and tree-ring data that show consistency between warming trends and growth increases since 1982 at the boreal–tundra ecotone, and decreases at the boreal–temperate ecotones.	Juday et al. (2015)		Warming extends growing season, allowing boreal forest expansion at poleward edge, and drought and thermal stress induces declines at equatorward edge.
Small Islands	**Observations:** *Pinus brutia* natural tree stands (>80 years old) on Samos Island (Eastern Aegean) experienced lethal desiccation of *Pinus brutia* natural tree stands in late summer of 2000. The evergreen sclerophyllous shrub vegetation (macchia) of the region was also damaged, with *Juniperus phoenicea* and *Phillyrea latifolia* affected the most.	Sarris et al. (2007), Körner et al. (2005)		
	Attribution: Correlative analysis used to attribute tree ring growth reductions to precipitation reductions.	Sarris et al. (2007), Körner et al. (2005)	Minor contribution of decreasing precipitation to changes in ecosystem structure, *low confidence* (*)	

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S24	Terrestrial ecosystems—Phenology shift			
Global	**Observations:** On average (five continents), animals (15 classes including insects, mammals, reptiles and birds) have advanced their spring phenological events significantly by about 3 d per decade. In freshwater systems, earlier spring phytoplankton and zooplankton development and fish spawning with growing season extension have occurred. A study on 677 species found advancement of spring phenology for 62%, no trend for 27% and a delay for 9%, with a mean advancement of 2.3 d per decade. Trends were documented for earlier arrival of migrant birds and butterflies, frog breeding, bird nesting, first flowering and tree budburst.	Chapter 2, Cohen et al. (2018), Parmesan and Yohe (2003) (*n* = 677 species)		
	Breeding phenology of amphibia: In 35% of the *n* = 59 studies, a statistically significant change in phenology was observed; mean advance 6.1 ± 1.65 d per decade (range, 17.5 d per decade delay to 41.9 d per decade advance); higher latitudes advanced more.	While and Uller (2014) (meta-analysis of 59 studies)		
	Breeding phenology of seabirds: Global study of seabirds (*n* = 209 time series, 145 breeding populations) showed no adjustment of breeding season (–0.020 d yr^{-1}) and no response to rise in sea surface temperature (–0.272 d per °C) from 1952 to 2015.	Keogan et al. (2018)		
	Herbarium records reveal consistent phenology shifts over decades to centuries.	Willis et al. (2017)		
	Northern Hemisphere deciduous trees: Delayed autumn senescence averaged 0.33 d yr^{-1} and 1.2 d per degree warming; more delay at low latitudes across Northern Hemisphere.	Gill et al. (2015)		
	Complex phenological responses are being observed, with vernalisation signals conflicting with retardation by extended growing season length in some species.	Chapter 2, Cook et al. (2012)		
	Attribution: Temperature increases have been identified as the primary driver of changes in animal phenology at mid-latitudes, with precipitation being more important at lower latitudes. In freshwater systems, rising temperatures are linked to growing season extension.	Cohen et al. (2018) (synthesis of hundreds of published time series, mainly from Europe, North America and Eastern Australia), Root et al. (2005) (synthesis of hundreds of published time series, mainly from Europe, North America and Eastern Australia)	Strong impact of climate change on changes in phenological behaviours, *high confidence* (***)	In freshwater systems, rising water temperatures, ice cover reductions and prolonged thermal stratification drive changes.
	Breeding phenology of amphibia: In 65% (30 out of 47) of studies, a significant relationship is shown between breeding phenology and temperature, supporting causality.	While and Uller (2014)		
	Northern Hemisphere deciduous trees: Warmer temperatures allow leaves to retain functionality later in the season, but delay is constrained due to day length limits at higher latitudes.	Gill et al. (2015)		
Africa	**Observations:** *Terrestrial vegetation*: Significant trends in land surface phenology have been observed in the remote sensing record for Africa as a whole, mainly indicating delays in the start of season and end of season dates, concentrated in the Sudano-Sahelian and Sudanian regions, after controlling for land cover change. An estimated 9% of the entire continent had delayed start of season.	Adole et al. (2018)		
	Migratory birds: Comparing arrival and departure dates for barn swallows in South Africa for the periods 1987–1991 and 2007–2011 showed that swallows departed 8 d earlier in northern parts of South Africa, thus shortening their stay. Swallows did not shorten their stay in other parts of South Africa.	Altwegg et al. (2012)		
	In the central Highveld of South Africa, arrival and departure timing shifted consistently for nine Palaearctic species but not for seven intra-African migratory species.	Bussière et al. (2015)		

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	Spatially variable and no coherent shifts for Afro-palaearctic migrant species	Beresford et al. (2019)		
	Attribution: Spearman's non-parametric rank correlation analysis on magnitude and direction of temporal trends in seasonal timing data (95% confidence level) made no climate attribution.	Adole et al. (2018)	Moderate impacts of changing seasonality on growing season timing and length (mainly in subtropical savanna and woodlands), and timing of migratory phenology of some migrant bird species, *low confidence* (*)	
	Nonlinear curve-fitting methods based on effort-adjusted reporting rate data from bird atlas data, comparing data between two atlas periods: 1987–1991 and 2007–2012. Significant changes identified mainly driven by waterbirds; similar analysis conducted for barn swallows.	Altwegg et al. (2012), Bussière et al. (2015)		
	Geographically weighted regression (GWR) models testing for relationship between climate and vegetation phenology trends and Afro-palaearctic bird population trends found spatially variable and no consistent migration-route-related associations between climate or vegetation phenology and bird population trends.	Beresford et al. (2019)		
Asia	**Observations:** Reproductive phenology of freshwater *Gymnocypris selincuoensis* advanced 2.9 d per decade on average from the 1970s to 2000s	Tao et al. (2018)		
	Lengthening flowering season in three species of alpine ginger *Roscoea,* advanced by 22 d or delayed by 8–30 d between 1913 and 2011.	Mohandass et al. (2015)		
	Advance in fruit ripening of *Myrica esculenta* by 10–15 d against historical record.	Alamgir et al. (2014)		
	Asian grassland: In general, advances in spring green-up and autumn senescence.	Huang et al. (2020)		
	Siberian boreal forest plants advanced their early season (leaf-out and flowering) and mid-season (fruiting) phenology by –2.2, –0.7 and –1.6 d per decade, and delayed the onset of senescence by 1.6 d per decade during 1976–2018. The growing season in the Siberian boreal forests has extended by approximately 15 d. (Results are based on >15,000 phenological records of 67 common Siberian plant species).	Rosbakh et al. (2021)		
	Attribution: Warming observed in parallel with shifts in phenology due to springtime warming during the 1970s and 1990s, and delayed onset of winter in the 2000s.		Strong effect of climate change (warming), *high confidence* (***)	Warming lengthens growing season by advancing the initiation of growth and retarding the cessation of growth, lengthening flowering and fruiting seasons.
	Asian grassland: Complex responses to multiple climate indicators. In general, warming advances growth initiation in spring and completion of life cycles, while water availability interacts to enhance or retard the response.	Huang et al. (2020)		
	Siberian plant species: Advancement of early season (leaf-out and flowering) and mid-season (fruiting) phenology has primarily been caused by (significantly) increasing spring and summer air temperatures.	Rosbakh et al. (2021)		
Australasia	**Observations:** Advancement of flowering time for 5 of 20 orchid species from 1950 to 2007; for one species, flowering was delayed; study of two donkey orchid species showed advancement of flowering time for *Diuris orientis* but no changes in flowering time for sympatric *Diuris behrii*.	Gallagher et al. (2009) (orchids), MacGillivray et al. (2010) (donkey orchids), Hoffmann et al. (2019)		
	Phenological advance in the emergence time of common brown butterflies by 1.5 d per decade over a 65-year period.	Kearney et al. (2010)		
	Phenological shifts in behaviour and life stages of multiple bird and insect species in several ecosystems, and plant phenology observed to have advanced an average of 9.7 d per decade ($n = 390$; 95% credible interval of 7.3–12.1 d per decade).	Beaumont et al. (2015)		

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Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
	Attribution: Changes in orchid flowering times coincided with increase in mean annual temperature of 0.74°C between 1950 and 2007, but with some influences of shifts from cold La Niña phase to a warm El Niño phase.	Gallagher et al. (2009)	Moderate impact of climate change on phenology of multiple animal species in several taxonomic groups (mainly due to warming, but interactions with timing of rainfall in some cases), and warming impacts on plant phenology, *high confidence* (***)	
	Physiologically based model of climatic influences on development and statistical analyses of climate data was used to attribute the response of the brown butterfly to anthropogenic warming.	Kearney et al. (2010)		
	Synthetic assessment applied to attribute phenological shifts in behaviour and life stages of multiple bird and insect species in several ecosystems, and meta-analysis used to reveal plant phenology advances.	Beaumont et al. (2015)		
Central and South America	**Observations:**			
	Attribution:		No assessment	
Europe	**Observations:** Across Austria, Germany and Switzerland, for the time period 1951–2018, 90% of 63,667 time-series data sets showed advanced leaf unfolding and flowering (-0.240 ± 0.002 d yr^{-1}), and 57% of 5971 data sets showed delayed leaf colouring (0.036 ± 0.007 d yr^{-1}). For farmed areas, 84% of 12,285 data sets showed lengthening of the growing season (mean trend of $+0.261 \pm 0.008$ d yr^{-1}) with 87% spring trends advance and 57% autumn trends delay.	Menzel et al. (2020) (Austria, Germany, Switzerland)		
	Mediterranean region: For 17 common amphibian species, earlier first spring appearances were observed from 1983 to 1997, but for most species the trend stopped or reversed in most species between 1998 and 2013.	Prodon et al. (2017)		
	Terrestrial and freshwater plants, UK: High consistency (84%, $n = 25{,}532$ time series, 726 taxa) in advancement of phenological trends (terrestrial plants 93% advancing, mean 5.8 d per decade, freshwater plants 62% advancing, mean 2.3 d per decade).	Thackeray et al. (2010)		
	Attribution: Attribution followed the methods proposed by (Rosenzweig et al., 2007; Rosenzweig et al., 2008) to positively link phenological responses to observed climatic change by frequency analysis of expected (based on climate trends) versus observed responses.	Menzel et al. (2020)	Strong advancement in spring phenology and delay in autumn phenology due to warming, *medium confidence* (**)	Warming lengthens the growing season by advancing the initiation of growth and retarding the cessation of growth.
	Linear mixed effects models used to distinguish rates of change among taxonomic groups, attribution to warming inferred.	Thackeray et al. (2010)		
	Generalised additive modelling and generalised linear modelling approaches used to identify relationships between phenological shifts and climate variables.	Prodon et al. (2017)		
North America	**Observations:** Earlier egg laying by seven shorebird and passerine bird species comparing 1984–1986 with 2007–2009.	Grabowski et al. (2013)		
	In rivers in Newfoundland and Labrador ($n = 13$), median return time of Atlantic salmon (*Salmo salar*) advanced by 12 d from 1978 to 2012.	Dempson et al. (2017)		
	Attribution: Earlier egg laying correlated with snowmelt and earlier resource availability. Salmon return time advancement associated with warmer climatic conditions.	Grabowski et al. (2013) (birds), Dempson et al. (2017) (fish)	Observed shifts in phenology mainly due to historical warming, *low confidence* (*), no assessment of other processes	
Small Islands	**Observations:**			
	Attribution:		No assessment owing to insufficient evidence	

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S25	Terrestrial ecosystems—Burned areas Note: This is exclusively about attribution of changes in **burned areas** and not about the attribution of changes in purely weather-based fire risk indices.			
Global	**Observations:** Globally, 4.2 million km^2 of land per year (about the size of the European Union) burned on average from 2002 to 2016 with the highest fire frequencies in the Amazon rainforest, African deciduous forests and savannas, and northern Australia. On average (2003–2016), the largest fires were found in Australia (17.9 km^2), boreal North America (6.0 km^2) and Northern Hemisphere Africa (5.1 km^2), while Central America (1.7 km^2), equatorial Asia (1.8 km^2) and Europe (2.0 km^2) had the smallest average fire sizes.	Giglio et al. (2018), Earl and Simmonds (2018), Andela et al. (2017), Andela et al. (2019)	*High confidence* in global decline (***) based on independent satellite products	
	Burned area decreased by 1.4 ± 0.5% yr^{-1} (GFED4, 1998–2015), 0.7% yr^{-1} (insignificant, GFED4, 1996–2015), and 0.7% yr^{-1} (insignificant, FireCCI50, 2001–2015). Decrease is dominated by reductions in regions with low or intermediate tree cover (tropical savannas of South America and northern hemispheric Africa, grasslands across the Asian steppe). Positive trends in closed-canopy forests.	Andela et al. (2017) (GFED4, 1998–2015), Forkel et al. (2019) (GFED4, 1996–2015; FireCCI50, 2001–2015)	*Moderate confidence* in decline (**)	
	Attribution: The overall decline is primarily driven by agricultural expansion and intensification. Based on empirical relationships between variations in precipitation and burned areas, climate change may have induced a decline in burned areas in addition to the effects of the other drivers.	Andela et al. (2017)	Minor climate-induced decrease of burned areas on global average, *low confidence* (*)	Climate change is expected to induce heterogeneous responses in terms of burned areas depending on vegetation types: climate influences wildfire potential primarily by modulating fuel availability in fuel-limited environments, and by modulating fuel aridity in flammability-limited environments.
Africa	**Observations:** Seventy percent of the global burned area lies in Africa. Burned area for the continent as a whole decreased 1–2% yr^{-1} from 2002 to 2016. The average decrease is dominated by the reduction in northern-hemisphere Africa (from 2002 to 2016 80% of the decline occurred in the Northern Hemisphere). Cropland burning shows a steeper negative trend than natural land covers in both hemispheres (2002–2015). Crop land accounts for about one-third of the overall decline in burned areas (2002–2015). Burned area regionally increased in extensive forest areas in west, central and southern Africa, but positive trends were often not significant.	van der Werf et al. (2010), Andela and Van Der Werf (2014), Zubkova et al. (2019), Wei et al. (2020), Wilson et al. (2010)		
	Attribution: The negative trend in burned areas in northern hemispheric burned areas is shown to be partly due to direct human forcing (agricultural expansion and changes in management, populations density), but observed changes in climate are estimated to have had a similar to higher contribution (2001–2012, 2002–2016), partly induced by indirect effects of climate change on net primary productivity. Direct human forcings seem to have a smaller contribution to the trends in southern hemispheric Africa where climate drivers seem to dominate but the overall trend is less clear and more dependent on the considered time window.	Andela and Van Der Werf (2014) (2001–2012), Zubkova et al. (2019) (2002–2016); Earl and Simmonds (2018), Wei et al. (2020), Forkel et al. (2019)	Moderate to strong climate-induced reduction of burned areas in Africa particularly driven by changes in northern hemispheric Africa, *medium confidence* (**) Overall, the observational records are still relatively short, which means that observed trends in climate drivers may partly be induced by climate oscillations such as ENSO. In particular, the trends in southern hemispheric Africa are quite dependent on the considered time window.	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
Asia	**Observations:** *Arctic tundra and boreal forest:* Since the end of the 20th century, Siberia has seen an increase in the area of forest fires. In extreme fire years (2002, 2003, 2012, 2019), the area burned by fire reached 10–12 × 10^6 ha. Catastrophic fires have also been observed in earlier times, but with much lower frequency. During the last decade, the area burned increased by approximately two-fold or even more depending on the region and considered time interval. In the Siberian Arctic, wildfires are migrating northward. Wildfires in Eastern Siberia have reached the Arctic Ocean shore.	Ponomarev et al. (2016), Nitze et al. (2018), Kharuk et al. (2021) (review)		
	Attribution: Extreme wildfires coincided with years of anomalously high air temperatures. The northern boundary of fires in Western Siberia is correlated with temperature anomalies. Overall, the evidence on the sensitivity of burned areas to weather conditions (air temperature anomalies, increasing climate aridity and drought events [Table SM16.23]) and the observed changes in climate indicate a contribution of climate change to the observed increase in burned areas. However, no attribution analyses have been conducted on relative influences of climate and non-climate factors.	Kharuk et al. (2021) (review)	Climate change has contributed to the observed increase in burned areas, *medium confidence* (**)	
Australia	**Observations:** The fraction of vegetated area burned increased significantly in 8 of the 32 bioregions in southeastern Australia from 1975 to 2009, up to 500%, but decreased significantly in three bioregions. In the southeastern state of Victoria, burned area increased significantly between the periods 1950–2002 and 2003–2020, with the area burned in the 2019–2020 fires the highest in the record. Insignificant trends in burned areas derived from satellite data and aggregated across Australia, but significant trends in certain regions (see below).	Andela et al. (2017), Bradstock et al. (2014), van Oldenborgh et al. (2020)		
	Mostly positive trends in burned areas in forested areas along the southeastern coast (1975–2009). Mostly no change in relatively dry, interior woodland bioregions.	Bradstock et al. (2014)		
	Record 2019–2020 bushfires: Unprecedented bushfire activity across Southeastern Australia (Queensland, New South Wales, Victoria, South Australia, Western Australia and Australian Capital Territory) in 2019/2020. The fires burnt more than 17 million hectares, resulting in the loss or displacement of nearly 3 billion animals. More than 23% of the temperate forests in southeastern Australia were burnt in the 2019/2020 fire season, making the scale of these forest fires unprecedented both in an Australian and global context.	van Oldenborgh et al. (2021), Lindenmayer and Taylor (2020), Chapter 11 Box 11.1		
	Attribution: See below.		Moderate to strong contribution of climate change to increase in forested areas burned in south-eastern Australia and increased probability of extreme fires in 2019/2020, *low confidence* (*), missing analyses elsewhere	
	Changes in fire risk indices are shown to contribute to positive trends in burned areas in the forested areas along the southeastern coast. There were no instances of change (increases or decreases) in areas burned across different vegetation types that occurred completely independently of change in the climatic predictors. *Extreme fires in 2019/2020:* Anthropogenic climate change has increased the likelihood of extreme fire weather conditions by 30%, and purely weather-based fire risk indices show a relatively high correlation with burned areas (~40% in summer), indicating an impact of climate change on the areas burned that, however, has not been quantified.	Chapters 2 and 11, Bradstock et al. (2014), van Oldenborgh et al. (2020)	Moderate contribution of climate change to increases in burned areas in primarily forested areas along the southeastern coast, *low confidence* (*)	
Central and South America	**Observations:** *Amazonia:* Burned areas mainly distributed across the southern boundary of the Amazon basin in Am (tropical monsoon) and Aw (tropical winter dry, ~93% of the mean annual burned areas, 1982–2017, 94% in the dry season, August–October). Annual total burned area (178.5 ± 65.4 × 103 km^2) in Am and Aw was relatively stable but expanded mainly in the transition season between May and August (mean fraction of burned area in Am increased from 3.7 ± 3.7%, 1982–2000, to 5.4 ± 3.4%, 2001–2017). Burned area increased mainly across the southern boundary of the Amazon basin at 'Arc of Deforestation'. Burned area in Acre, Brazil, increased 36-fold from 1984 to 2016.	Xu et al. (2020) Garreaud 2018, Nobre et al. (2016), Marengo et al. (2018), Silva et al. (2018) (Acre)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Chile: In contrast to the number of fires, the size of the burnt areas does not show a statistically significant change in the period 1984–2016.	Úbeda and Sarricolea (2016) (1984–2016), Urrutia-Jalabert et al. (2018) (central and south-central Chile, 1976–2013)		
	Attribution: *Amazonia:* Burning in the Amazon coincides spatially and temporally with deforestation and forest degradation from agricultural expansion. Deforestation fragments the rainforest and increases the dryness and flammability of vegetation. From 1981 to 2018, the Amazon forest cover loss reduced moisture inputs to the lower atmosphere, increasing drought and fire in a self-reinforcing feedback. In the Amazon, deforestation exerts an influence on wildfire that can be stronger than climate change.	van Marle et al. (2017), da Silva et al. (2018), Xu et al., 2020, Alencar et al. (2015)	Moderate contribution of climate change to observed increases in burned areas in Amazonia, *medium confidence* (**)	
	Chile: While the inter-annual variability of burned areas is associated with weather conditions (Table SM16.23), the impact of climate change on long-term changes in burned areas is unclear.			
Europe	**Observations:** Burned area for Mediterranean Europe as a whole decreased from 1985 to 2011.	Turco et al. (2016), Turco et al. (2017), Turco et al. (2018)		
	Portugal: Insignificant increase in burned areas, 1980–2017. Record extent of burned areas in 2017.	Turco et al. (2019)		
	Spain: Burned area for Spain as a whole did not show significant long-term trends from 1968 to 2010. Negative trend in burned areas in Northeastern Spain 1970–2007.	Moreno et al. (2014), Turco et al. (2014)		
	Attribution: While burned area in Mediterranean Europe was correlated to summer drought, fire suppression exerted a stronger influence.	Turco et al. (2013), Turco et al. (2017), Pereira et al. (2013)	Minor contribution of climate change to observed negative trends in northeast Spain to moderate contribution of climate change to positive trend that is reduced by other direct human influences in Portugal, *low confidence* (*)	
	Portugal: In Portugal, variations in drought conditions and time under extremely high temperatures can explain more than 60% of the observed annual variability of burned areas. Based on this empirical relationship, climate change has increased burned areas compared with a baseline with stationary drought and heat conditions. The observed trend is weaker (and not significant) than the purely climate-driven trend, an effect that may be due to a general decline in forest areas. Extreme extent of burned areas in 2017 is in line with the model accounting for climate change and cannot be explained by the model assuming stationary fire weather conditions.	Turco et al. (2019)		
	Northeastern Spain: Pure climate change may have induced a slightly negative trend in burned areas as the higher fuel flammability induced by climate change is counterbalanced by the negative effect of rising extreme temperatures on fuel availability and fuel connectivity. Improved fire prevention and fire extinction are considered a main cause for the observed decline in burned areas.	Turco et al. (2014), Moreno et al. (2014)	Minor contribution of climate change on observed negative trends in burned areas, *low confidence* (*)	
North America	**Observations:** No significant change in total burned areas across North America as a whole, but significant trends in individual regions (see below).	Andela et al. (2017)	*Low confidence* in trends in total burned areas	
	Western USA (excluding Alaska): Strong increases in burned areas: area burned in large (>400 ha) forest fires increased significantly (1973–2012) with 123,000 ha (~390% of the average of the first decade) per decade and to a lesser extent in large non-forest wildfires (40,585 ha per decade; ~65% of the average of the first decade).	Westerling (2016), Holden et al. (2018), Abatzoglou and Williams (2016), Williams and Abatzoglou (2016)	High confidence in strong increase	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Western USA (excluding Alaska): Climate change is a major driver of the observed trends. Based on a robust close relationship between weather-related fire risk indicators and burned areas, anthropogenic climate change is estimated to have doubled the cumulative area burned from 1984 to 2015 compared with a situation without anthropogenic climate change. The positive trend in potential evapotranspiration accounts for ~78% of the positive trend in burned area from 1884 to 2015.	Holden et al. (2018), Abatzoglou and Williams (2016), Williams and Abatzoglou (2016)	Strong contribution of climate change to increase in burned areas; *high confidence* (***)	Increased temperature has increased vapour pressure deficit, which increases fuel aridity. Anthropogenic climate change accounted for 55% of the increases in fuel aridity, 1979–2015.
	California (as sub-region of western USA): Five-fold increase in annual burned area from 1972 to 2018 mainly induced by an ight-fold increase in summer forest-fire extent (1972–2018); weaker signal in autumn burned area increased by ~40% per decade during 1984–2018.	Williams et al. (2019), Goss et al. (2020)	High confidence in strong increase (***)	
	California (as sub-region of western USA): Climate change strongly increased the burned areas. Robust inter-annual relationships between purely weather-based fire risk indices and summer forest-fire area in California indicate that 70% and more of the observed trends summer forest-fire area can be explained by climate change. Climate change effects were less evident in non-forested lands and in fall.	Williams et al. (2019), Goss et al. (2020)	Strong adverse impact of climate change on summer forest-fire area, *high confidence* (***)	Increased summer vapour pressure deficit, caused by increased temperatures, and decreases in autumn precipitation. In autumn, changes in wind events and delayed onset of winter precipitation contribute to increased weather-based fire risk.
	Alaska, USA: Burned area in 2015 was the second highest in the 1940–2015 record.	Partain Jr et al. (2016)		
	Alaska, USA: Climate model simulations indicate climate change has increased the likelihood of fuel conditions at 2015's levels or higher by 34–60%. A systematic assessment of the correlation between the annual fluctuations of the indicator of fuel conditions and total burned areas is missing, i.e., the contribution of climate change to the extent of burned areas has not been quantified but seems to exist based on independent studies indicating linkages between fire weather indices and actually burned areas.	Partain Jr et al. (2016), Ziel et al. (2015)	Unquantified but positive contribution of climate change to burned areas, *moderate confidence* (**)	High temperatures and low relative humidity caused high fuel aridity.
	Canada: Burned area in British Columbia (BC) in 2017 was the highest in the 1950–2017 record, 40% greater than the previous record in 1958. Positive trends in burned areas in BC (1950–2017) and Canada as a whole (1959–1999).	BC Wildfire Service (2017), Kirchmeier-Young et al. (2019), Gillett et al. (2004)	High confidence in positive trends	
	Canada: Anthropogenic climate change has induced a positive trend in weather-based fire risk indices. Based on the observed correlation between fire weather indices and annual variations in burned areas, it is estimated that climate change has contributed to the positive trend in burned areas across Canada and can explain the trends in BC. Anthropogenic climate change has increased burned areas 7 to 11 times over the area of natural burning, comparing the period 2011–2020 with the period 1961–1970.	Kirchmeier-Young et al. (2017b), Kirchmeier-Young et al. (2019), Gillett et al. (2004)	Major contribution of temperature positive trends to trend in burned areas; *medium confidence* (**); *high confidence* that observed temperature trend is induced by anthropogenic emissions of climate forcers	Trends in fire risk are primarily driven by temperature increase.
	Attribution: Identification of climate impacts on burned areas is focused on positive trends in forested Western North America (see below). In some of these regions, a strong impact has been identified with *high confidence*, while in other regions (in particular in regions with negative trends) an assessment is not possible as there are no studies.	See below	Strong contribution of climate change to positive trends in burned areas, *high confidence* (***) in certain regions, missing evidence in others	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
Small Islands	**Observations:**			
	Attribution:		No assessment	
S16	Water distribution—Reductions in water availability + induced damages and fatalities This is not about droughts themselves, which are considered climatic events and therefore addressed in Table SM16.21 on climate attribution. This section does not address the direct impacts of drought on crop yields, conflict, malnutrition, etc. that are addressed in individual dedicated sections.			
Global	**Observations:** Changes in low flow indicators vary across regions, and trends often also depend on the considered time period. Strong reductions in low flow indicators are observed in Southern Australia and Northeast Brazil from 1971 to 2010, but weak opposite trends from 1961 to 2000 and 1951 to 1990, respectively. A persistent negative trend is observed in the European Mediterranean region (strong) and Southern Africa (weaker). Increases in observed low flow indicators are strongest in East Asia (mainly data from Japan) and weak but relatively persistent in Central and Northern Europe, Central and Western North America, and Southeastern South America.	Gudmundsson et al. (2019) (annual minimum of daily discharge, annual 10th percentile of daily discharge across three 40-year periods from 1951 to 2010), Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)		
	Large economic losses and food insecurity induced by limited water availability (listed in the regional sections below).	Chapter 4.2.5, Table 4.5		
	Attribution: Multi-model historical simulations forced by observed climate show that changes in climate can explain a considerable part of the observed spatial pattern of trends in the annual 10th percentile of daily discharge. Effects of historical water and land management only have a minor effect on the simulated trends. Historical hydrological simulations forced by simulated historical climate accounting for natural and anthropogenic radiative forcing also basically reproduce the observed spatial pattern of trends that does not emerge in simulations forced by simulated pre-industrial climate and only accounting for historical changes in land use and water management. This indicates that external climate forcing acts as a causal driver of the general spatial patterns of trends in the annual 10th percentile of daily average river discharge at the global scale (1971–2010) that is not explained by direct human influences.	Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)	The general spatial pattern of trends in low river flows can largely be explained by observed changes in weather conditions, i.e., climate change is a major driver of observed increases and decreases in low flows, *low confidence* (*) as based on one study Anthropogenic climate forcing has increased likelihood of a range of large-impact droughts, *medium confidence* (**)	
Africa	**Observations:** Due to limited data availability, regional trends in the annual 10th percentile of daily discharge are only estimated for Southern Africa where trends have been negative in the early period (1951–2000) but particularly weak and not significant from 1971 to 2010.	Gudmundsson et al. (2019) (annual minimum of daily discharge, annual 10th percentile of daily discharge across three 40-year periods from 1951 to 2010), Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)		
	Cape Town water crisis: Water shortage in Cape Town reached a peak at the beginning of 2018 when Cape Town was expected to run out of water in March 2018. To avoid the 'day zero', extreme restrictions on water usage were implemented, including completely ceasing irrigation. This induced significant losses in agriculture but finally avoided the 'day zero'. The direct cost of the water crisis induced by reduced water revenue, losses in agricultural jobs and production, and indirect costs such as a drop in tourism have been estimated to reach more than 2.5 billion South African rands (USD 181 million). Farmers lost 14 billion South African rands.	Otto et al. (2018b) Muller (2018)		
	East Africa, 2014: Some isolated food security crises.	Section 4.2.5, Table 4.4		
	East Africa, 2017: Food insecurity approaching near famine conditions in East Africa, 2017.	Section 4.2.5, Table 4.4		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Southern Africa, 2016: Millions of people were affected by famine, disease and water shortages. In addition, a 9-million-ton cereal deficit resulted in 26 million people in need of humanitarian assistance.	Section 4.2.5, Table 4.4		
	Attribution: Multi-model hydrological simulations forced by observed climate change and direct human influences show stronger negative trend in Southern Africa than the observed trend in the annual 10th percentile of daily discharge that is mainly induced by direct human influences, while climate forcing alone does not induce a trend in the considered regional low flow indicator. This may indicate that climate change has had a minor influence on the low flow indicator, but the discrepancy between the simulated (climate + direct human forcing) and observed trends means that our understanding of the observations is not yet sufficient to explain the observations and allow for attribution on the considered regional level.		Anthropogenic climate forcing has contributed to individual severe regional water restrictions and associated consequences, *medium confidence* (**) No assessment elsewhere	
	Cape Town water crisis: The water crisis occurred at the end of three consecutive years of below average rainfall from 2015 to 2017 leading to a prolonged drought that has been attributed to anthropogenic climate forcing (Table SM16.21). However, at the same time, Cape Town’s population continues to grow, such that increased water demand and withdrawal over the year leading to the crisis could provide another explanation for the extreme water shortage reached in the reservoirs beginning of 2018. Currently, there are no published hydrological simulations quantifying the effect of recent changes in demand on 2018 reservoir levels. However, Cape Town has been internationally recognised for having stabilised water demand growth to around 2% per annum, indicating that the drought was the major driver of the observed water limitations and associated losses in 2018. The assessment explicitly does not include any statement about the management measures that could have avoided the crisis as according to the definition climate impact attribution is comparing the observed state of the system to the state of the same system without climate change.	Otto et al. (2018b)		
	East Africa 2014: Region affected by drought conditions that have been attributed to anthropogenic climate forcing (Table SM16.21).	Section 4.2.5, Table 4.4		
	East Africa, 2017: Tanzania, Ethiopia, Kenya and Somalia were affected by an extensive drought that has been attributed to anthropogenic climate forcing (Table SM16.21).	Section 4.2.5, Table 4.4		
	Southern Africa, 2016: Region was affected by drought conditions that have been attributed to anthropogenic climate forcing (Table SM16.21).	Section 4.2.5, Table 4.4Section 4.2.5, Table 4.4		
Asia	**Observations:** Due to limited data availability, regional trends in the annual 10th percentile of daily discharge are only estimated for India and Japan where trends have been slightly positive from 1971 to 2010 (no trend or very weak trend in India and slightly stronger positive trend in Japan).	Gudmundsson et al. (2019) (annual minimum of daily discharge, annual 10th percentile of daily discharge across three 40-year periods from 1951 to 2010), Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)		
	Yunnan, southwestern China, 2019: Water scarcity affected nearly 7 million residents and resulted in crop failure over at least 1.35 × 104 km^2 cropland (Fig. 1). More than 94% of the total area in the province was drought-stricken, and around 2 million people faced drinking water shortages, with a direct economic loss of about 6.56 billion RMB.	Section 4.2.5, Table 4.4		
	Southwestern China, 2019: Over 640,100 hectares of crops with rice, corn and potatoes extensively damaged. Over 100 rivers and 180 reservoirs dried out. Over 824,000 people and 566,000 head of livestock having a severe lack of drinking water, with a direct economic loss of 2.81 billion Chinese Yuan (USD 400 million).	Section 4.2.5, Table 4.4		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
	South China, 2019: A lightning-caused forest fire in Muli County killed 31 firefighters and burned about 30 ha of forest.	Section 4.2.5, Table 4.4		
	South China, 2018: Shrinking reservoirs, water shortages. Area and yield for early rice reduced by 350,000 ha and 1.28 million tons relative to 2017.	Section 4.2.5, Table 4.4		
	Middle and lower reaches of the Yangtze River, China, 2019: Reduced agriculture productivity and increased load on power system supplies and transportations, and on human health.	Section 4.2.5, Table 4.4		
	Thailand 2016: Loss of crops, such as rice and sugarcane; losses in the agricultural production of about half a billion USD.	Section 4.2.5, Table 4.4		
	Attribution: Multi-model hydrological simulations forced by observed climate change and direct human influences well reproduce the positive trend in Japan and slightly overestimate it in India. Simulated trends are barely influenced by direct human drivers in Japan and only very weakly reduce the positive trend in the annual 10th percentile of daily discharge in India. So, climate change is estimated to have contributed to the observed (weak) increase in river low flow across 1971–2010. Only in Japan does a weak increase in the low flow indicators also occur in hydrological simulations forced by an ensemble of historical climate model simulations accounting for anthropogenic and natural forcings, indicating that part of the weak increase in annual 10th percentile of daily discharge may be due to external forcing rather than internal climate variability.	Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)	Climate change has slightly increased the annual 10th percentiles of daily discharge from 1971 to 2010 in Japan and India, *low confidence* (*) as based on only one study. Anthropogenic climate forcing has increased likelihood of individual severe drought-induced regional water restrictions and associated consequences, *medium confidence* (**)	
	Yunnan, Southwestern China, 2019, Southwestern China, 2019, South China, 2018, 2019: Events induced by droughts whose likelihood has been increased by anthropogenic climate forcing (Table SM16.21).	Section 4.2.5, Table 4.4		
	Middle and lower reaches of the Yangtze River, China, 2019: Event induced by drought whose likelihood has been decreased by anthropogenic climate forcing.	Section 4.2.5, Table 4.4		
	Thailand, 2016: Losses induced by drought affecting 41 Thai provinces; likelihood has been increased by anthropogenic climate forcing.	Section 4.2.5, Table 4.4		
Australasia	**Observations:** Due to limited data availability, a regional trend in the annual 10th percentile of daily discharge is only estimated in Southern Australia where it is significantly negative from 1971 to 2010 while slightly and not significantly positive from 1961 to 2000.	Gudmundsson et al. (2019) (annual minimum of daily discharge, annual 10th percentile of daily discharge across three 40-year periods from 1951 to 2010), Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)		
	In New Zealand, the 2007/2008 drought cost 2017 was NZ$3.2 billion, and the 2012/13 drought cost 2017 was NZ$1.6 billion (total costs estimated by an economic model).	Frame et al. (2020a)		

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Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: The observed strong negative trend is well reproduced by multi-model hydrological simulations forced by observed climate change and direct human influence where the direct human influences barely affect the simulated trends. This indicated that the observed climate change has been a major driver of the observed reduction of the annual 10th percentiles of daily discharge (1971–2010). The observed trend is, in contrast, not reproduced by hydrological simulations forced by an ensemble of historical climate model simulations accounting for natural and human forcings. This indicates that the observed changes in low discharge may be induced by internal climate variability rather than by external climate forcings.	Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)	Climate change has strongly reduced the annual 10th percentiles of daily discharge from 1971 to 2010 in Southern Australia, *low confidence* (*) as based on only one study Anthropogenic climate forcing has contributed to the observed water restrictions and associated damages in New Zealand by increasing the probability of the underlying droughts, *low confidence* (*)	
	New Zealand, damages induced by droughts: Anthropogenic climate forcing has increased the probability of circulation patterns like those associated with the droughts with the fraction of attributable risks (FAR) reaching 15% in 2007/2008 and 20% in 2012/2013 (FAR = 1 – P_0/P_1, with P_0 and P_1 being the probabilities under natural and observed climate forcing, respectively). By increasing the likelihood of the drought, anthropogenic climate forcing has also increased the likelihood of the associated damages. However, there is no estimate of the fraction of the damages that can be attributed to a potential anthropogenic intensification of the droughts.	Frame et al. (2020a)		
Central and South America	**Observations:** Observed trends in the annual 10th percentile of daily discharge are very weak in Southeastern South America and the Amazon region, while a strong decline is observed in Northeast Brazil from 1971 to 2010.	Gudmundsson et al. (2019) (annual minimum of daily discharge, annual 10th percentile of daily discharge across three 40-year periods from 1951 to 2010), Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)		
	Attribution: The observed changes in annual 10th percentiles of daily discharge are not well reproduced by multi-model hydrological simulations forced by observed climate change and direct human influence except for an also negative but much weaker trend Northeast Brazil. Direct human influences seem to only very slightly contribute to the simulated reduction. So, there is some indication that observed climate change has contributed to the strong reduction in the annual 10th percentiles of daily discharge, but our overall understanding of the observed changes does not allow for a comprehensive attribution.	Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)	Minor impact of climate change on water crisis in São Paulo 2015, *low confidence* (*), no assessment elsewhere	
Europe	**Observations:** The annual 10th percentile of daily discharge has increased in Northern Europe, decreased Southern Europe and barely changed in Central Europe (1971–2010). In particular the reduction in Southern Europe is strong and persistent across different 40-year time windows from 1951 to 2010.	Gudmundsson et al. (2019) (annual minimum of daily discharge, annual 10th percentile of daily discharge across three 40-year periods from 1951 to 2010), Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)		
	Attribution: The observed pattern of changes in the annual 10th percentile of daily discharge is very well reproduced by multi-model hydrological simulations forced by observed climate change and direct human influence, where the direct human influences barely affect the simulated trends. This indicated that the observed changes in climate have been a major driver of the observed changes in the annual 10th percentiles of daily discharge. In addition, the observed pattern of changes in low flows is also reproduced by hydrological simulations forced by an ensemble of historical climate model simulations accounting for natural and human forcings. This indicates that the observed changes in low flows are induced by external climate forcing rather than internal climate variability.	Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)	Climate change has been a major driver of the observed reduction in the annual 10th percentiles of daily discharge in Southern Europe and the increase in annual low flows in Northern Europe (1971–2010), *low confidence* (*) as based on only one study	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
North America	**Observations:** From 1971 to 2010, the annual 10th percentile of daily discharge has decreased in Eastern North America, while changes have been minor in western and central North America.	Gudmundsson et al. (2019) (annual minimum of daily discharge, annual 10th percentile of daily discharge across three 40-year periods from 1951 to 2010), Gudmundsson et al. (2021) (annual 10th percentile of daily discharge, 1971–2010)		
	USA, Northern Great Plains, 2017: 'Billion-dollar disaster'; widespread wildfires (one of Montana's worst wildfire seasons on record) compromised water resources, destruction of property, livestock sell-offs, reduced agricultural production, agricultural losses of $2.5 billion.	Section 4.2.5, Table 4.4		
	Washington State, USA, 2015: USD 335 million loss for the agricultural industry.	Section 4.2.5, Table 4.4		
	California drought 2012: Beginning in 2012, California experienced acute water shortages, groundwater overdraft, critically low streamflow, and enhanced wildfire risk. The water shortage has led to water use restrictions, fallowed agricultural fields and ecological disturbances such as large wildfires and tree mortality.	Diffenbaugh et al. (2015), Williams et al. (2015)		
	Attribution: The observed pattern of changes in the annual 10th percentile of daily discharge (1971–2010) is to some degree reproduced by multi-model hydrological simulations forced by observed climate change and direct human influence (very weak trends in Western and Central America, but also very weak reduction in eastern North America where the observed reduction is much stronger). This indicates that climate change only had a minor impact on trends in annual low flows in western and central North America, but observations in eastern North America are not yet understood well enough to allow for an attribution.		Anthropogenic climate had only a minor impact on annual low flows in western and central North America (1971–2010), *low confidence* (*). Anthropogenic climate forcing has increased likelihood of individual severe drought-induced regional water restrictions and associated consequences, *medium confidence* (**).	
	USA, Northern Great Plains, 2017: Losses induced by drought whose likelihood has been increased by anthropogenic climate forcing (Table SM16.21).	Section 4.2.5, Table 4.4		
	Washington State, USA, 2015: Losses induced by drought whose likelihood has been increased by anthropogenic climate forcing (Table SM16.21).	Section 4.2.5, Table 4.4		
	California drought 2012: Anthropogenic climate forcing has increased the probability of co-occurring warm–dry conditions like those that created the 2012–2014 drought conditions leading to the acute water shortages (see 'Atmosphere—Drought', Table SM16.21'). The impact of other direct human drivers is not explicitly assessed such that the impact on climate change cannot be set into perspective.	Diffenbaugh et al. (2015), Williams et al. (2015)		
Small Islands	**Observations:** *Caribbean 2013–2016:* Over 50% of crop production lost. More than two million people were pushed into food insecurity, with Haiti particularly affected (one million people [~10% of its population]) severely affected by food insecurity and required immediate assistance).	FAO (2016), OCHA (2015), Herrera et al. (2018)		
	Attribution: Losses induced by the pan-Caribbean drought whose intensity and extent has been increased by anthropogenic climate forcing (Table SM16.21).	Herrera et al. (2018)	Anthropogenic climate forcing has increased drought-induced regional water limitations and associated consequences in 2013–2016, *low confidence* (*) No assessment elsewhere	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
S15a	Water distribution—Flood hazards (peak discharge, flood volume and flooded areas)			
Global	**Observations** *Global annual maximum flood volume:* Heterogeneous trends (negative trends in South Europe, western North America, South Australia, Northeast Brazil; positive trends in Northwestern Europe, eastern North America, parts of southeastern South America). More stations (out of 9213) with significantly negative trends than significantly positive trends. *Flood frequency:* Significant increase in the occurrence of moderate- and long-duration floods on global and latitudinal level. From before to after the year 2000, the frequencies of long-duration floods increased by a factor of 4 and 2.5 events per year across the tropics and northern midlatitudes, respectively. Changes were not monotonic, but frequencies reached a maximum in 2003 and decreased afterwards. No significant trend in short-term flood events. *Flood duration*: Significant monotonic increase in median flood durations at global scale from 4 d in 1985 to 10 d in 2015. Similar patterns at latitudinal bands. *Timing and level of maximum discharge*: Across 1744 catchments without major dams in Australia, Brazil, Europe and the USA, the occurrence of the largest daily discharge within 1980–2009 more often fell into the second 15 years than in the first 15 years, and the maximum levels reached in the first 15 years were on average smaller than the maximum levels reached in the second period. However, the trend in occurrence frequencies is non-monotonic but reaches a peak in 1995 and may strongly depend on the considered time window.	Do et al. (2017) (annual maximum streamflow, analysis of 9213 stations across the globe), Blöschl et al. (2019) (annual maximum discharge, Europe, 3738 stations, 1960–2010), Gudmundsson et al. (2019) (maximum annual discharge, over 30,000 stations around the world, 1951–2010), Najibi and Devineni (2018) (frequency and duration, 1985–2015), Berghuijs et al. (2017) (time of occurrence of maximum), Wasko and Sharma (2017)	Variations of maximum discharge often depend on low-frequency climate oscillations, making trends dependent on the considered time periods. Confidence in long-term changes strongly depend on the considered regions (see individual regional assessments in the following rows)	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
	Attribution: Model simulations forced by observed weather variations excluding changes in other direct human forcings show a purely climate induced increase in annual maximum flood volume (1990–2010), but no significant trend between 1980 and 2010. Changes in historical radiative forcing (including natural and anthropogenic) act as a causal driver of the general spatial patterns of trends in the annual 90th percentile of daily average river discharge at the global scale (1971–2010) that cannot be explained by direct human influences. Multi-model historical simulations forced by observed climate can explain a considerable part of the observed spatial pattern of trends in high river flows, while the simulated effects from historical water and land management are minor. *Flooded areas:* Model simulations forced by observed weather variations excluding changes in other direct human forcings show a purely climate induced positive trend (0.15% yr^{-1} from 1960 to 2013). *Timing and level of maximum discharge*: The restriction to largely unmanaged catchments indicates that the observed variation in the timing and level of maximum discharge is primarily climate induced. *Flood frequency*: After adjusting for the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) on global scale and AMO and Pacific Decadal Oscillation (PDO) in the tropics, there is no significant trend in flood frequencies anymore, i.e., the trend across the globe and tropics can be largely explained by decadal and multi-decadal climate variability. However, as in the considered time period AMO is highly correlated with global mean temperature change, the alternative explanation that trends are forced by anthropogenic warming cannot be ruled out. *Flood duration:* The positive monotonic trend is not explained by climate oscillations, though in a minority of basins, flood duration is correlated with ENSO. The long-term trends could be induced by long-term monotonic changes in climate but also by direct human influences such as land use changes.	Jongman et al. (2015) (flood volume, 1990–2010 and 1980–2010), Gudmundsson et al. (2021) (7250 stations around the world, annual 90th percentile of daily average river discharge, 1971–2010), Tanoue et al. (2016) (changes in flooded areas, 1960–2013), Ward et al. (2014b) (influence of El Niño-Southern Oscillation [ENSO] on maximum annual discharge, 1958–2000), Ward et al. (2016); Berghuijs et al. (2017) (timing of the occurrence of the largest observed daily flow rate during the period 1980–2009, 1744 catchments located in Australia, Brazil, Europe and the USA), Do et al. (2017) (effects from historical water and land management), Najibi and Devineni (2018) (association of changes in flood frequency or duration and climate oscillation such as the Atlantic Multidecadal Oscillation, North Atlantic Oscillation and Pacific Decadal Oscillation, 1985–2015)	Minor increase of global average annual maximum discharge and flooded areas induced by climate change, *medium confidence* (**) Variations in flood frequencies and the timing of maximum discharge in the historical period are strongly influenced by climate variations (*high confidence*), which means that global and regional trends partly depend on the considered time window. However, the general spatial pattern of trends (1971–2010) in high river flows can largely be explained by observed changes in weather conditions.	
Africa	**Observations:** *Flood volume:* Annual maximum flood volume derived from in situ observations show both positive and negative trends in the Sahel region. Of the entire continent of Africa, only southern Africa has more than 50 stations allowing for a regional analysis of long-term trends. Weak decline in regional average maximum annual discharge (trend is significant from 1961 to 2000 and insignificant from 1971 to 2010), nearly no trend in 90th percentile of daily discharge, heterogeneous trends on station level. Declining annual maximum discharge in western Africa in data sets of at least 30 years within 1955–2014, but number of stations and the covered time period is too limited to draw strong conclusions. Annual maximum discharge and peak over threshold discharge show positive trend in three Sahelian basins for 1970–2010. No significant signal was found in the eight basins in West Africa during the same period.	Do et al. (2017), Gudmundsson et al., 2019 (South Africa, 1951–1990, 1961–2000 and 1971–2010), Aich et al. (2014), Aich et al. (2015), Nka et al. (2015) (Sahel region)	Weak regional reduction in maximum annual discharge in South Africa, *low confidence* due to *low agreement* across sub-regions and time windows	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: *Flood volume:* Model simulations show that both climate and land use change contributed to observed increase in maximum annual discharge in the Sahel Zone. Models are not yet able to fully reproduce and explain the observed changes in observed trends in maximum annual discharge. Minor or weakly negative trends in high flow indicators in southern Africa are associated with drying conditions in the region and might have been intensified through human water and land management. However, hydrological simulations forced by observed climate and direct human influences show a stronger decline in the 90th percentile of daily average river discharge than observed (1971–2010).	Aich et al. (2015) (Sahel region), Gudmundsson et al. (2021), Gudmundsson et al. (2019) (90th percentile of daily average river discharge)	Inconclusive because of limited agreement between modelled and simulated discharge or no assessment because of missing data	
Asia	**Observations:** *Flood volume:* In North Asia, the annual 90th percentile of daily discharge increases significantly from 1951 to 1990 and 1961 to 2000, but annual maximum discharge does not. In East Asia, observations show significant increases in annual maximum flows over the time period 1961–2000 but decrease in annual maximum daily discharge in Yellow River for 1950–2010. In South Asia, a significant decline in annual maximum discharge and the annual 90th percentile of daily discharge has been identified from 1971 to 2010. An analysis of individual station data with more than 30 years of record in 1955–2014 show a smaller number of stations with increasing trends than stations with decreasing trends, where maximum annual discharge tended to increase in the far-eastern region of Russia. However, data coverage is too limited to draw solid conclusions. Along the East River, three of four stations have recorded a decline of annual maximum stream flow from 1954 to 2009.	Do et al. (2017), Gudmundsson et al. (2019), Bai et al. (2016) (Yellow river), Zhang et al. (2015) (East Asia)		
	Attribution: There are only very limited studies attributing the observed changes. The decrease in annual maximum daily discharge in the Yellow River seems to be driven by a decrease of precipitation extreme upstream and human activities in midstream and downstream without a quantification of the individual contributions. Changes of annual maximum stream flow along the East River are mostly driven by natural climate variability and the water reservoirs, with only a minor contribution of climate change. Overall, there are only limited observational discharge data available to cover the entire region. High flow indicator (90th percentile of daily discharge) averaged across India shows a relatively strong decline that is, however, not well reproduced by historical hydrological simulations accounting for observed changes in climate and direct human influences, which means that we do not have a sufficient understanding of the observed changes to attribute them. In Japan, there are only very minor changes in high river flows in the observations and the simulations.	Bai et al. (2016), Zhang et al. (2015), Gudmundsson et al. (2021), (India, Japan, 1971–2010)	Inconclusive analysis in India, no assessment because of insufficient data coverage in West Asia, Central Asia, Tibetan Plateau and Southeast Asia	
	The probability for the occurrence of the 2018 extreme flooding over the upper Yellow River basin decreased by 34% due to anthropogenic climate change, which causes a decrease in surface runoff due to reduced seasonal precipitation.	Ji et al. (2020)		
Australasia	**Observations:** In Southern Australia and New Zealand, strong and significant negative regional trends of high flows (maximum annual discharge and annual 90th percentile of daily discharge) have been recorded from 1971 to 2010. Negative trends in annual maximum discharge in Southeastern Australia supported by analysis of individual station data. In non-urban areas, where the flood response is also dependent on antecedent catchment conditions, there is no empirical evidence of increasing flood magnitudes in Australia except for the most extreme events.	Do et al. (2017), Gudmundsson et al. (2019), Frame et al. (2020a), Johnson et al. (2016), Sharma, (2018), Ishak, (2013), Zhang et al. (2016), Bennett, (2018), Wasko, (2019)		
	Attribution: Strong negative trends in annual 90th percentiles of daily discharge in South Australia have also been found in multi-model simulations forced by observed weather (1971–2010). Human intervention such as river engineering or urbanisation seems to play a minor role. The decline in the annual 90th percentiles of daily discharge in South Australia is not reproduced by hydrological simulations forced by historical climate generated by an ensemble of climate model simulations accounting for historical radiative forcing (including natural and anthropogenic). This could be a hint that the observed trends in climate may be introduced by internal variability rather than external forcing.	Gudmundsson et al. (2021) (annual 90th percentile of daily discharge)	Strong contribution of observed climate change to observed reduction in high river flows in Southern Australia, *low confidence* (*), no assessment in other regions owing to data constraints	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
South and Central America	**Observations:** *Flood volume:* In the Amazon region, observed high river flows have increased significantly from 1971 to 2010. In Northeast Brazil, discharge indices show a significantly increasing regional trend in the 1951–1990 period, but have significantly declined in the 1971–2010 period. From 1951 to 2010, annual maximum discharge has increased in Southeastern South America.	Berghuijs et al. (2017), Do et al. (2017), Gudmundsson et al. (2019)	*Low confidence* in regional trend because of limited data availability and strong dependence of trends on the considered time period	
	Lake Palcacocha, Peru: The lake grew in area from 0.08 km^2 in 1995 to 0.49 km^2 in 2018.	Stuart-Smith et al. (2021)		
	Attribution: Multi-model hydrological simulations forced by observed historical climate and human management are in line with the observed increase in high river flows in Southeastern South America (1971–2010). The simulations suggest that the influence of land and river management on the regional trends is minor. Hydrological simulation forced by simulated historical climate does not reproduce the observed increase in the high flows in that area, which may be a hint that the observed changes in climate are partly due to internal variability.	Gudmundsson et al. (2021) (annual 90th percentile of daily discharge)	Observed climate change has increased high river flows in southeastern South America, *low confidence* (*) No assessment elsewhere because of insufficient observational data or *low agreement* between simulated and observed trends in high flows	
	Lake Palcacocha, Peru: The Lake Palcacocha area expanded due to the rapid retreat of the Palcaraju glacier. This retreat is entirely attributable to the observed temperature trend, of which 85–105% is attributable to human greenhouse gas emissions. The increase in lake area enhances the risk of flooding. The study does not enter the synthesis statement for the figure as it does attribute an observed flood event or trends in peak discharge, flood volume or flooded area. Nevertheless, it attributes an observed change in a physical hazard indicator for flooding and is therefore mentioned.	Stuart-Smith et al. (2021)		
Europe	**Observations:** *Flood volume:* A range of different studies confirm a general pattern of increasing annual maximum discharge in North and Central Europe (Northwestern Europe: +2.3% per decade, 1960–2010; northern UK: +6.6% per decade, 1960–2010) but decreasing trends in Mediterranean region (Southern Europe: –5% per decade, 1960–2010) and Eastern Europe (–6% per decade, 1960–2010). Across Europe, occurrence frequencies and magnitudes of station-specific maximum 1980–2009 discharge increase with time.	Blöschl et al. (2019) (trends in maximum annual discharge, medium to large catchments, 1960–2010), Mediero et al. (2015), Mediero et al. (2014), Mangini et al. (2018), Berghuijs et al. (2017) (timing of occurrence of maximum 1980–2009 discharge values), Gudmundsson et al. (2019), Hodgkins et al. (2017) (changes in 25-, 50- and 100-year events)	Spatially heterogeneous trends in maximum annual discharge, *high confidence*	Floods in the considered medium and large catchments are produced by long-duration synoptic storms, while small catchments are more affected by local short-duration convective storms with high intensities as well as soil compaction, abandoned terraces and land cover changes. Therefore, flood trends in small catchments may differ from the ones described here.
	Flooded areas: Using reported flood events (river and coastal flooding) and assuming that associated flood extents correspond to simulated inundation areas associated with 100-year flood events, there is a positive trend in inundated areas from 1870 to 2016 even after correcting for potential underreporting of events (~1.5% yr^{-1}).	Paprotny et al. (2018b)	*Low confidence* (limited observations of flooded area, remaining events gap-filled using reports on which sub-national administrative units were affected and simulated 100-year flood extents)	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: In Northwestern Europe, increasing maximum annual discharge is mainly induced by increasing autumn and winter rainfall; decreasing precipitation and increasing evaporation have led to observed decrease in annual maximum discharge in Southern Europe, while changes in Eastern Europe are due to decreasing snow cover and snowmelt, resulting from warmer temperatures. Increasing trends in high flows in Northern and Central Europe as well as negative trends in the Mediterranean have also been identified in observation-driven hydrological simulations. Simulations show a minor effect of historical land and river management. Hydrological simulations forced by historical simulations from an ensemble of climate models also show positive trends in high flows in Northern Europe and the negative trends in the Mediterranean (1971–2010) and indicate that the observed trends can also be traced back to external climate forcing. *Extreme flooding in the UK in autumn 2000:* Anthropogenic greenhouse gas emissions are estimated to have increased the probability for river runoff of the observed magnitude or higher by more than 20%.	Blöschl et al. (2019), Mediero et al. (2015) (Spain), Gudmundsson et al. (2021) (annual 90th percentile of daily discharge), Pall et al. (2011) (extreme flooding in the UK in autumn 2000)	Strong contribution of observed climate change to observed positive trends in high flow indices in Northern Europe and negative trends in Southern Europe, *medium confidence* (**)	The occurrence of major flood events is affected by long-term climate oscillations. Annual maximum discharge in Europe is least affected by ENSO compared with other world regions. Also, PDO only plays a minor role in Europe annual maximum discharge and has been shown to be correlated with NAO and AMO variations. As, since about 1975, the AMO shows an increase very similar to global mean temperature, it cannot be decided yet whether the observed changes are due to anthropogenic GHG emissions or a long-term climate oscillation. Thus, the assessment explicitly refers to attribution 'to long-term climate change', not necessarily to 'anthropogenic climate change'.
North America	**Observations:** Stark regional patterns of changing flood frequencies between 1985 and 2015: increases in flood risk around the upper Midwest/Great Lakes region and decreases on the Gulf Coastal Plain, the southeastern USA, and California. The magnitude of 100-year flood events has increased by 20% in the Mississippi River in the period 1897–2015 compared with 1500–1800. From 1962 to 2011, observations indicate significant increases in the frequency but not in the magnitude of flood events in the central USA. For basins across USA and Canada, there is no clear systematic pattern of changes in the probability of exceeding certain threshold levels of discharge from 1931 to 2010 and 1961 to 2010. The annual 90th percentile of daily discharge has decreased in eastern and western North America (1971–2010).	Slater and Villarini (2016) (USA, 1985–2015) Munoz et al. (2018), (Mississippi, 1500–2000), Mallakpour and Villarini (2015) (central USA, 1962–2011), Hodgkins et al. (2017) (changes in 25-, 50- and 100-year events, 1931–2010 and 1960 and 2010), Gudmundsson et al. (2018) (1971–2010)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: Between 1971 and 2010, decreasing high flows in western and eastern North America are also found in hydrological simulations forced by observed changes in climate and direct human influences, where the direct human influences only play a minor role. Hydrological simulations derived from an ensemble of historical climate model simulations also show negative trends in high flows in these regions. This indicates that the observed declines in high river flows are at least partly attributable to external climate forcing. However, in the highly managed Mississippi basin, 75% of the increase in river discharge is attributed to river engineering. Changes in flood behaviour along rivers across the central USA (1962–2011) can be largely attributed to concomitant changes in rainfall and temperature. The occurrence probability of major floods (changes in 25-, 50- and 100-year events) seems to be dominated by multi-decadal variability, i.e., may be induced by long-term trends in climate that are difficult to attribute to external forcing or internal variability given the length of the observational period.	Gudmundsson et al. (2021), Munoz et al. (2018) (Mississippi) (1500–2000), Mallakpour and Villarini (2015) (1962–2011) (central USA), Hodgkins et al. (2017) (changes in 25-, 50- and 100-year events)	Observed climate change has contributed to the decline in high river flows in western and eastern USA (1971–2010), *low confidence* (*) The observed trends may be partly due to internal climate variability No assessments for Alaska, Canada, Greenland or Iceland owing to insufficient data coverage	
Small Islands	**Observations:**			
	Attribution:		No assessment	
S15b	Water distribution—Flood-induced fatalities			
Global	**Observations:** The annual total number of reported fatalities from flooding shows a positive trend (1.5% yr^{-1} from 1960 to 2013). The number of fatalities has declined in high-income countries but increased in lower-middle-income countries. No clear trend across low-income countries. A substantial inter-annual variability of reported fatalities is observed.	Jongman et al. (2015) (Munich RE's NatCatSERVICE, 1980–2010), Kundzewicz et al. (2014), Tanoue et al. (2016) (EM-DAT, 1960–2013), Formetta and Feyen (2019) (Munich RE's NatCatSERVICE, 1980–2016)	*Medium confidence* in trends in fatalities because of potential reporting biases in particular before 1980	
	Attribution: The increase in the number of fatalities on global scale is most likely not due to climate change as there only is a much smaller increase in the areas affected by flooding derived from observational weather data (0.15% yr^{-1} from 1960 to 2013). Increasing exposure has probably contributed to the trend in fatalities as modelled exposed population derived from observed weather data and observed changes in population patterns shows a much stronger trend than affected areas (1.5% yr^{-1}). The exposure-driven increase in risk has been dampened by a reduction in vulnerability across income groups. Thus, the number of fatalities in high-income countries has declined, even though the number of potentially exposed people has not. In lower-middle-income countries, the number of fatalities has been rising, but not as rapidly as the number of potentially exposed people.	Ward et al. (2014c) (effects of ENSO), Jongman et al. (2015), Kundzewicz et al. (2014), Tanoue et al. (2016) (change in mortality rates induced by population shifts), Formetta and Feyen (2019) (1980–2016)	Minor impact of climate change on observed increase in fatalities induced by river floods, *medium confidence* (**)	
Africa	**Observations:**			
	Attribution:		No separate assessment	
Asia	**Observations:** Flood-related fatalities from large floods in southeastern Asia, corrected for population growth, had no significant trend for 1985–2018. Decrease in flood fatalities relative to population in Turkey 1930–2020. For all Asia, a slight decrease in deaths (unadjusted) reported for 1980–2019, with increase in Western and Southeastern Asia, and decrease in China and India; decline in flood fatalities in Japan (1925–2007).	(Chen et al., 2020a) (DFO data set), Haltas et al. (2021) (compilation for Turkey), Wang et al. (2021) (EM-DAT), Huang (2014) (Japan)		
	Attribution: No attribution of trends made other than population growth or decrease in vulnerability due to economic growth.		No assessment (not enough evidence for the region)	
Australasia	**Observations:**			
	Attribution:		No separate assessment	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
Central and South America	**Observations:**			
	Attribution:		No separate assessment	
Europe	**Observations:** Flood-related fatalities declined by 1.4% yr^{-1} since 1870 and 4.3% since 1950 until 2016. Stronger decline was reported for flash floods compared with large-scale river floods. No significant trend in the Mediterranean region for fatalities (1980–2015).	Paprotny et al. (2018b) (river floods + coastal flooding), Petrucci et al. (2019) (MEFF: Mediterranean Flood Fatalities database)		
	Attribution: The observed decline is mainly driven by a reduction in vulnerability. Climate-related hazards (affected areas, see above) show a positive trend. In addition, changes in population patterns have induced a positive trend in affected people estimated from reported flood events and associated 100-year flood extents in contrast to the observed decline in the number of fatalities.	Paprotny et al. (2018b) (river floods + coastal flooding)	Minor impact of climate change on observed negative trends in the number of fatalities, *medium confidence* (**)	
North America	**Observations:**			
	Attribution:		No separate assessment	
Small Islands	**Observations:**			
	Attribution:		No assessment	
S15c	Water distribution—Flood-induced economic damages			
Global	**Observation:** Recorded economic losses increased by 6.3% of the annual mean from 1960 to 2013; from 1980 to 2010, a significant positive trend of 4.4% yr^{-1}, compared with the baseline annual average damage (1980–1995), was observed; and also over the extended time period 1980–2016, global damages show a significant increase. In both high- and low-income countries, absolute losses have increased in the period 1990–2010 compared with 1980–1990. In areas where discharge maxima show rising trends over the period 1971–2010 (major parts of Europe and Asia and Latin America), damage trends have significantly increased by 8.7% from 1980 to 2010, but also in areas where discharge maxima have decreased (major parts of Africa, North America and Australasia) damages have increased significantly.	Jongman et al. (2015), Neumayer and Barthel (2011) (1980–2009), Tanoue et al. (2016) (1960–2013), Sauer et al. (2021) (1980–2010), Formetta and Feyen (2019) (1980–2016)	*Medium confidence* in positive trends (reporting biases especially in early time periods may contribute to upwards trends in reported losses, but confidence increases with improved reporting after 1980)	
	Attribution: Direct human influences are major drivers of these increases. After removing trends in population patterns and economic growth, no significant trends in losses can be observed across income groups on global scale. However, after regional disaggregation according to regions with positive or negative trends in maximum annual discharge, an impact of climate change on damages can be quantified: assuming fixed 2010 socioeconomic conditions, model simulations suggest that climate change has significantly increased the expected median damage in 2010 by 84.3% of the baseline damage compared with 1971 in regions with positive discharge trends, and decreased damages insignificantly by –46.8% in regions with negative discharge trends. The confidence in the assessment is limited; the full model accounting for changes in exposure, vulnerability and climate change can explain at least 45% of the observed variance of annual damages in regions with positive discharge trends. In regions with negative discharge trends, the model cannot sufficiently explain the observed variance of annual damages. A mainly exposure-driven increase in potential damages has been dampened by a global reduction in vulnerability: the global loss rate (recorded damage/exposed GDP) declined significantly in all studied time periods and across all income groups. There is a tendency of convergence in vulnerability between low- and high-income countries.	Neumayer and Barthel (2011), Ward et al. (2014a) (effects of ENSO on damages), Jongman et al. (2015), Kundzewicz et al. (2014), Formetta and Feyen (2020), Tanoue et al. (2016); Sauer et al. (2021)	Minor contribution of climate change to observed damages on global scale, moderate contribution (compared with other drivers) in sub-regions with increasing discharge trends, *low confidence* (*)	Annual variations in damages appear to be affected by large-scale climate oscillations. In the considered regions, long-term trends may be induced by the AMO, which, during the study period, cannot be separated from a potential influence of global mean temperature change. Thus, we explicitly only attribute to long-term climate change (including AMO) instead of anthropogenic climate change.

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
Africa	**Observation:** In South and Sub-Saharan Africa, economic damages have significantly increased by 2.2% yr^{-1}, compared with the baseline annual average damage (1980–1995), from 1980 to 2010. In areas where maximum discharge has increased (mainly the Sahel region), economic damages have increased significantly by 11.3% derived from trend analysis.	Sauer et al. (2021) (Munich RE's NatCatSERVICE, 1980–2010)		
	Attribution: Across the entire South and Sub-Saharan Africa (SSA) region and the North Africa + Middle East (NAF) region, total damages induced by river floods cannot yet be well explained by model simulations accounting for observed weather fluctuations and changes in exposure and vulnerability. For this reason, we do not provide attribution assessments.		Still insufficient understanding	
Asia	**Observations:** In Eastern Asia, damages have increased significantly by 4.8% yr^{-1} between 1980 and 2010 compared with annual average damages from 1980 to 1995. In areas of Eastern Asia with positive discharge trends from 1971 to 2010, damages increased by 7.6% yr^{-1} compared with the baseline. In Central Asia and Russia, no significant changes in damage trends have been observed from 1980 to 2010. In South and Southeastern Asia, observed damages have increased significantly by 4.8% in areas where discharge maxima increased between 1980 and 2010. These areas encompass basically parts of Southwestern India and Pakistan, great parts of Indonesia, Thailand, Vietnam and Cambodia. Annual average flood losses recorded in the period 1984–2018 in China reached $19.2 billion (normalised to 2015 values), which accounted for 0.5% of the national GDP in China and 54% of the total national direct economic losses due to climate and weather.	Sauer et al. (2021) (Munich RE's NatCatSERVICE, 1980–2010), Jiang et al. (2020)		
	Attribution: *Eastern Asia:* In Eastern Asia as well as in its associated sub-region of increasing trends in annual maximum discharge, damage records can be well explained by model simulations accounting for historical weather fluctuations and changes in exposure and vulnerability (55% to 70% explained variance). For entire Eastern Asia, model simulations assuming fixed 2010 socioeconomic conditions indicate that climate change has increased the median damage in 2010 by 67.8% (106% in areas with positive discharge trends) since 1971. However, this effect is still much smaller than the effect of a significant increase in exposure that has only been compensated by a strong decrease in vulnerability. *South, Southeastern Asia and Central Asia:* In South and Southeastern Asia and Central Asia, damage records cannot yet be well explained by model simulations accounting for historical weather fluctuations and changes in exposure and vulnerability, and therefore we do not provide an associated assessment. Only in the sub-region with positive discharge trends of South and Southeastern Asia does the full model, accounting for changing climate and changes in exposure and vulnerability, explain over 50% of the annual variability of observed damage. Model simulations assuming fixed 2010 socioeconomic conditions indicate that climate change has increased the median damage in 2010 significantly by 302.3% since 1980. However, the climate contribution is not significant for the time period 1971–2010.	Sauer et al. (2021)	Strong adverse impact of climate change in some regions with increasing trends in discharge, *low confidence* (*), no assessment in parts of Asia	
Australasia	**Observations:** In Australasia, an insignificant increase in damages of 0.8% yr^{-1} has been observed from 1980 to 2010. Areas with decreasing trends in discharge maxima, mainly southern and eastern Australia, show also an insignificant increase of 0.75%. No significant trend in insured flood losses in Australia between 1966 and 2017 was found after correcting for growth in exposure.	Sauer et al. (2021) (Munich RE's NatCatSERVICE, 1980–2010), McAneney et al. (2019) (insured losses)		
	At the same time from mid-2007 to mid-2017, 12 major extreme rainfall events caused NZ$472 million in insured flood losses in New Zealand.	Frame et al. (2020a)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: Across entire Australasia and the sub-region of decreasing hazards, inter-annual variability and trends in damage records can be well explained by model simulations accounting for historical weather fluctuations and changes in exposure and vulnerability (60–70%); in other sub-regions, observed damages cannot be well explained. Therefore, we do not provide an associated attribution assessment for the sub-region with increasing discharge trends. Model simulations assuming fixed 2010 socioeconomic conditions indicate that climate change has decreased the expected median damage risk in 2010 by 9.7% since 1971 in the sub-region with decreasing discharge trends; for the entire region, the risk reduction is not significant. The increase in observed damages appears to be mainly attributable to increasing vulnerability.	Sauer et al. (2021)	Moderate climate-change-induced decline in damages in areas with decreasing maximum annual discharge in Australia, and strong increase in damages in New Zealand induced by anthropogenic climate change, *low confidence* (*)	
	In New Zealand, NZ$140 million of the insured NZ$472 million damages could be attributed to anthropogenic climate change, where the estimate is based on the strong assumption that damage attributable to anthropogenic climate forcing can be approximated by multiplying the actual damage by the ‘fraction of attributable risk (FAR)’ of the observed droughts, where FAR = 1 – P_0/P_1, with P_0 and P_1 being the probabilities of an event of this magnitude under natural and observed climate forcing, respectively.	Frame et al. (2020a)		
Central and South America	**Observations:** In Latin America, an insignificant damage reduction of –0.2% yr^{-1}, compared with annual average losses from 1980 to 1995, was observed 1980–2010. Across the sub-region of increasing maximum annual discharge (mainly areas of the Amazonian region, southeastern South America and areas of Central America and the Caribbean), economic damages show an insignificant increase of 0.2% yr^{-1} from 1980 to 2010.	Sauer et al. (2021) (Munich RE’s NatCatSERVICE, 1980–2010)		
	Attribution: Across Latin America and the sub-region of increasing hazards, inter-annual variability and trends in damage records can partly be explained by model simulations accounting for historical weather fluctuations and changes in exposure and vulnerability (explained variances ~30%). Across the area of increasing maximum annual discharge (Amazonian areas, Southeastern South America and areas of Central America and the Caribbean), model simulations assuming fixed 2010 socioeconomic conditions indicate that climate change has increased the median damage in 2010 significantly by 69.3% compared with expected median damages in 1971. The minor changes in observed damages seem to be due to an increase in exposure that is counterbalanced by a reduction in vulnerability. In the entire region and the regions with increasing trends in annual maximum discharge, climate is estimated to only have had a minor insignificant effect on damages. For the sub-region with decreasing discharge trends, no assessment can be made, due to a limited explanatory power of model simulations.	Sauer et al. (2021)	Minor impact of climate change on flood-induced damages aggregated across Latin America as a whole and the sub-region of increasing maximum annual discharge, *low confidence* (*); but anthropogenic climate forcing is estimated to have increased the probability of individual high-impact events, *low confidence* (*) No assessment elsewhere because of insufficient process understanding	
Europe	**Observations:** Records of reported flood events that have caused severe damages show phases of flood-rich and flood-poor periods since 1500, with 1990–2016 being the strongest since 1840–1870 across Europe (except Spain and Scandinavia). There is some evidence of a positive trend in flood losses (corrected for inflation) in Europe between 1970 and 2010, although the trends are not significant and may partly be induced by reporting biases. From 1980 to 2010 a significant increasing trend of 3.5% yr^{-1}, compared with the baseline annual damage from 1980 to 1995, was observed in Europe. In areas where discharge maxima show rising trends over the period 1971–2010 (basically Northwestern Europe), damage trends have significantly increased, while in areas where discharge maxima have decreased (mainly Mediterranean areas), no significant trend in damages was detected. In southern England, a series of storms in the winter of 2013/2014 caused severe floods and £451 million insured losses in the Thames basin.	Hall et al. (2014), Montanari (2012), Nobre et al. (2017), Barredo (2009), Barredo et al. (2012), Stevens et al. (2016), Paprotny et al. (2018b) (river floods + coastal flooding), Sauer et al. (2021) (Munich RE’s NatCatSERVICE, 1980–2010), Schaller et al. (2016) (UK winter flood in 2013/2014), Blöschl et al. (2020) (flood-poor/rich periods)	*Medium confidence* in increasing flood-induced damages since 1980	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
	Attribution: Flood-rich and flood-poor phases are strongly linked to long-term memory of hydrological processes and large-scale climate variabilities, such as ENSO, NAO and the East Atlantic pattern. NAO was significantly correlated with economic loss in most of Northwestern and Central Europe (1950–2018). Changes in population patterns, increasing per capita real wealth and asset values are the main drivers of the observed increase in losses. After correcting for increasing exposure due to population and economic growth, no significant trends remained in economic losses (Europe 1900–2016, Spain 1971–2008, Switzerland 1972–2016). These purely empirical findings could be supported by a semi-empirical approach building on process-based simulations of flooded areas: the observed inter-annual fluctuations in damages from 1980 to 2010 can be well explained by observed weather fluctuations and changes in exposure and vulnerability (explained variance ~30%). Model simulations assuming fixed 2010 socioeconomic conditions indicate that climate change has only insignificantly decreased the expected median damage risk in 2010. Increasing exposure and slightly decreasing vulnerability basically explain the recorded damage increases, while climate contributions remain insignificant. In the sub-regions of increasing or decreasing maximum annual discharge, the explanatory power of the model is not sufficient to allow for attribution. Thus, minor impacts of climate on damages in Europe as a whole may be due to heterogeneous trends in hazards whose effects on damages cancel out in regional aggregation. For events similar to the 2013/2014 flood in the UK, about 1000 more properties are placed at risk of fluvial flooding, and potential losses have been increased by £24 million relative to a climate without anthropogenic GHG emissions (best estimates). However, large uncertainty is found in the climate model ensemble.	Hall et al. (2014), Montanari (2012), Nobre et al. (2017), Barredo (2009), Barredo et al. (2012), Stevens et al. (2016), Paprotny et al. (2018b) (river floods + coastal flooding), Sauer et al. (2021) (Munich RE's NatCatSERVICE, 1980–2010), Andres and Badoux (2019), Zanardo et al. (2019) Schaller et al. (2016), Kay et al. (2018) (ensemble simulation of 2013/2014 event)	Minor impact of climate change on flood induced damages in Europe as a whole, *medium confidence* (**), no assessment in sub-regions with increasing or decreasing hazards and Europe due to insufficient process understanding	
North America	**Observations:** In North America, damages induced by river floods increased insignificantly from 1980 to 2010 in the region as a whole (0.5% yr^{-1}, compared with annual average losses from 1980 to 1995).			
	Attribution: The observed inter-annual fluctuations in damages from 1980 to 2010 can be well explained by model simulations accounting for observed weather fluctuations and changes in exposure and vulnerability (explained variance >80%). Model simulations assuming fixed 2010 socioeconomic conditions suggest that climate change has increased the expected median damage risk in 2010 in the region as a whole by 8.3% since 1971, though the effect is insignificant. In the USA, around one-third of the cumulative economic flood damage from 1988 to 2017 was caused by precipitation change. Climate models show that anthropogenic climate forcing has increased the probability of exceeding precipitation thresholds at the upper intensity quantiles causing most of the damage.	Sauer et al. (2021) (Munich RE's NatCatSERVICE, 1980–2010) Davenport et al. (2021)	Minor to strong increase in flood-induced damages due to climate change, *medium confidence* (**) in the sign of the effect, but *low agreement* on the order of the effect	
Small Islands	**Observations:**			
	Attribution:		No assessment	
S17	Water distribution—Water-borne diseases			
Global	**Observations:**			
	Attribution: There is no attribution of changes to climate change but an 'identification of weather sensitivity' (see 'S17 Water distribution – Water-borne diseases', Table SM16.23).		No assessment	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
S18	Food system—Crop yields:			
Global	**Observations:** Crop yields are improving in most areas. Among maize, wheat, soy and rice, recent rates of global mean yield growth were highest for maize and lowest for wheat. However, a stagnation or decline in yields is observed on 30% (maize), 39% (wheat), 37% (rice) and 24% (soy) of harvested areas (data from 1961 to 2008). Stagnation of yields affects high-yield systems for rice in East Asia (China, Republic of Korea and Japan), wheat in northwest Europe (UK, France, Germany, the Netherlands, Denmark) and India, and maize in South Europe (Italy and France), but stagnation or very low rates of yield increases are also observed in low-yield systems such as maize in east Africa.	Iizumi et al. (2018b) (maize, rice, wheat and soybeans, 1980–2008), Ray et al. (2012) (maize, rice, wheat and soybeans, 1961–2008), Ray et al. (2013) (maize, rice, wheat and soybean, 1961–2008), Grassini et al. (2013) (wheat, rice, maize, 1965–2011)	*High confidence* in mostly increasing maize, wheat, rice and soy yields	
	Attribution: *Effects of climate change:* The considered estimates of global average impacts of historical climate change are subject to some important limitations: current process-based estimates are forced by simulated historical climate in comparison with simulated pre-industrial climate conditions and miss a clear evaluation to what degree models are able to reproduce observed yields when forced by observed climate conditions (Iizumi et al., 2018). The applied empirical models considered on global scale do not explicitly account for the impacts of extreme events (Ray et al., 2019, Lobell et al., 2011 based on growing season average temperature and precipitation), although the relevance of extremes has been demonstrated in regional studies (e.g., Butler et al., 2017 for maize in the USA). In addition, studies are constrained by only fragmented information about historical growing season adjustments. *Wheat:* Empirical models indicate a purely climate-induced reduction in global average wheat (0.9% reduction of recent yields compared with counterfactual situation not accounting for climate trends from 1974 to 2008, 5.5% reduction of average 1980–2008 yields induced by climate trends over the same period, ~3% reduction in 2002 yields induced by climate trends since 1981). Reduction is supported by a process-based model estimating a purely climate-induced reduction in wheat yields by comparing yield simulations forced by simulated historical climate with simulations forced by a pre-industrial reference climate (about 5% loss of 1981–2010 yields not accounting for CO_2 fertilisation); mostly (20 out of 30 representative global sites) negative responses to historical warming (1980–2010) derived from the median of 30 process-based models that has been shown to reproduce temperature responses of field experiments. *Maize:* Empirical estimates of historical climate-induced yield changes range from no change of recent yields by climate trends from 1974 to 2008, to about 2% reduction in 2002 yields induced by climate trends since 1981, and 3.5% reduction of average 1980–2008 yields induced by climate trends over that period. Process-based simulations indicate a ~6% reduction of 1981–2010 yields when comparing yields derived from simulated historical climate with yields under simulated pre-industrial climate not accounting for CO_2 fertilisation. *Rice:* Minor reduction in yields (0.3% reduction of recent yields compared to counterfactual situation not accounting for climate trends from 1974 to 2008; 0.1% reduction of average 1980–2008 yields induced by climate trends over the same period; less than 0.5% reduction in 2002 yields induced by climate trends since 1981, and ~2% reduction of 1981–2010 yields compared with counterfactual pre-industrial climate conditions) derived from three empirical models and one process-based model simulation comparing simulation forced by simulated historical climate with simulations forced by simulated pre-industrial climate. *Soy:* Empirical estimates of historical climate induced yield changes range from a 3.5% increase of recent yields by climate trends from 1974 to 2008, to 1% increase in 2002 yields induced by climate trends since 1981, and 1.7% reduction of average 1980–2008 yields induced by climate trends over that period. Processed-based model simulations estimate a 7% loss of yields induced by simulated historical climate change compared with pre-industrial climate (not accounting for CO_2 fertilisation). *Others:* Empirical estimates indicate that climate change from 1974 to 2008 has reduced recent yields of barley (–7.9%), cassava (–0.5%), oil palm (–13.4%) and increased yields of rapeseeds (0.5%), sorghum (2.1%) and sugarcane (1.0%).	Iizumi et al. (2018b) (process-based crop model simulations forced by simulated historical versus pre-industrial climate), Asseng et al. (2015) (wheat at 30 representative global locations), Ray et al. (2019), Lobell and Field (2007) (empirical estimates)	Mixed global-scale responses of yields to climate change across different crops. Moderate decline of global average wheat yields induced by climate change (*medium confidence*, **), Mostly inconclusive for other crops because (*limited evidence* and agreement)	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
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	Effects of increasing atmospheric CO_2 concentrations: Process understanding represented in crop models and empirical evidence indicate a general positive effect of rising atmospheric CO_2 on crop yields. However, global average process-based model simulations indicate that the effect has not compensated for the negative effects of climate change induced by anthropogenic emissions of climate forcers on maize and soybean yields, while it may have for wheat and rice. An empirical model fit to national yield statistics (aggregated indicator across a range of crops) shows mostly positive trends induced by increasing CO_2 concentrations, except for a range of countries in Europe and only a few individual countries in Africa, Asia and South America. However, the model does not allow for a separation of trends induced by CO_2 fertilisation and climate change. Instead, CO_2 concentrations are considered a proxy for the combined effect adjusted for additional climate-related predictors (El Niño-Southern Oscillation, Palmer Drought Severity Index and geopotential height anomalies).	Iizumi et al. (2018a), Najafi et al. (2018)	Moderate positive effect of increasing atmospheric CO_2 concentrations, *medium confidence* (**)	
Africa	**Observations:** Large areas of stagnation or decline in maize production with the exception of some West African countries and individual countries in southern Africa showing increasing trends across different data sets. Divergent or missing information about trends of soy, wheat or rice yields in large areas of the continent. Estimated trends show relatively strong national patterns. Based on census data for maize, wheat, rice and soy from 1961 to 2008 areas affected by 'no (further) increase in yields' are estimated to be 0% (maize in South Africa), the crop for which South Africa belongs to the top ten producers.	Iizumi et al. (2018a)	*Low confidence* in trends in wheat, soy and rice yields; *medium confidence* in declining maize yields in large parts of Central Africa	

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	Attribution: *Effects of climate change: Wheat, Sub-Saharan-Africa:* An empirical study comparing present-day yield levels with the ones estimated for a counterfactual climate not accounting for trends from 1974 to 2008 indicates weak losses in wheat yields by the historical change in climate (2.3%). A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by simulated pre-industrial climate support a mostly negative combined impact of historical climate change and increasing atmospheric CO_2 concentration on wheat. *Northern Africa:* Empirical estimates indicate a moderate positive effect of climate change on wheat yields from 1974 to 2008 (present-day yields are estimated to be 12% higher than compared with a counterfactual world without the historical trend in climate). In contrast, process-based crop model simulations forced by simulated historical climate versus simulated pre-industrial climate indicate no significant combined impact of climate change and CO_2 fertilisation on wheat yields. *Maize, Sub-Saharan Africa:* Technological advances are empirically estimated to explain most of the observed trend in maize yields from 1962 to 2014 (13 kg ha^{-1} yr^{-1} of the overall 15 kg ha^{-1} yr^{-1} increase in maize yields), where the estimated trend in time could also be partly driven by increasing atmospheric CO_2 concentrations. Climate variables are estimated to have played a comparatively small role where increasing temperatures are estimated to have had a negative effect. An empirical study comparing present-day yield levels with the ones estimated for a counterfactual climate not accounting for trends from 1974 to 2008, maize yields are estimated to have been reduced by about 5.8% by climate change. A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by simulated pre-industrial climate indicates a mostly negative combined impact of climate change and increasing atmospheric CO_2 concentrations on maize yields. *Northern Africa:* In an empirical study comparing present-day yield levels with the ones estimated for a counterfactual climate not accounting for trends from 1974 to 2008, maize yields are estimated to have been reduced by 4.3% by climate change. Process-based crop model simulations forced by simulated historical climate versus simulated pre-industrial climate support mostly negative impacts of climate change on maize yields. *Soy, Sub-Saharan Africa:* An empirical study comparing present-day yield levels with the ones estimated for a counterfactual climate not accounting for trends from 1974 to 2008 indicates yield losses of 1.6% induced by climate change. A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by simulated pre-industrial climate supports a mostly negative impact of climate change on soybean yields in Sub-Saharan Africa that is not even compensated by increasing atmospheric CO_2 concentrations. *Northern Africa:* Empirical estimates indicate a moderate positive effect of climate change on soy yields from 1974 to 2008 (present-day yields are estimated to be 11% higher than compared with a counterfactual world without a trend in climate). In contrast, process-based crop model simulations forced by simulated historical climate versus simulated pre-industrial climate show a mostly negative but regionally very confined combined impact of climate change and increasing CO_2 concentrations on soy yields. *Rice, Sub-Saharan Africa:* Empirical estimates indicate a negative effect of climate change on rice yields from 1974 to 2008 (1.3% reduction of present-day yields compared with a counterfactual world without a trend in climate). A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by simulated pre-industrial climate indicates mixed positive and negative combined impacts of climate change and increasing atmospheric CO_2 concentrations on rice yields. *Northern Africa:* Empirical estimates indicate a negative effect of climate change on rice yields from 1974 to 2008 (1.3% reduction of present-day yields compared with a counterfactual world without a trend in climate). A comparison of process-based crop model simulations forced by simulated historical climate with simulations based on pre-industrial climate indicates regionally confined and mixed combined impacts of climate change and CO_2 fertilisation on rice yields.	Hoffman et al. (2018) (empirical model, maize, sorghum and groundnut in Sub-Saharan Africa), Iizumi et al. (2018b) (process-based); Sultan et al. (2019) (process-based, millet and sorghum in West Africa), Ray et al. (2019) (empirical model)	Mixed impacts of climate change on crop yields in Africa ranging from strong reductions in millet and sorghum yields in West Africa to moderately positive impacts on cassava, sorghum, soybean and wheat in Northern Africa, *low confidence* (*)	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
	Others, Sub-Saharan Africa: Technological advances are empirically estimated to explain most of the observed trend in groundnut and sorghum yields from 1962 to 2014 (2.8 kg ha^{-1} yr^{-1} of the overall 3.7 kg ha^{-1} yr^{-1} increase in groundnut yields, and 3.2 kg ha^{-1} yr^{-1} of the overall 3.8 kg ha^{-1} yr^{-1} increase in sorghum yields), where the estimated trend in time could also be partly driven by increasing atmospheric CO_2 concentrations. Climate variables are estimated to have played a comparatively small role. Increasing temperatures are estimated to have reduced yields. A minor effect of historical climate change on sorghum (0.7% increase of present-day yields) is supported by an empirical study comparing present-day yield levels with the ones estimated for a counterfactual climate not accounting for observed trends from 1974 to 2008. The same empirical study finds minor negative effects of historical climate change on barley (0.6% reduction) and slightly higher losses of sugarcane yields (3.9%), but no, minor and strong positive effects on oil palm (0%), cassava (1.7%) and rapeseeds (24.9%), respectively. *Northern Africa:* Empirical estimates indicate a negative effect of climate change on barley and sugarcane yields from 1974 to 2008 (6.8% and 5.1% reduction of present-day yields compared with a counterfactual world without a trend in climate), but also show moderate positive effects of climate change on cassava, sorghum (18% increase in present-day yields compared with a counterfactual situation without the historical trend in climate). *West Africa:* The comparison of process-based crop model simulations forced by simulated historical climate versus pre-industrial climate over the period 2000–2009 show stronger impacts of climate change on millet than on sorghum. Averaged across West Africa, one model not accounting for CO_2 fertilisation simulates yield losses of 17.7% for millet and 15.0% for sorghum. A second model accounting for CO_2 fertilisation shows weaker losses (10.9% for millet and 5.9% for sorghum).			
Asia	**Observations:** Mostly increasing maize, wheat, rice and soybean yields, with the exception of maize in northeastern China, soybean in parts of China, rice in parts of China and Central Asia, and larger parts of the wheat production area in China and India where yields are stagnating or decreasing. Based on census data for maize, wheat, rice and soy from 1961 to 2008, areas affected by 'no (further) increase in yields' are estimated to have reached 52.2% (China), 37% (India), 2% (Indonesia) of harvested areas of maize; 55.5% (China), 70% (India), 13% (Pakistan), and 64% (Turkey) of harvested areas of wheat; 79% (China), 37% (India), 81% (Indonesia), 0% (Bangladesh), 2% (Vietnam), 2.6% (Thailand), 0% (Myanmar), 12% (Philippines), and 19% (Japan) of harvested areas of rice; 58% (China), 51% (India), and 59% (Indonesia) of harvested areas of soy. Results are only listed for the crops (out of maize, wheat, rice and soy) for which the countries belong to the top 10 producers.	Grassini et al. (2013), Iizumi et al. (2018a)	*Low confidence* regarding regions of stagnation (differences between individual data sets)	
	Attribution: *Impacts of climate change:* *Maize:* A comparison of process-based model simulations for 1981–2010 forced by simulated historical climate, and pre-industrial climate indicates climate-induced losses of maize yields over central and southern parts of Asia (between 5% and 10% in China and India not accounting for changes in CO_2 fertilisation) and some gains in higher latitude. A loss of about 7% of 1980–2008 average yields induced by climate change is also estimated empirically for China, but the study also shows a slight increase in yields for India. Another empirical study also indicates gains in maize yields (5.1% and 1% increase in recent yields in comparison with yields under counterfactual climate conditions not accounting for trends from 1974 to 2008 for Central/Eastern Asia and Western/Southern/Southeastern Asia, respectively). Other process-based simulations explicitly accounting for changes in growing seasons and cultivars enabled by historical climate change estimate an associated 7–17% gain in yields per decade in Northern China from 1980 to 2009. A similar study based on process-based model simulations for the Loess Plateau in the centre of China also shows historical climate change may have had a negative impact on maize yields but also enabled the adjustments of cultivars that may have compensated for the climate induced losses assuming early cultivars. However, the simulated trends in yields are not compared with the observed ones and not based on reported adjustments of cultivars. Nepal: An empirical study of maize yields in the Koshi River basin shows strongly varying impacts of climate change in terms of the considered region and elevation.	Iizumi et al. (2018a) (process-based model, global gridded, maize, wheat, rice, soy), Ray et al. (2019) (empirical model, world regions, 10 most important crops), Lobell et al. (2011) (empirical, major producers, maize, wheat, rice, soy), Meng et al. (2014) (process-based, China, maize), Bu et al. (2015) (process-based, China, maize) Bhatt et al. (2014) (Nepal, 1967–2008)	Minor impact of climate change on rice yields, *medium confidence* (**); mostly inconsistent findings for other crops	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Wheat: Process-based model simulations forced by simulated historical versus pre-industrial climate show moderate purely climate-driven reductions in Russia (about 5% purely climate-induced loss of 1981–2010 yields compared with pre-industrial climate conditions, potentially compensated by CO_2 fertilisation). An empirical study indicates gains and minor losses in wheat yields in larger areas (4.5% increase and ~1% loss in recent yields compared with yields under counterfactual climate conditions not accounting for trends from 1974 to 2008 for Central/Eastern Asia and Western/Southern/Southeastern Asia, respectively). China: Process-based model simulations forced by simulated historical versus pre-industrial climate show a moderate reduction of wheat yields in China (about 5% purely climate driven loss of 1981–2010 yields compared with pre-industrial climate conditions). Empirical estimates indicate a slightly positive effect of climate change on average Chinese wheat yields (recent yields compared with yields under counterfactual climate conditions not accounting for trends from 1974 to 2008). Further empirical evidence derived from 120 agricultural meteorological stations accounting for growing season adjustments also estimated that changes in growing season average temperature, precipitation and solar radiation increased wheat yields in northern China by 1–13% and reduced wheat yield in southern China by 1–10% over the period from 1981 to 2009. From 1981 to 2009, climate trends were associated with a ≤30% (or ≤1.0% yr^{-1}) wheat yield increase at 23 stations in eastern and southern parts of Huang-Huai-Hai Plain, western China and a ≤30% (or ≤1.0% yr^{-1}) reduction at 11 other stations. Increases have been associated with increases in daily minimum temperatures supported by additional studies of field data across major Chinese winter wheat regions and Tibet. India: Process-based model simulation forced by simulated historical versus pre-industrial climate show a strong reduction of wheat yields in India (about 20% lower average yields in 1981–2010 compared with pre-industrial climate conditions). An empirical study finds slightly negative impacts of climate change on wheat yields in India (recent yields compared with yields under counterfactual climate conditions not accounting for trends from 1974 to 2008). A panel regression of yield data from 208 districts and growing seasons average daily minimum and maximum temperatures, solar radiation and total precipitation indicates that wheat yields have been 5.2% lower than they would have been if temperatures had not increased during the study period (1981–2009). *Nepal:* An empirical study of wheat yields in the Koshi River basin shows strongly varying impacts of climate change in terms of the considered region and elevation.	Iizumi et al. (2018b) (process-based model, global gridded, maize, wheat, rice, soy), Ray et al. (2019) (empirical model, world regions, 10 most important crops), Lobell et al. (2011) (empirical, major producers, maize, wheat, rice, soy), Tao et al. (2014) (wheat, comparison northern and southern China, 1981–2009), Tao et al. (2017) (wheat, Huang-Huai-Hai Plain), Zheng et al. (2017) (wheat, China, 1980 and 2015), Zheng et al. (2016) (wheat, Tibet, China, 1988–2012), Gupta (2017) (wheat, India, 1981–2009), Bhatt et al. (2014) (Nepal, 1967–2008)		
	Rice: Mainly small reductions (<5%) in rice yields induced by historical climate change in China, India, Indonesia, Bangladesh and Vietnam derived from process-based simulations comparing 1981–2010 yields under historical climate forcing with associated yields under pre-industrial climate conditions. Empirical estimates show relatively small changes in rice yields induced by historical climate change (0.9% gain and 0.8% loss of recent yields in comparison with yields under counterfactual climate conditions not accounting for trends from 1974 to 2008 for Central/Eastern Asia and Western/Southern/Southeastern Asia, respectively). Process-based model simulations across nine provinces in China indicate that observed temperature increase has had a minor non-significant impact on trends in rice yields from 1961 to 2003. Observed positive trends are estimated to have been clearly dominated by increasing N inputs and technological progress such as genetic improvement. Another empirical study indicates that potential negative effects of climate change on national crop production in China during 1945–2015 have been counterbalanced by northwards movements of production. If the spatial distribution of rice areas had not changed after 1949–1951, country-level rice yield would have been 162 kg ha^{-1} lower than the actual yield in 2011–2015. The joint effects of temperature increase, changes in precipitation and radiation are estimated to have increased yields of early and late rice by 0.5% and 2.8%, respectively (1980–2012, Southern China). Nepal: An empirical study of rice yields in the Koshi River basin shows strongly varying impacts of climate change in terms of the considered region and elevation.	Iizumi et al. (2018b) (process-based model, global gridded, maize, wheat, rice, soy), Ray et al. (2019) (empirical model, world regions, 10 most important crops), Lobell et al. (2011) (empirical, major producers, maize, wheat, rice, soy), Liu et al. (2016b) (rice, Southern China, 1980–2012), Wang and Hijmans (2019) (empirical model, rice, China), Sawano et al. (2015) (China, rice), Bhatt et al. (2014) (Nepal, 1967–2008)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Soy: Process-based crop model simulations forced by simulated historical climate versus pre-industrial climate estimate mostly negative effects of historical anthropogenic climate change on soy yields in Southeastern Asia with an about 7% purely climate-induced reduction in China (1981–2010). An empirical study has found non-significant slight negative effects of climate change on soy yields in China (1980–2008). In contrast, a slight increase was found in an empirical study comparing 1974–2008 yields with yields under counterfactual climate conditions not accounting for the recent 1974–2008 trends. The same statistical approach shows minor effects of climate change in Central and Eastern Asia, and a 3.2% reduction of current yields compared with yields under counterfactual climate conditions in Western, Southern and Southeastern Asia.	Iizumi et al. (2018b) (process-based historical simulations, not based on observed yields, 1981–2010), Ray et al. (2019) (empirical model, 1974–2008), Lobell et al. (2011) (empirical, 1980–2008)		
	Others: An empirical study of yields in Western + Southern + Southeastern and Central + Eastern Asia comparing 1974–2008 yields with yields under counterfactual climate conditions not accounting for the recent 1974–2008 trends has found largest yield losses induced by climate change for oil palm in the Western + Southern + Southeastern regions (~16%) and largest climate induced gains for rapeseed in the Central + Eastern Asia region (~6%).	Ray et al. (2019) (empirical, 1974–2008)		
	Impacts of CO_2 fertilisation: Empirical estimates indicate that CO_2 fertilisation has increased 2002–2006 Chinese soy yields by 5.10% compared with assuming 1980 levels of CO_2. Process-based estimates indicate that the effect of CO_2 fertilization may have compensated for climate-induced losses in soy and wheat yields and even slightly overcompensated the losses in rice yields in China (1981–2010). Process-based rice yields simulations for nine provinces in China also indicate a slight increase from 1961 to 2003 overcompensating small non-significant negative effects of temperature increase but still minor compared with the effects of change in fertilizer inputs and technological progress.	Sakurai et al. (2014) (soy, China, 2002–2006), Iizumi et al., 2018 (rice, wheat, soy, process-based, China 1981–2010), Sawano et al. (2015) (China, rice, 1961 and 2003)	*High confidence* on positive effects of CO_2 fertilisation	
Australasia	**Observations:** *Wheat:* National wheat yields have increased steadily from 1900 to 1990, but growth appears to have stalled since 1990, with no significant trend from 1990 to 2015. Based on census data from 1961–2008, areas affected by 'no (further) increase in yields' are estimated to have reached 60% of harvested areas, the crop for which Australia belongs to the top 10 producers. *Maize, soy, rice:* Inconsistent trends or missing information.	Iizumi et al. (2018b), Hochman et al. (2017), Ray et al. (2012)	*Medium confidence* in negative wheat trends, *low confidence* in trends of the other crops	
	Attribution: *Impact of climate change:* *Maize:* A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by pre-industrial climate shows mixed effects of historical anthropogenic climate change and CO_2 fertilisation on 1981–2010 maize yields in Australia and mostly positive impacts in New Zealand. A slight purely climate-induced reduction was found in an empirical study comparing 1974–2008 yields with yields under counterfactual climate conditions not accounting for the recent 1974–2008 trends (1.2%).	Iizumi et al. (2018b) (process-based, 1980–2010), Ray et al. (2019)	Inconsistent estimates of climate-induced trends in wheat yields and mostly minor effects on other crops (e.g., maize), *low confidence* (*)	
	Rice: A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by pre-industrial climate show mostly non-significant changes in 1981–2010 rice yields induced by climate change and CO_2 fertilisation. A purely climate-induced increase in rice yields was found in an empirical study comparing 1974–2008 yields with yields under counterfactual climate conditions not accounting for the recent 1974–2008 trends (4.1% increase with respect to the 1974–2008 average).	Iizumi et al. (2018b) (process-based, 1980–2010), Ray et al. (2019) (empirical, 1974–2008)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Wheat: A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by pre-industrial climate show mostly non-significant changes in 1981–2010 wheat yields induced by climate change and CO_2 fertilisation. Some negative effects in northern Australia and positive effects in southern Australia and New Zealand. A purely climate-induced reduction in wheat yields was found in an empirical study comparing 1974–2008 yields with yields under counterfactual climate conditions not accounting for the recent 1974–2008 trends (5.8% loss with respect to the 1974–2008 average). Empirical modelling supports that climate trends increased wheat yields in four sub-regions of New South Wales by 8.5 to 21.2% from 1922 to 2000. Highly detailed process-based crop model simulations forced by station-based daily weather data at 50 sites representative for Australia's agro-ecological zones and of soil types in the national grain zone indicate a strong decline in water-limited yield potential by 27% from 1990 to 2015. This is mainly driven by trends in rainfall that dominate over negative effects of increasing daily maximum temperatures. The decline in potential yields does not translate into declines in actual yields that tripled from 1990 to 2015 mostly driven by technological progress closing the gap between potential and actual yields from 40% in 1990 to 55% in 2015.	Iizumi et al. (2018b) (process-based, 1980–2010), Wang et al. (2015) (New South Wales, 1922–2000), Hochman et al. (2017) (potential water limited wheat yields), Ray et al. (2019) (empirical, 1974–2008)		
	Soy: A comparison of process-based crop model simulations forced by simulated historical climate versus simulations forced by pre-industrial climate show mostly non-significant changes in 1981–2010 soy yields induced by climate change and CO_2 fertilisation. Some negative effects in northern Australia and positive effects in southern Australia. A purely climate-induced reduction in soy yields was found in an empirical study comparing 1974–2008 yields with yields under counterfactual climate conditions not accounting for the recent 1974–2008 trends (6.3% loss with respect to the 1974–2008 average).	Iizumi et al. (2018b) (process-based, 1980–2010), Ray et al. (2019) (empirical, 1974–2008)		
	Others: An empirical study comparing 1974–2008 yields with yields under counterfactual climate conditions not accounting for the recent 1974–2008 trends has found largest yield losses induced by climate change for Sorghum (~30.5%) and largest climate-induced gains for rice (~4%).			
	Impact of CO_2 fertilisation: The effect of CO_2 fertilisation is estimated to have prevented a further 4% reduction in potential wheat yields relative to 1990 yields over 1990–2015.	Hochman et al. (2017)		
Central and South America	**Observations:** General increase in maize, wheat, soy and rice yields in South America. Based on census data for maize, wheat, rice and soy from 1961 to 2008, areas affected by 'no (further) increase in yields' are estimated to have reached 19% (Brazil) and 5% (Argentina) of the harvested area of maize; 21% (Brazil) of the harvested areas of rice; 14% (Brazil), 12% (Argentina), 98% (Paraguay) and nearly 100% (Bolivia) of the harvested area of soy. Results are only listed for the crops (out of maize, wheat, rice and soy) for which the countries belong to the top 10 producers.	Iizumi et al. (2018b), The PLOS ONE Staff (2017), Ray et al. (2012)		
	Attribution: *Impacts of climate change:* *Maize:* Estimates of climate-induced changes in maize yields in Brazil range from about 10% reduction in 1980–2010 yields derived from process-based simulations forced by simulated historical versus pre-industrial climate; a purely climate-induced gain of about 6% derived from an empirical model forced by climate data accounting for 1974–2008 trends and counterfactual data not accounting for the trends (2.7% gain for the Caribbean and South America as a whole); and an empirically derived climate induced loss of 1980–2008 yields about 7.5% in Brazil. An empirical study of 33 counties in the Pampas region of Argentina indicates climate-induced yield losses of 5.4% compared with a situation without trends in climate from 1971 to 2012.	Iizumi et al. (2018b) (1980–2010), Ray et al. (2019) (1974–2008), Lobell et al. (2011) (1980–2008), Verón et al. (2015) (county-level wheat, maize and soy yields at the county level in the Pampas region of Argentina, 1971–2012)	Moderate mostly negative impacts of climate change on wheat yields, *medium confidence* (**), inconsistent findings or inconclusive findings for other (maize, soy and rice)	
	Rice: The comparison of 1980–2010 yields derived from process-based simulations forced by simulated historical versus pre-industrial climate indicates primarily positive combined impacts of climate change and CO_2 fertilisation on rice yields. A minor purely climate-induced loss of about 1% derived from an empirical model forced by climate data accounting for 1974–2008 trends and counterfactual data not accounting for the trends.			

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Wheat: The comparison of 1980–2010 yields derived from process-based simulations forced by simulated historical versus pre-industrial climate indicates primarily negative impacts of climate change on wheat yields even though additionally accounting for the effect of CO_2 fertilisation. An empirical model also indicates a climate-induced reduction in wheat yields (1.6%) in South America + Caribbean induced by climate change from 1974 to 2008. An empirical study of 33 counties in the Pampas region of Argentina indicates climate-induced yield losses of 5.1% compared with a situation without trends in climate from 1971 to 2012. *Soy:* The comparison of process-based simulations forced by simulated historical climate and simulated pre-industrial climate indicate a purely climate-induced reduction of 1980–2010 yields of 5–10% in Brazil and Argentina and even slightly stronger losses in Paraguay. In contrast, empirical models indicate a 5% gain in soy yields in South America + Caribbean induced by climate change from 1974 to 2008 and gains (~2.5%) in soy yields in Argentina (1980–2008), while an empirical study of 33 counties in the Pampas region of Argentina indicates climate-induced yield losses of 2.6% compared with a situation without trends in climate from 1971 to 2012.			
	Impacts of CO_2 fertilisation: Process-based CO_2 fertilisation is estimated to have increased 2002–2006 soy yields in Brazil by 7.57% compared with assuming 1980 levels of CO_2. Positive effects of a similar order are supported by process-based crop model simulations.	Sakurai et al. (2014)		
Europe	**Observations:** *Wheat:* After decades of increasing yields, wheat yields have reached a plateau in northwest Europe. Over the time period from 1961 to 2014, wheat yields seem to have reached a plateau in Germany, France and the UK while being affected by a deceleration in Belgium. In contrast, yields increased linearly in Spain and Italy. Based on census data from 1961–2008, areas affected by 'no (further) increase in yields' are estimated to have reached about 80% of harvested areas in France and Germany, both belonging to the top 10 producers globally. *Maize:* In aggregate, maize yields seem to be increasing (e.g., linear increases in Germany and Spain, 1961–2014) but may have reached a plateau in Italy and Belgium and be affected by deceleration in France (1961–2014). Based on census data from 1961–2008, areas affected by 'no (further) increase in yields' are estimated to have reached 10.5% of harvested areas in France and 59.2% in Italy, both countries belonging to the top 10 producers globally. *Soy:* Based on census data from 1961–2008, areas affected by 'no (further) increase in yields' are estimated to have reached nearly 100% of harvested areas in Italy. which belongs to the top 10 producers globally.	Grassini et al. (2013), Iizumi et al. (2018b), The PLOS ONE Staff (2017), Agnolucci and De Lipsis (2019) (wheat and maize)	*High confidence*	
	Attribution: *Impacts of climate change:* *Maize:* Estimated impacts of observed climate change on maize yields are still inconsistent. The comparison of process-based simulations forced by simulated historical climate and simulated pre-industrial climate indicates a purely climate-induced increase of 1981–2010 yields of ~10% in France and even more than 15% when additionally accounting for CO_2 fertilisation. The same study estimates a primarily positive combined effect of climate change and CO_2 fertilisation on 1981–2010 in most of Europe except for negative impacts in the southern Mediterranean region. These findings are in line with an empirical approach indicating that in Italy about 20% of the long-run increase in maize yields over time (1961–2014) has been cancelled out by the adverse impact of weather (about 5% in Spain), while climate change has had a positive contribution on the long-term trends in Belgium (1.6%), France (5%) and Germany (3.2%). Additional support for the general spatial pattern and the direction of the impact of climate change is provided by another empirical study of 1989–2009 crop yields indicating a minor positive effect of climate change on overall European maize yields (0.3%) but significant negative impacts on yields in Spain, Italy and Portugal. However, another empirical study finds purely climate induced reductions in 1974–2008 maize yields of ~6% in Western + Southern Europe and ~25% in Eastern + Northern Europe.	Moore and Lobell (2015) (wheat, maize, barley and sugar beet, 1989–2009, empirical), Ray et al. (2019) (empirical, 1974–2008), Iizumi et al. (2018b) (process-based building on simulated historical versus pre-industrial climate, 1981–2010), Agnolucci and De Lipsis (2019) (empirical analysis of wheat and maize yields, 1961–2014)	Mixed impacts of climate change across different crop types ranging from negative impacts on overall wheat yields to primarily positive but weaker effects on maize yields, *medium confidence* (*) because of limited agreement of studies Low consistency of findings and *limited evidence* for other crops	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Wheat: Estimated impacts of observed climate change on wheat yields are still inconsistent. The comparison of process-based simulations forced by simulated historical climate and simulated pre-industrial climate indicate a purely climate-induced increase of 1981–2010 yields of ~10% in France and even more than 15% when additionally accounting for CO_2 fertilisation. Accounting for climate change and CO_2 fertilisation, the same study finds mostly insignificant or positive impacts on 1981–2010 wheat yields in most of Europe. These findings are in contrast to an empirical approach indicating that in Germany about 30% of the long-run increase in wheat yields over time (1961–2014) has been cancelled out by the adverse impact of weather (about 9% in Belgium, 20% in France, 11% in Italy, and 7% in Spain). In contrast, climate change is estimated to have increased the UK's long-run growth rate by two-thirds. Large-scale negative impacts of climate change on European wheat yields are additionally supported by another empirical study of 1989–2009 crop yields (2.5% reduction of recent yields compared with a situation without climate change) and an empirical study of 1974–2008 wheat yields indicating a purely climate-induced reduction of yields in Western + Southern Europe (~9%) and Eastern + Northern Europe (2.1%).			
	Rice: Mostly positive combined impact of climate change and CO_2 fertilisation derived from process-based model simulations forced by simulated historical climate and simulated pre-industrial climate (1981–2010). Empirically derived negative impacts (3.2% purely climate induced reduction of 1974–2008 yields in Western + Southern Europe, minor 0.4% reduction in Eastern + Northern Europe).			
	Soy: Mostly positive combined impact of climate change and CO_2 fertilisation derived from process-based model simulations forced by simulated historical climate and simulated pre-industrial climate (1981–2010). Empirically derived negative impacts (21% purely climate-induced reduction of 1974–2008 yields in Western + Southern Europe, 3.8% reduction in Eastern + Northern Europe).			
	Others: Empirical analysis indicates that long-term temperature and precipitation trends since 1989 have reduced continent-wide barley yields by 3.8%, i.e., climate change can explain 10% of the observed slowdown in barley yields. Negative impacts on barley yields supported by an additional empirical study (16% purely climate induced reduction of 1974–2008 yields in Western + Southern Europe, 9% reduction in Eastern + Northern Europe). In addition, climate change is estimated to have slightly increased sugar beet yields (would have been 0.2% lower without trend in growing season temperature and precipitation).	Moore and Lobell (2015) (barley and sugar beet, 1989–2009, empirical), Ray et al. (2019) (empirical, 1974–2008)		
	Impacts of CO_2 fertilisation: Based on process-based model simulation, the increase in CO_2 from pre-industrial levels to 1980–2010 has led to an increase in maize and wheat yields in France by 5–10%.	Iizumi et al. (2018b) (process-based building on simulated historical versus pre-industrial climate)		
North America	**Observations:** General increase in maize, wheat, soy and rice yields in North America. For example, maize yields have increased by 1.28 tonnes ha^{-1} per decade across the Midwest since 1981. However, regionally yields also show a stagnation or decline.	Butler et al. (2018), Iizumi et al. (2018b), Ray et al. (2019)	*High confidence* in increasing wheat, maize, rice and soy yields (*high agreement* between individual data sets)	
	USA: In the period 1936–2009, yields for maize, wheat, rice, soy, barley and oats grew by more than 1.0% yr^{-1}, with particularly high growth rate of maize yields (2.99% yr^{-1}). However, growth rates appear to have slowed down, i.e., higher rates in 1936–1990 (1.81% yr^{-1}, average across six crops) than in 1990–2009 (1.17% yr^{-1}). The slowdown is strongest for maize (from 3.43% yr^{-1} to 1.75% yr^{-1}), wheat (from 2.09% yr^{-1} to 0.62% yr^{-1}), barley (from 2.14% yr^{-1} to 1.39% yr^{-1}), and oats (1.73% yr^{-1} to 0.62% yr^{-1}) and less severe for rice (from 1.64% yr^{-1} to 1.31% yr^{-1}) and soy (from to 1.61% yr^{-1} to 1.34% yr^{-1}). Based on census data for maize, wheat, rice and soy from 1961–2008, areas affected by 'no (further) increase in yields' are estimated to have reached 7.6% (maize), 36% (wheat) and 9% (soy) of harvested areas, the three crops for which the USA belongs to the top 10 producers.	Ray et al. (2012), Andersen et al. (2018)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
	Canada: While yields are mostly increasing, they seem to have reached a plateau or show a decline in some areas in recent years. Based on census data for maize, wheat, rice and soy from 1961–2008, areas affected by 'no (further) increase in yields' are estimated to have reached 0.8% (wheat) and 0% (soy), the two crops for which Canada belongs to the top 10 producers. *Mexico:* While yields are mostly increasing, they seem to have reached a plateau or show a decline in some areas in recent years. Based on census data for maize, wheat, rice and soy from 1961–2008, areas affected by 'no (further) increase in yields' are estimated to have reached 31% (maize), the crop for which Mexico belongs to the top 10 producers.			
	Attribution: Impacts of climate change vary from region to region and across crops (see individual assessments below).	Ray et al. (2019) (all empirical), Iizumi et al. (2018b) (process-based)	Mixed estimated impacts of climate change on yields across different crops and regions ranging from positive effects (e.g., maize in the USA) to moderate negative effects (e.g., wheat in the USA), *low confidence* (*) because of divergent estimates in the USA and only *limited evidence* elsewhere	
	USA: There is no clear attribution of the observed slowdown of yields from 1936–1990 to 1990–2009 as climate attribution studies mostly only cover the recent decades from about 1980 and partly focus on specific regions rather than the USA as a whole.	Iizumi et al. (2018b) (wheat, maize, rice, soy, based on simulated historical climate compared to pre-industrial climate, process-based)		
	Maize: Weather conditions have affected maize yields by (i) increasing mean temperatures and decreased exposure to extreme heat assuming fixed growing seasons and (ii) allowing for adjustments of growing seasons and prolonged grain filling phases. The combination of both effects is estimated to have contributed about 25–28% to the observed positive trend in maize yield (1980–2017), with about equal contributions of both components. Positive effects of an expansion of the grain filling period (by 0.37 d from 2000 to 2015 and probably induced by variety renewal) are supported by an independent study of county-level data and are estimated to account for roughly one-quarter (23%) of the positive trend in yields reported for 2000–2015. The remaining positive trend may be partly due to CO_2 fertilisation and technological progress, in particular the adoption of genetically engineered varieties after 1996. In the Midwestern states, the latter effect is estimated to have increased growth rates of maize from 0.94% yr^{-1} before 1996 to 1.59% yr^{-1} afterwards. The positive effect of observed changes in weather conditions assuming fixed growing seasons is partly due to reduced exposure to extremely high temperatures. Only minor climate-induced gains in maize yields (0.1% of current levels, 1974–2008) found by an independent empirical study may be due to not accounting for extreme temperatures. Process-based simulations based on simulated historical climate only accounting for anthropogenic emissions of climate forcers do not account for indirect effects of agricultural management on temperatures and show a purely climate driven reduction in 1981–2010 US maize yields by about 5% compared with pre-industrial climate conditions.	Butler et al. (2018) (empirical, combined effect of changes of weather within growing seasons and growing season adjustments 1980–2017), Zhu et al. (2019) (effect of expansion of grain filling period, maize, 2000–2015), Ortiz-Bobea and Tack (2018) (estimated yield increase induced by technological development, maize, county-level data, 1981–2015), Iizumi et al. (2018b) (wheat, maize, rice, soy, based on simulated historical climate compared with pre-industrial climate, process-based, 1981–2010), Ray et al. (2019) (10 crops, empirical, 1974–2008)		*Maize:* While the favourable increase in growing season average temperature is assumed to be due to anthropogenic emissions of climate forcers, the reduction in exposure to extreme heat is assumed to be directly induced by increased evapotranspiration driven by agricultural management changes.
	Wheat: Based on a simple statistical model accounting for annual and growing season average temperature and precipitation variations, wheat yields are estimated to have been reduced by climate change (1.4% of current levels, 1974–2008). Process-based simulations forced by simulated historical climate and simulated pre-industrial climate conditions indicate a loss of about 7% of 1981–2010 yields induced by anthropogenic climate forcing not accounting for CO_2 fertilisation.	Ray et al. (2019) (empirical, 1974–2008), Iizumi et al. (2018b) (based on simulated historical climate compared with pre-industrial climate, process-based, 1981–2010)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Soy: Based on a simple statistical model accounting for annual and growing season average temperature and precipitations variations, soybean yields are estimated to have increased due to climate change (+3.7% of current levels, 1974–2008); accounting for within-season variations of temperature and precipitation, climate change is estimated to have had a negative effect on trends in soy yields from 1994–2013 (without climate change, soybean yield trends might have been 30% higher than the observed one); process-based crop model simulations support a negative effect of simulated historical climate change on observed soy yields (1980–2010 average yields accounting for climate change are about 6% smaller than yields derived from pre-industrial climate conditions not accounting for CO_2 fertilisation).	Ray et al. (2019) (empirical, 1974–2008), Mourtzinis et al. (2015) (soy, empirical, 1994–2013), Iizumi et al. (2018b) (based on simulated historical climate compared with pre-industrial climate, process-based, 1981–2010)		
	Rice: Based on a statistical model accounting for annual and growing season average variations in temperature and precipitation, rice yields have been reduced (minor effect) by climate change (0.3% of current levels, 1974–2008). Mostly insignificant effects of climate change + CO_2 fertilisations on 1981–2010 yields also found in process-based crop model simulations forced by simulated historical climate and simulated pre-industrial climate.	Ray et al. (2019) (empirical, 1974–2008), Iizumi et al. (2018b) (based on simulated historical climate compared with pre-industrial climate, process-based, 1981–2010)		
	Others: Empirical estimates indicate that climate change from 1974 to 2008 has reduced yields of barley (2.8%), and increased yields of sorghum (12.7%) and sugarcane (6.5%).	Ray et al. (2019) (empirical, 1974–2008)		
	Effects of increasing atmospheric CO_2 concentrations: *Maize:* Process-based model simulations indicate that the effect of CO_2 fertilisation may have compensated for about half of the simulated historical climate induced reduction of 1981–2010 maize yields. *Wheat:* Process-based model simulations indicate that the effect of CO_2 fertilisation may have compensated for the simulated climate-induced reduction of 1981–2010 wheat yields. *Soy:* CO_2 fertilization is estimated to have increased 2002–2006 US soy yields by 4.34% compared with assuming 1980 levels of CO_2. Process-based model simulations indicate that the effect may have compensated for the climate induced reduction of 1981–2010 soy yields.	Sakurai et al. (2014) (effect of CO_2 fertilisation on 2002–2006 soy yields), Iizumi et al. (2018b) (wheat, maize, rice, soy, based on simulated historical climate compared with pre-industrial climate, process-based)		
	Canada: Based on a statistical model accounting for annual and growing season average temperature and precipitation variations, the following impacts of climate change on 1974–2008 yields are estimated: maize: +6.0%, wheat: –1.5%, barley: –5.1%, rapeseed: –0.7%.	Ray et al. (2019) (empirical, 1974–2008)		
	Mexico: Based on a statistical model accounting for annual and growing season average temperature and precipitation variations, the following impacts of climate change on 1974–2008 yields are estimated: maize: +4.9%, wheat: –8.5%, rice: +5.1%, soy: +19.1%, barley: +5.6%, oil palm: +34.3%, sorghum: –2.2%, sugarcane: +7%.	Ray et al. (2019) (10 crops, empirical)		
Small Islands	**Observations:** Missing studies. **Attribution:** Missing studies.		No assessment	
S19	Food system—Food prices			
Global	**Observations:** **Attribution:** There is no attribution of changes in food prices to climate change but an ‘identification of weather sensitivity’ (see ‘S19 Food system – Food prices’, Table SM16.23.		No assessment	
S20	Food system—Malnutrition			
Global	**Observations:** **Attribution:** There is no attribution of changes in malnutrition to climate change but only a ‘detection of weather sensitivity’ (see part 3 of this table).		No assessment	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
S28	Other societal impacts—Heat-related mortality			
Global	**Observations:** *Heat-related mortality:* Most evidence on temporal trends in heat-related excess mortality stems from developed countries in North America, Europe, Australasia and East Asia. The majority of studies find that attributable fractions (percent deaths attributable to heat exposure out of total deaths) have declined over recent decades, with notable exceptions in countries where unprecedented heatwaves occurred recently. Studies considering the entire 20th century mostly find declining trends in heat-related excess mortality over time, with some indication of a slowing trend in more recent decades. *Cold-related mortality:* Inconclusive evidence on temporal trends in the fraction of deaths associated with cold exposure, with only few locations (e.g., in Asia and Australasia) showing decreasing trends, and several countries/regions reporting no or even increasing trends in cold-related mortality fractions.	Arbuthnott et al. (2016) (review), Kinney (2018) (review; heat), Sheridan and Allen (2018) (review), Vicedo-Cabrera et al. (2018) (multi-country assessment)		Trends in the overall heat and cold death burden are determined by shifts in the temperature distributions, changes in the susceptibility to heat and cold, and demographic parameters (population, age structure). If climate change were the sole driver of changes in temperature-related excess mortality, one would have expected rising heat-related excess mortality and declining cold-related excess mortality over recent decades.
	Attribution: *Heat-related mortality:* It is generally understood that alterations in the vulnerability to heat have dominated the temporal change in the fraction (or number) of deaths associated with heat exposure. Thus, where no or decreasing trends in heat-related excess mortality have been observed, decreases in vulnerability have outpaced the impact of climate change, which alone would have caused an increase in heat-related excess mortality. Empirical temperature–mortality relationships show that a significant relative risk persists at high temperatures despite reductions in vulnerabilities. Independently, studies clearly indicate a contribution of GHG emission to increasing temperatures and rising frequency and intensity of heatwaves (see 'heatwaves' in part 1 of the table). This implies that the observed heat-related excess mortality would have been much lower without climate change. Accordingly, a recent study estimates around 37.0% (range 20.5–76.3%) of the average heat-related excess mortality in 1991–2018 across 43 countries to be attributable to anthropogenic climate change. *Cold-related mortality:* No existing evidence in a multi-country setting.	Vicedo-Cabrera et al. (2018) (trends, cold and heat, 10 countries), Vicedo-Cabrera et al. (2021) (heat, 732 locations in 43 countries), Sera et al. (2021) (multi-country assessment; heat)	Minor to strong impact of climate change on fractions (number) of deaths associated with heat exposure, *medium confidence* (**)	
Africa	**Observations:** No evidence on temporal trends in heat- and cold-related excess mortality in Africa. Regarding average temperature-mortality associations estimated for African countries, see entries on weather sensitivity in part 3 of the table.			
	Attribution: *Heat-related mortality*: A recent study finds that 43.8% of current heat-related mortality (1991–2018) in South Africa can be attributed to human-induced climate change. *Cold-related mortality:* No conclusive evidence.	Vicedo-Cabrera et al. (2021) (South Africa)	Strong increase in heat related-mortality due to climate change, *low confidence* (*)	
Asia	**Observations:** *Heat-related mortality–temporal trends:* Studies on trends in heat-induced excess mortality only exist for East Asian countries where they generally indicate reductions in mortality fractions/heat risks over time, albeit one study finds recent increases in heat-related excess mortality in Japan. *Cold-related mortality–temporal trends:* Mixed evidence on trends in susceptibility to cold exposure/cold attributable mortality fractions in East Asia, with a tendency of observing declining cold-related excess mortality in most locations.	Lee et al. (2018) (South Korea, Japan, Taiwan Province of China), Vicedo-Cabrera et al. (2018) (Japan, South Korea)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems (‘Impact Attribution’)				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Heat-related mortality–individual extreme events: Upwards of 2200 excess deaths are estimated to have occurred in the Indian heatwave 2015 and at least 700 alone in the megacity of Karachi during the Pakistani heatwave of the same year.	Masood et al. (2015), Ratnam et al. (2016)		
	Attribution: *Heat-related mortality:* Studies on the vulnerability towards heat tend to show reductions over recent decades. However, in general, sensitivity of mortality to heat does not disappear over time. In combination with the observed increase in probability and intensity of heatwaves (see part 1 of this table), these results imply that climate change has induced excess mortality. The only existing quantitative attribution study including data on Asia finds that the proportion of heat-related excess mortality (averaged over 1991–2018) attributable to human-induced climate change is on the order of 21.3% (China) to 67.7% (Kuwait) across the nine Asian countries studied. With regard to specific extreme events, deadly heatwaves in India and Pakistan in 2015 were found to be exacerbated by anthropogenic climate change (see part 1 of the table). Thus, their impacts in terms of excess mortality are considered attributable to anthropogenic climate change, too. *Cold-related mortality:* No conclusive evidence.	Gasparrini et al. (2015a) (South Korea, Japan), Chung et al. (2018) (Japan), Kim et al. (2019) (South Korea), Chung et al. (2017) (South Korea, Japan, Taiwan), Vicedo-Cabrera et al. (2021) (only heat; 1991–2018; Iran, Kuwait, South Korea, Japan, China, Thailand, Vietnam, Philippines, Taiwan), Vicedo-Cabrera et al. (2018) (Japan, South Korea)	Moderate to strong impacts of climate change on heat-related mortality, *low confidence* (*)	
Australasia	**Observations:** *Heat-related mortality:* Evidence for decreasing heat-associated deaths during the course of the 20th century. By contrast, over recent decades, heat-related mortality fractions tend to increase, at least in major Australian cities. In Australia, during 1987–2016, natural disasters caused an estimated 971 deaths, of which more than 50% were associated with heatwaves in cities. *Cold-related mortality*: *Limited evidence* points to decreasing trends in cold-related mortality fractions since the late 1980s in Australia.	Coates et al. (2014) (Australia), Gasparrini et al. (2015b) (three Australian cities), Vicedo-Cabrera et al. (2018) (three Australian cities), Deloitte (2017)		
	Attribution: *Heat-related mortality:* Qualitative evidence that increasing temperatures have contributed to the trend of increasing heat-related mortality fractions in Australian cities. The impact of climate change may even have been amplified by increasing sensitivities. A recent attribution study suggests that, between 1991 and 2018, 35–36% of average heat-related mortality in Brisbane, Sydney and Melbourne was attributable to climate change, amounting to about 106 deaths a year on average.	Vicedo-Cabrera et al. (2018), Vicedo-Cabrera et al. (2021)	Moderate to strong impact of climate change on heat-related excess mortality, *medium confidence* (**)	
	Cold-related mortality: Increase in the ratio of summer versus winter death over 40 years can be related to rising temperatures due to climate change. Evidence suggests that the shift in ratio is largely due to decreasing winter deaths. However, studies indicate a non-climate-related decrease in susceptibility to cold that makes it difficult to quantify the pure climate-induced contribution to the effect.	Bennett et al. (2014)	Unquantified decrease in cold-related mortality induced by climate change, *low confidence* (*)	
Central and South America	**Observations:** Only evidence on mortality trends stems from Brazil during 1996–2011: *Heat-related mortality:* No temporal trend in heat-attributable mortality fractions. *Cold-related mortality:* Decreasing trend in cold-related mortality fractions.	Vicedo-Cabrera et al. (2018) (Brazil)		
	Attribution: *Heat-related mortality:* Between approximately 20.5% (Argentina) and 76.6% (Ecuador) of current heat-related excess mortality (1991–2018) across 13 Latin American countries is estimated to be attributable to human-induced climate change. No conclusive evidence regarding attribution of temporal trends. *Cold-related mortality:* No conclusive evidence.	Vicedo-Cabrera et al. (2021) (Guatemala, Mexico, Panama, Puerto Rico, Colombia, Paraguay, Costa Rica, Peru, Ecuador, Chile, Uruguay, Brazil, Argentina)	Moderate to strong impact of climate change on heat-related excess mortality, *low confidence* (*)	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

Region	Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems	Reference	Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence	Underlying mechanism
Europe	**Observations:** *Heat-related mortality–temporal trends:* Evidence on decreasing trends in heat-attributable mortality during recent decades (since approximately 1980s/1990s) in most European countries, with some exceptions. Tendency of southern, warmer locations showing decreasing trends and northern, cooler locations showing increasing trends in heat-related excess mortality. Notable differences in trends exist between cause-specific mortality categories (all-cause, cardiovascular, respiratory), sex and age groups. Studies investigating heat-related excess mortality since the early 20th century in Europe generally find more pronounced decreasing trends than studies focusing on recent decades. *Cold-related mortality–temporal trends:* Mixed evidence on trends in cold-attributable mortality fractions over time, some countries showing decreasing trends, other countries stable or even increasing trends.	Arbuthnott et al. (2016) (review; citing studies from UK, Sweden, the Netherlands, Austria, Czech Republic, France), De'Donato et al. (2015) (only heat; nine European cities), Achebak et al. (2018), Achebak et al. (2019) (Spain), Vicedo-Cabrera et al. 2018 (Switzerland, Spain, UK, Ireland), Åström et al. (2018) (Sweden), Díaz et al. (2019) (only cold, Spain)		
	Heat-related mortality–extreme events: Significant heat-related mortality (with up to 70,000 excess deaths) observed during 2003 European summer heatwave and 11,000 excess deaths in Moscow alone reported during 2010 Russian heatwave.	Robine et al. (2008) D'Ippoliti et al. (2010), Schewe et al. (2019) Muthers et al. (2017), Shaposhnikov et al. (2014)		
	Attribution: *Heat-related mortality:* Formal detection and attribution studies suggest that rising temperatures from climate change alone would have increased heat-related mortality during recent decades. However, where no or decreasing trends in heat-related mortality over time have been observed, decreasing susceptibility to heat have outweighed the impacts of climate change. Considering the average heat-related mortality in 1991–2018, a recent study finds that the proportion of heat-related deaths attributable to human-induced climate change is on the order of 20–45% across 17 European countries studied. This is in accordance with another study from Sweden which finds that mortality related to heat extremes in the period 1980–2009 in Stockholm has doubled compared with what would have been observed under the climate of the early 20th century. Another study looking at the 2003 summer heatwave in London and Paris found that 20% and 70%, respectively, of the heat-related excess summer deaths are attributable to anthropogenic climate change. For the UK, it has been estimated that around 50% of the excess deaths registered during the 2003 and 2018 heatwave can be attributed to human-made climate change. The contribution of anthropogenic climate change to the European summer heatwave 2003 and the Russian heatwave 2010 has been firmly established (see part 1 of this table). Therefore, at least part of the associated heat-related excess mortality is attributable to climate change.	Christidis et al. (2010) (1976–2005; UK), Vicedo-Cabrera et al. (2021) (only heat; 1991–2018; 17 European countries), Åström et al. (2013) (1980–2009, Sweden), Mitchell et al. (2016) (2003 heatwave; UK, France), Clarke et al. (2021) (2003 and 2018 heatwaves; UK)	Moderate to strong impact of climate change on heat related excess mortality, *medium confidence* (**)	
	Cold-related mortality: Very little research has addressed the contribution of climate change to observed temporal trends in cold-related mortality in a quantitative manner. One study finds that anthropogenic climate change has contributed to a decrease in cold-related mortality observed in the UK. Another study from Sweden finds increased mortality attributable to extreme cold due to a higher frequency of cold spells in recent decades compared with early 20th century climate.		Minor to moderate impact of climate change on cold-related mortality; contradictory in terms of adverse versus beneficial; *low confidence* (*)	

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North America	**Observations:** *Heat-related mortality:* Consistent evidence for North America that heat-related excess mortality (and vulnerability to heat) has decreased over time, with strongest decline observed since the 1960s. Declining trends also found in Canada. *Cold-related mortality:* Mixed evidence on trends in cold-related excess mortality, with some studies finding no change and some even positive trends.	Gasparrini et al. (2015b), Kinney (2018), Petkova et al. (2014), Nordio et al. (2015), Barnett (2007)		
	Attribution: *Heat-related mortality:* Increasing prevalence of central air conditioning has been shown to explain some of the decline in heat-related excess mortality in the USA, yet not all studies agree on this finding. Changes in the susceptibility to heat have largely determined trends in heat-related mortality since the 1980s. However, the reduction of vulnerability does not mean that societies get insensitive to heat. Excess mortality is still observed at high temperatures, i.e., comparing the observed declining heat-related mortality with a counterfactual baseline where vulnerability to heat declines over time according to observations but climate does not change would still show a purely climate-driven change in heat-related mortality. Accordingly, in a study that considers average vulnerability during recent decades (1991–2018) 34.7% (USA) and 38.5% (Canada) of present-day heat-related excess mortality have been attributed to human-induced climate change. *Cold-related mortality:* No conclusive evidence.	Barreca et al. (2016), Bobb et al. (2014), Vicedo-Cabrera et al. (2018), Vicedo-Cabrera et al. (2021), Sera et al. (2021)	Moderate impact of climate change on heat-related excess mortality, *medium confidence* (**)	
Small Islands	**Observations:** No evidence on temporal trends in heat- and cold-related excess mortality in Small Island states. Regarding average temperature–mortality associations estimated for Small Islands, see entries on weather sensitivity in part 3 of the table.			
	Attribution: According to a recent study, 51.9% of heat-related mortality over 1991–2018 in the Caribbean island of Puerto Rico is attributable to human-induced climate change.	Vicedo-Cabrera et al. (2021)	Strong impact of climate change on heat-related excess mortality, *low confidence* (*)	
S27	Other societal impacts—Vector-borne diseases			
Global	**Observations:** *Dengue:* Globally, dengue cases have increased over eight-fold during the last two decades.	WHO (2021); Zeng et al. (2021)		
	Malaria: The incidence and endemicity of malaria overall is declining but is expanding in areas experiencing socio-political challenge and highland areas that were previously malaria-free.	Gething et al. (2010), Colón-González et al. (2021)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
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	Attribution: *Malaria:* Expansion of malaria into highland areas is a result of warmer temperatures allowing for transmission at higher altitudes. Where malaria has declined, this has predominantly been driven by improved healthcare access, surveillance, control and treatment. *Dengue*: Increases in dengue are mostly dominated by socioeconomic changes (i.e., urbanisation, sanitation, travel, reporting, protective measures). Increased urbanisation and population mobility are thought to be the main drivers of dengue expansion in the last 20 years. However, climate change is an important driver allowing for the observed expansion to higher latitudes. Climate suitability for the dengue mosquito vector increased by 15% between 1950 and 2018.	Watts et al. (2021), Feachem et al. (2019) Ryan et al. (2019), Watts et al. (2021)	Climate change has increased malaria transmission in highland areas; *medium confidence* (**). Climate change has expanded the distribution of dengue transmission to more temperate latitudes; *medium confidence* (**).	*Malaria:* Malaria is a disease caused by *Plasmodium* parasites, the most common being *P. falciparum* and *P. vivax*. Malaria is transmitted by infected female *Anopheles* mosquitoes. *Dengue:* Dengue fever is a disease caused by the dengue virus, and transmitted by *Aedes* mosquitoes. Both malaria and dengue are sensitive to climatic conditions, which influence various life-history traits of both the mosquito vectors and the malaria parasite and dengue virus. For example, the extrinsic incubation period (time taken for the parasite or virus to develop inside the mosquito) is influenced by temperature, as is mosquito development and longevity. In general, a combination of climate-associated expansion in the geographic range of vector species and non-climatic factors such as globalisation, increased levels of international travel and trade, urbanisation, poor environmental hygiene and ineffective vector control measures has driven observed vector-borne disease trends.

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Africa	**Observations:** *Malaria*: Although malaria cases have declined since the late 1990s, more of Sub-Saharan Africa is experiencing year-round malaria transmission. In particular, there has been substantial geographical expansion of malaria in the East African highlands, with more frequent outbreaks in these areas.	Pascual et al. (2006) (malaria, highlands), Ryan et al. (2015) (malaria, Africa)		
	Dengue and chikungunya: Reported dengue and chikungunya cases have increased in Sub-Saharan Africa. Between 1960 and 2017, more than 20 dengue epidemics were reported in over 20 African countries.	Tjaden et al. (2017) (chikungunya), Simo et al. (2019) (dengue, Africa), Amarasinghe et al. (2011) (dengue epidemics, Africa), Humphrey et al. (2016), Pabalan et al. (2017)		
	Attribution: *Malaria:* Higher temperatures and changes in rainfall have shifted the distribution of malaria vectors in sub-Saharan Africa, allowing vectors to colonise at higher altitudes. Using data between 1950 and 2002, the warming trend in four highland sites was associated with an increase in incidence of malaria in the East African highlands since the end of the 1970s. There is also further evidence of malaria distribution shifting to higher altitudes in Ethiopia between 1993 and 2005, during warmer years. A study estimated that recent climate change (1990–2000) has contributed to an increase of more than 21% in the number of malaria cases across African countries, including Algeria, Malawi and the Central African Republic. Between 2015 and 2019, suitability for malaria transmission in highland areas was 38.7% higher in the African region compared with a 1950s baseline. Warming trends between 1950 and 2002 have been associated with increases in epidemic malaria in the African highlands in four sites in Kenya, Uganda, Burundi and Rwanda. Despite some controversy associated with the lack of high-quality long-term data, and socioeconomic and biological factors, such as drug resistance, that may have amplified malaria increases due to warming, there is *medium confidence* that climate change has increased the number of malaria cases in African highlands.	Pascual et al. (2006) (malaria, four highland sites 1950–2002), Siraj et al. (2014) (Ethiopia 1993–2005), Egbendewe-Mondzozo et al. (2011) (multiple African countries 1990–2000), Watts et al. (2021) (2015–2019 transmission suitability)	Moderate contribution of climate change to the observed increase in malaria cases in African highlands; *medium confidence* (**); moderate contribution of climate change to the observed increase in dengue cases in Africa; *low confidence* (*)	Warmer temperatures increase transmission of malaria by speeding up the development of *Anopheles* mosquitoes, and replication of the parasite inside the mosquito. Elevated temperatures as a result of climate change allows *Anopheles* species to colonise higher altitudes at the edges of their historical ranges. Rainfall provides an important *Anopheles* mosquito breeding habitat, in the form of stagnant pools of water that allow for the aquatic life cycle stage to be completed.

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	Dengue: Urbanisation and globalisation (increased mobility) are the dominant drivers of the observed increase in dengue epidemics in Sub-Saharan Africa, but climate change has added to this positive trend by expanding suitable conditions for the vector.	Tong et al. (2021) (dengue, African region)		Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance. Urbanisation and population density increase the abundance of arbovirus vectors that breed in artificial containers inside or near to urban dwellings.
Asia	**Observations:** *Dengue:* Incidence has risen dramatically in Southeast Asia (46% increase in cases 2015–2019), with high increases in urban areas and recent spread to rural areas. In Singapore, dengue cases between 1978 and 1999 increased 10-fold from 384 to 5285.	WHO (2008), WHO (2021) (dengue, Singapore)		
	Malaria and Japanese encephalitis: Other vector-borne diseases, including malaria and Japanese encephalitis, have expanded to non-endemic mountainous areas. There has been an increase in the number of seasonal malaria epidemics observed in highland areas of Nepal with an increase in the proportion of *Plasmodium falciparum* malaria cases recorded. However, in Southeast Asia between 2000 and 2017, cases declined by 8%.	Dhimal et al. (2015), Dhimal et al. (2014), Battle et al. (2019)		
	Attribution: *Dengue:* The expansion of dengue is predominantly a result of rapid urbanisation and increases in population density, but may have been facilitated by warming temperatures that allow for year-round suitability in transmission. However, consistent evidence linking climate change and dengue outbreaks in Asia is lacking. Outbreak risk of mosquito-borne disease, including dengue in Southeast Asia, was shown to peak at the highest monthly temperatures of 33.5°C. Due to climate change, these high monthly temperatures now occur in previously colder areas, allowing dengue transmission to shift polewards. In Singapore, increases in dengue cases between 1978 and 1999 have been attributed to warming annual temperatures, which increased by 1.5°C during the same period.	Servadio et al. (2018) (dengue, Southeast Asia), WHO (2008) (dengue, Singapore)	Minor increase in dengue in Southeast Asia induced by climate change; *low confidence* (*) Moderate increase in malaria at higher altitudes due to climate change; *medium confidence* (**)	*Dengue:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance. Urbanisation and population density increase the abundance of arbovirus vectors that breed in artificial containers inside or near to urban dwellings.

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')

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	Malaria: The increasing number of warmer days and rising temperature trends observed at higher altitudes of Nepal allow malaria vectors to persist, which has contributed to increased malaria outbreaks. Using data from 1999–2008, mean annual temperature increases were correlated with an increase in malaria cases in an endemic district of Nepal.	Bhandari et al. (2013), Dhimal et al. (2014) (malaria, Nepal)		
Australasia	**Observations:** *Dengue:* Arbovirus transmission including dengue has shifted further south, and outbreaks are becoming more common.	Ryan et al. (2019), Hanna et al. (2003)		
	Chikungunya: Outbreaks of vector-borne diseases are becoming more common in Australia. For example, chikungunya cases in northern Australia have increased between 2008 and 2017, with the largest number of annual imported cases of 134 occurring in 2013.	Tjaden et al. (2017), Huang et al. (2019)		
	West Nile Fever: West Nile outbreaks are becoming more common in Australia, particularly between 2009 and 2011, and West Nile mosquito vectors are expanding into southern regions.	Prow (2013)		
	Attribution: *Chikungunya:* Evidence shows that increasing temperatures have shifted the mosquito vector further south in Australia and have expanded its range. Increasing trends in arboviruses can be explained by a 13.7% increase in vectorial capacity of the *Aedes aegypti* mosquito from the 1950s to 2016.	Hill et al. (2014), Zhang et al. (2018b)	Moderate contribution of climate change to increase in dengue, chikungunya and West Nile fever vectors (*Aedes* and *Culex*) in southern Australia; *low confidence* (*)	*Chikungunya*: Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. The range limits of the *Aedes* vector are being expanded as a result of increasing climate suitability in areas previously inhospitable.
	West Nile Fever: Peak and total *Culex* abundance has changed due to warming temperatures, with the peak occurring earlier in the year with populations maintained for longer, increasing the risk of West Nile transmission. Extensive flooding has also been shown to promote the *Culex* mosquito life cycle. Climate change and warmer temperatures have shifted the distribution of arbovirus vectors to cooler southern regions of Australia, where summer temperatures are more suitable for West Nile virus amplification.	Frost et al. (2012), Prow (2013), Paz (2015)		*West Nile Fever:* Temperature speeds up the vectorial capacity of *Culex* mosquitoes as well as viral replication of West Nile virus. Abundance of *Culex* mosquitoes is sensitive to rainfall, with large amounts flushing out habitats and drought conditions, bringing hosts and mosquito vectors into close contact due to water storage practices.
Central and South America	**Observations:** *Dengue:* Over the last four decades, the incidence of dengue has increased from 1.5 million cumulative cases between 1980 and 1989 to 16.2 million between 2010 and 2019, with an estimated 500 million people in the Americas now at risk. Dengue epidemics are also increasing in frequency and magnitude, the transmission season has lengthened and dengue has expanded into more temperate areas at the southern fringes. There is evidence that mosquito vectors of dengue have expanded into higher-altitude regions of Mexico.	Robert et al. (2019), PAHO: Puntasecca et al. (2021), Equihua et al. (2017) (Mexico)		

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	Malaria: The malaria transmission season has lengthened and expanded into higher-altitude areas in Colombia. In Venezuela and neighbouring countries, malaria incidence has dramatically increased.	Siraj et al. (2014) (malaria, Colombia), Grillet et al. (2019) (malaria, Venezuela), WHO (2020)		
	Mayaro: Outbreaks of Mayaro virus in urban areas are increasing in frequency across Latin and South America and in particular in central and northern Brazil.	Caicedo et al. (2021), Esposito and Fonseca (2017), Acosta-Ampudia et al. (2018)		
	Attribution: *Dengue and other arboviruses:* The expansion of the primary dengue vector *Aedes aegypti* into temperate areas and to higher elevations, such as South Brazil, northern Argentina and Mexico, is a result of warmer temperatures that favour establishment and increased transmission.	Barcellos and Lowe (2014) (dengue, Brazil), Robert et al. (2019) (dengue, Argentina), Lozano-Fuentes et al. (2012) (dengue, Mexico)	Moderate contribution of climate change to the observed increased dengue cases, *medium confidence* (**); moderate contribution of climate change to the increasing number of malaria cases in higher altitudes, *medium confidence* (**)	*Dengue:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance.
	Zika: The rapid spread of Zika in Brazil has primarily been attributed to rapid urbanisation and population mobility, although may have been facilitated by increasing temperatures that allow mosquito vectors to persist in favourable climatic conditions.	Paz and Semenza (2016) (Zika, Brazil)		*Zika:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance.
	Malaria: Increased malaria cases have been observed at higher-altitudes areas during warmer years in Colombia, as a result of climate change allowing for range expansion of mosquito vectors. Recent increases in cases of malaria in some areas including Venezuela and Brazil are a result of socioeconomic factors, including political instability and population mobility.	Siraj et al. (2014) (malaria, Colombia), Grillet et al. (2019) (malaria, Venezuela)		*Malaria:* Warmer temperatures increase transmission of malaria, by speeding up the development of *Anopheles* mosquitoes, and replication of the parasite inside the mosquito. Warmer temperatures at higher altitudes allow *Anopheles* mosquitoes to persist at higher elevations and expand their range limits.

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Europe	**Observations:** *Lyme disease and tick-borne encephalitis:* Expanded from western Europe northwards to Sweden, Norway and the Russian Arctic and to higher elevations in Austria and the Czech Republic over the last few decades.	Jaenson et al. (2012) (Sweden), Jore et al. (2014) (Norway), Medlock et al. (2013) (Europe review), Tokarevich et al. (2017) (Russian Arctic), Daniel et al. (2003) (high altitudes, Central Europe), Heinz et al. (2015) (Austria)		
	Chikungunya: Transmission of arboviruses such as dengue and chikungunya has expanded in Southern Europe, including France, Italy and northeast Spain.	Roiz et al. (2015)		
	Attribution: *Lyme disease and tick-borne encephalitis:* The increased abundance of ticks has been attributed to high availability of tick maintenance hosts (particularly deer) during the last three decades, as well as a warmer climate with milder winters and a prolonged growing season that permits greater survival and proliferation over a larger geographical area of both the tick itself and deer.		Moderate contribution of climate change to the observed increase in tick-borne diseases (Lyme and tick-borne encephalitis) in Europe, *medium confidence* (**)	*Lyme:* Warmer temperatures shorten the life cycle and increase abundance of *Ixodes* ticks that carry Lyme disease. High temperatures also expand the distribution and range of rodent and deer hosts, as well as their activity, increasing human exposure to Lyme disease. Dry conditions can leave tick larval nymphs susceptible to desiccation, which can lead to subsequent decreases in Lyme disease.
	Dengue: There is evidence of increased climate suitability for mosquito vectors due to warmer winter temperatures in Western Europe. Vectorial capacity for the *Aedes aegypti* vector in Europe has increased by 25.8% compared with a 1950s baseline.	Caminade et al. (2012), Watts et al. (2021), Salami et al. (2020)		*Dengue and chikungunya:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance.

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
North America	**Observations:** *Lyme and tick-borne disease:* In temperate regions of the USA, Lyme and tick-borne diseases such as tick-borne encephalitis have expanded northwards. Lyme disease incidence has been increasing since the 1980s, with annual infections tripling between 2004 and 2016.	Kugeler et al. (2015), Bisanzio et al. (2020), Lin et al. (2019), Schwartz et al. (2017), Rosenberg et al. (2018), Rochlin et al. (2019b)		
	West Nile Fever: West Nile was the most common vector-borne disease reported in the USA between 2004 and 2016. Larger outbreaks of West Nile Fever are being recorded, with a gradual northward spread.	Ronca et al. (2021), Nelson et al. (2015), Rochlin et al. (2019b), Rosenberg et al. (2018)		
	Dengue: Increase in outbreak intensity and spatial distribution of dengue in the USA, with an increased number of outbreaks in the southern USA including Florida, Texas and Hawaii.	Braithwaite et al. (2016), Brathwaite Dick et al. (2012), Bouri et al. (2012), Brady and Hay (2020), Whitehorn and Yacoub (2019)		
	Attribution: *Lyme and tick-borne disease:* Increasing incidence of Lyme disease has been associated with warming annual temperatures, as has the northward range expansion of the tick vector *Ixodes scapularis* in North America and Canada. Non-climatic factors, however, are also important in explaining increasing trends of Lyme, due to increased awareness and surveillance, as well as host mobility. Increased human outdoor activity as a result of shorter winters and longer summer conditions also contributes to increased exposure to ticks and Lyme infection. Overall, even without robust quantification of the contribution of other drivers, there is *moderate confidence* that climate change has contributed to the observed increase in Lyme disease incidence.	Clow et al. (2017a), Clow et al. (2017b), McPherson et al. (2017), Kilpatrick et al. (2017), Ostfeld and Brunner (2015), Scott and Scott (2018), Couper et al. (2020)	Moderate contribution of climate change to increased tick-borne disease; *high confidence* (***) Minor impact of climate change on increased arbovirus incidence; *low confidence* (*)	*Lyme:* Warmer temperatures shorten the life cycle and increase abundance of *Ixodes* ticks that carry Lyme disease. Higher temperatures also expand the distribution and range of rodent and deer hosts, as well as their activity, increasing human exposure to Lyme disease. Dry conditions can leave tick larval nymphs susceptible to desiccation, which can lead to subsequent decreases in Lyme disease.
	Dengue: Expansion patterns have mainly been driven by trade and travel, although transmission potential has increased. This is due to increased climate suitability (warmer temperatures) for the mosquito vectors at range limits.	Butterworth et al. (2017), Robert et al. (2019)		*Dengue:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance.

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
Small Islands	**Observations:** *Dengue:* Observed increase in the number of outbreaks of dengue and Zika in the Caribbean islands, and the Pacific, including in the Marshall Islands, Fiji and Micronesia over the last decade.	Lowe et al. (2020), Arima et al., Cao-Lormeau and Musso (2015)		
	Mayaro virus: In Trinidad, mosquitoes tolerant to brackish water that cause the Mayaro virus are now found in coastal mangrove ecosystems where they never occurred before.	Ali et al. (2019), Mohammed and van Oosterhout (2020)		
	Attribution: *Dengue:* There is evidence of a link between drought and dengue outbreaks in Barbados. Tidal inundation from sea level rise is providing more permanent aquatic breeding habitats for dengue mosquitoes. Disruption from tropical cyclones is increasing population mobility, making it easier for mosquitoes to transmit dengue and other vector-borne diseases. However, there is limited assessment of the role of climate change in driving observed outbreaks in arboviruses in the Pacific.	Lowe et al. (2018b), Leal Filho et al. (2019)	Moderate contribution of climate change to increases in vector borne disease in small islands; *medium confidence* (**)	*Dengue:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance.
	Mayaro virus: The new occurrence of the Mayaro virus in mangrove ecosystems of Trinidad is a result of consistent rises in coastal temperatures and sea level rise that provides new breeding habitat.	Ali et al. (2019), Mohammed and van Oosterhout (2020)		
S14	Coastal systems—Damages			
Global	**Observations:** No assessment on global scale.			
	Attribution: No assessment on global scale.		Not enough studies available for assessment	
Africa	**Observations:** *Coastal erosion:* Shoreline retreat rates along the Palmarin Peninsula (Senegal) have been sharply increasing in recent decades (1982–2018), destroying buildings and tourist camps.	Enríquez-de-Salamanca (2020)		
	Attribution: *Coastal erosion:* In absence of significant human factors, sea level rise has been identified as the most reasonable explanation for the observed increase in shoreline retreat rates along the Palmarin Peninsula.	Enríquez-de-Salamanca (2020)	Strong contribution of sea level rise to shoreline retreat along the Palmarin Peninsula, *low confidence* (*) as based on only one study No assessment elsewhere	
Asia	**Observations:** No clear trend in damage from individual tropical cyclones is found in China.	Chen et al. (2013)		
	Concerning more general coastal disasters in China, including rough seas, storm surges, sea ice and algal blooms, no significant trend is observed in the period 1989–2014 for economic losses; fatalities declined. Algal bloom events cause minor economic impact compared with the other disaster types, but they only have started to occur in the Yellow and East China Sea since the 2000s, causing threat to the overall health of coastal ecosystems.	Fang et al. (2017a)		
	A statistically significant decrease in fatalities caused by storms and floods including TCs is identified for Japan for the period 1968–2014.	Ushiyama (2017), Lee et al. (2020)		
	Normalised cost of damages caused by TCs has increased in the Philippines since 1971, while there were no statistically significant trends reported in the frequency, intensity and landfall of TCs. Typhoon Haiyan in 2013 caused damages with socioeconomical cost of 2 billion USD due to a devastating storm surge, reaching twice the level of the second-largest damage event in the historical record.	Cinco et al. (2016), Lee et al. (2020)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: *Coastal erosion:* Most areas along the Sindh coastline (Pakistan) have experienced significant erosion in the period 1989–2018, positively correlated with sea level rise.	Kanwal et al. (2020)	Sea level rise has increased coastal damages in Pakistan, *low confidence* (*) as based on individual studies only No assessment elsewhere	
Australasia	**Observations:** A swell-dominated ocean beach in Tasmania shows an abrupt change of long-term shoreline position variability circa 1980, from episodic erosion and accretion since at least 1947 to persistent recession with no recovery up to the present. The frequency of occurrence of coastal nuisance flooding has been doubling every 20 years in Brisbane, Australia since 1977 and every 34 years in Townsville, Australia since 1959.	Sharples et al. (2020), Hague et al. (2020)		
	Attribution: Recent sea level rise and increasing winds driving increased wave setup have sufficient explanatory power to account for the observed changes. No formal attribution statement for Brisbane and Townsville Nuisance flooding.	Sharples et al. (2020), Hague et al. (2020)	Locally minor to moderate increase in damages induced by (relative) sea level rise, *low confidence* (*), missing studies elsewhere	
Central and South America	**Observations:** No studies available.			
	Attribution: No studies available.		Not enough studies available for assessment	
Europe	**Observation:** Local government decides to no longer defend a village and relocate its residents over the next 50 years (Fairbourne, Wales, UK).	Gwynned Councyl (2019), Williams et al. (2018)		
	Catalan coast: Storm-induced coastal damage has increased at a rate of about 40% per decade during the last 50 years along the Catalan coast.	Jiménez et al. (2012)		
	Attribution: Rising sea levels leads to decision of abandonment for coastal village (Fairbanks, Wales, UK).	Gwynned Councyl (2019), Williams et al. (2018)	Locally no to moderate increase in damages induced by storm-related hazards and (relative) sea level rise, respectively, *low confidence* (*), Missing studies elsewhere	
	European coastal wetlands and small beaches may have initiated a shift toward erosion in the 1990s, suggesting influence of sea level rise.	Le Cozannet et al. (2020)		
	Catalan coast: The increase in damages has been attributed to urban growth along the coastal fringe and the generalised erosive behaviour of beaches, while no temporal trend in storm-related hazards has been detected.	Jiménez et al. (2012)		
North America	**Observations:** *Tropical cyclones.* Three of the five costliest storms in US history were in 2017: Harvey, Irma and Maria. The other two are Katrina and Sandy, which flooded New Orleans in 2005 and New York in 2012 (non-normalised costs), respectively. In September 2017, Hurricane Harvey hit the south of the USA (in particular Texas and Louisiana), causing an estimated direct damage of USD 85–125 bn.	Frame et al. (2020b), Wehner and Sampson (2021)		
	Depending on the normalisation technique, normalised direct economic losses increase over time or not.	Grinsted et al. (2019), Weinkle et al. (2018)		
	Nuisance flooding. Across 27 locations in the USA, the number of nuisance flood days (defined by the National Weather Service as the flood level at which minor impacts start to occur) has risen from an average of 2.1 d yr^{-1} during 1956–1960 to 11.8 d yr^{-1} during 2006–2010. In Annapolis, the number threshold of nuisance floods was exceeded on 63 d in 2017 and led to reduction of visits to the historic downtown by 1.7%, and loss of city businesses equivalent to 0.7–1.4% of their potential revenue without flood occurrence.	Sweet et al. (2018) (27 locations across the USA), Hino et al. (2019) (Annapolis, Maryland)		
	Alaska: 184 of 213 of Alaska Native villages are subject to flooding and erosion affecting infrastructure such as schools and health clinics and residents' livelihoods as traditional modes of transport and hunting practices become increasingly untenable. In Kivalina, an Inupiaq Inuit community on Alaska's western coast, the frequency of high-damage storms is reported to have increased with 80% of reported storms since 1970 having occurred in the last 15 years.	GAO (2009), Smith and Sattineni (2016), Fang et al. (2017a) (Kivalina), Albert et al. (2018)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Herschel Island, Yukon Territory, Canada (UNESCO World Heritage candidate site): Study area is characterised by widespread erosion. Mean coastal retreat decreased from –0.6 m yr^{-1} to –0.5 m yr^{-1}, for 1952–1970 and 1970–2000, respectively, and increased to –1.3 m yr^{-1} in the period 2000–2011.	Radosavljevic et al. (2016)		
	Land loss, Louisiana: Louisiana lost approximately 4833 km^2 of coastal wetlands between 1932 and 2016, amounting to a decrease of approximately 25%.	Couvillion et al. (2017)		
	Attribution: *Tropical cyclones.* Sea level rise has contributed to the increase in damages of Hurricane Sandy by USD 11.1 billion and the number of people affected by 100,000. Flood modelling with precipitation counterfactuals attributes USD 13 billion of damages from Harvey to anthropogenic climate change. The fraction of attributable risk for the extreme rainfall associated with Harvey (contribution of anthropogenic climate forcing to occurrence probability) is estimated 0.75 (range 0.67–0.9). Assuming that Harvey's heavy rainfall was a major driver of the damages, the fraction of attributable risk of the observed damages is also considered 0.75.	Strauss et al. (2021) (Hurricane Sandy), Wehner and Sampson (2021), Frame et al. (2020b) (Hurricane Harvey)	Individual case studies (hurricanes Harvey and Sandy, nuisance flooding in Annapolis and coastal erosion in Alaska) indicate a strong adverse impact of relative sea level rise, increased precipitation associated with tropical cyclones, and sea ice retreat on coastal human systems, *medium confidence* (**) Relative sea level rise in New York, Louisiana and Alaska is partly induced by subsidence not related to anthropogenic climate forcing, but its influence has been decreasing over time such that today an increasing fraction is related to sea level contributors driven by anthropogenic climate change (see global assessment above) Changes in sea ice retreat and permafrost thawing are dominated by anthropogenic climate forcing (see part 1 of this table) No dedicated attribution of damages elsewhere	
	Nuisance flooding. In Annapolis, nuisance floods in 2017 could almost entirely be attributed to sea level rise (almost 1 ft since 1950) that has increased the number of flood hours from about 1 h yr^{-1} in 1950–1965 to more than 40 h yr^{-1} in 2010–2017 (63 h in 2017).	Hino et al. (2019) (Annapolis, Maryland)		
	Alaska: Relative sea level rise, permafrost thawing and loss of coastal protection against storms due to sea ice loss are considered possible drivers of the observed erosion. Permafrost thawing and sea ice retreat are mainly driven by anthropogenic climate forcing (see 'permafrost' and 'sea ice section' in the first part of this table). Relative sea level rise is partly induced by vertical land movements not related to anthropogenic climate forcing, but its influence has been decreasing over time. A detailed study in *Kivalina* indicates that sea ice retreat may be a critical climate-related driver: while there is no significant trend in the timing of the first day of the open-water season, the autumn freeze-up has been delayed by 4.7 d per decade 1979–2015 (>2 weeks over the entire observation period). Each high-damage storm event occurred during the open water season for that year.	Smith and Sattineni (2016), Fang et al. (2017a) (Kivalina), Albert et al. (2018)		
	Herschel Island, Yukon Territory, Canada: There is no explicit attribution of erosion to individual drivers. In the absence of other known drivers, sea level rise, higher waves through a lengthened open water season, and permafrost thaw through warmer coastal surface waters are plausible drivers of erosion linked to climate change.	Radosavljevic et al. (2016)		
	Land loss, Louisiana: The loss of coastal wetlands in Louisiana is due to relative sea level rise, including local, regional and global factors such as global mean sea level rise, subsidence, oil and gas extraction, or altered hydrology.	Couvillion et al. (2017)		
Small Islands	**Observations:** The base of the beach predominantly exhibited retreat in a high mountain tropical island (Tubuai, French Polynesia) over 1982–2014. The coastline of Ouani experienced degradation and retreat in recent decades (Anjouan, Comores).	Salmon et al. (2019), Ratter et al. (2016)		
	Solomon Islands: Loss of five vegetated reef islands (1–5 ha in size) by permanent inundation, further six islands subject to severe shoreline recession leading to destruction of two villages that have existed since at least 1935 and associated community relocations at two sites. *Fiji:* Vunidogoloa village relocated in early 2014 to reduce their vulnerability to encroaching sea level and inundation events that regularly devastated the community.	Albert et al. (2016), McNamara and Jacot Des Combes (2015)		
	TC Maria 2017: Significant disturbance across 50% of Puerto Rico. In the 6 months after the event, 1000–3000 excess deaths in Puerto Rico. Mortality was higher in lowest-developed municipalities. Considered as the worst natural disaster on record in Dominica and Puerto Rico; large impact on the vegetation of these islands. *TC Irma 2017:* Most powerful hurricane that struck the northern Caribbean over the last 100 years. In Saint Martin Island, approximately 80% of the mangrove area was damaged by the hurricane.	de Beurs et al. (2019) (TC Maria), Hu and Smith (2018) (TC Maria), Walcker et al. (2019) Santos-Burgoa et al.) (TC Irma)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: The observed damages in Solomon Islands and Fiji are driven by relative sea level rise. In the Solomon Islands, this can be traced back to anthropogenic climate forcing as the influence of non-climate driven vertical land movement is minor and absolute sea level rise in the Indo Pacific is majorly induced by anthropogenic climate change (see 'S08a Coastal systems – Mean seal level rise' of Table SM16.21*). Fiji:* For the observed damages in Fiji, there is no assessment of the potential local contributions of non-climate-driven vertical land movement.	Albert et al. (2016), McNamara and Jacot Des Combes (2015)	Strong contribution of relative sea level rise to observed damages on Fiji and combined with wave dynamics on Solomon Islands, contribution of increased rainfall to damages induced by TC Irma and Maria, 2017, *medium confidence* (**) In the Solomon Islands, relative sea level rise is dominated by anthropogenic climate forcing (*medium confidence*) No assessment elsewhere.	
	TC Irma and Maria: Climate change is estimated to have increased the amount of rainfall associated with hurricanes Irma and Maria by 6% and 9%, respectively (see 'climate attribution: Heavy rainfall', Table SM16.21). There is no process-based simulation translating the additional amount of rainfall into the additional area flooded and associated damages, but assuming that higher rainfall is increasing the damage, anthropogenic climate has contributed to the observed damage induced by both hurricanes.	Clarke et al. (2021)		
S31	Other societal impacts—Macroeconomic output			
Global	**Observations:** Over the period 1980–2010, global annual GDP growth was 0.255 percentage points on average.	World Development Indicator database of the World bank (Nominal GDP per cap in constant 2011 USD), Diffenbaugh and Burke (2019)		
	Attribution: Climate change (increasing temperatures) has lowered global annual GDP growth by 0.002 percentage points on average. Median losses exceed 25% (relative to a world without anthropogenic forcing) over large swaths of the tropics and subtropics. Median gains can be at least as large in the high latitudes.	Carleton and Hsiang (2016), Diffenbaugh and Burke (2019)	Impacts range from a moderate increase in GDP (in high latitudes) to strong reduction (in subtropics and tropics) induced by climate change; *low confidence* (*) (studies are not independent but based on the same empirical relationship)	Estimates are based on an empirical relationship between annual national temperature fluctuations and production observed by Burke et al. (2015).
	Since 2000, warming has already cost both the USA and the EU at least USD 4 trillion in lost output, and tropical countries are >5% poorer than they would have been without this warming.	Burke and Tanutama (2019)		In contrast to Burke et al. (2015), estimates are derived from sub-national data. Study verifies the inverse U-shaped relationship between production and annual temperature fluctuations observed by Burke et al. (2019).
Africa	**Observations:** By the second half of the 1970s, the average pace of growth of African economies began to slow down, and by the 1980s even resulted in economic contraction.	Barrios et al. (2010)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: Rainfall had a significant effect on economic growth in Sub-Saharan Africa (SSA). If rainfall in SSA had remained at its high 1955–1960 level or at its lower average levels across 1901–1959, the gap in GDP per capita between SSA and non-SSA developing countries would have been about 40% or 15% less than what was observed in in actuality at the end of the 19th century (1997).	Barrios et al. (2010)	Decline in long-term rainfall trends caused a strong reduction of GDP growth in SSA countries; *low confidence* (*) (hypothesis needs support by independent studies)	Agriculture and hydro-energy supply are considered the main channels through which rainfall is likely to have reduced GDP growth in SSA countries.
Asia	**Observations**			
	Attribution:		No assessment.	
Australasia	**Observations**			
	Attribution:		No assessment.	
Central and South America	**Observations:**			
	Attribution: No studies.		No assessment	
Europe	**Observations:**			
	Attribution: No studies.		No assessment	
North America	**Observations:**			
	Attribution: No studies.		No assessment	
Small Islands	**Observations:**			
	Attribution: No studies.		No assessment	
S31	Other societal impacts—Between-country inequality			
Global	**Observations:** Globally between-country inequality has decreased over the past half century (1961–2010). The ratio between the population-weighted 90th percentile and the 10th percentile country-level per capita GDP ('90:10') decreased from about 150 to 50 within this period.			
	Attribution: Based on the inverse U-shaped relationship between national annual temperature fluctuations and GDP, it is estimated that anthropogenic climate change has slowed down the observed reduction of inequality. Global economic inequality (measured by '90:10' ratio) is estimated to be about 25% larger than in a counterfactual scenario without anthropogenic forcing. Without calculating its long-term effect, independent studies support an inverse U-shape relationship between GDP growth and annual temperature fluctuations derived from historical data. The relationship implies that warming increases GDP growth in countries whose long-term average temperature lies below critical threshold temperature, while warming decreases GDP growth above this threshold. Such a relationship would have increased inequality between developed and developing countries since in most developed (developing) countries annual mean temperatures are below (above) the threshold.	Diffenbaugh and Burke (2019) (estimation of impact of long-term historical temperature rise), Pretis et al. (2018), Kalkuhl and Wenz (2020) (sensitivity of annual national GDP growth on temperature variations)	Strong increase of between countries inequality induced by climate change, *low confidence* (*)	Dependence of GDP growth and annual temperature has been found to have followed an inverse U-shape with growth rate increases and decreases below and above a critical threshold temperature (see 'Other societal verarching impacts—Macroeconomic outputSensitivity of economic growth to variations in weather conditions', Table SM16.23).
Africa	**Observations:** Until the early 1970s, there was little difference between the growth performance of African and other developing countries. By the second half of the 1970s, however, the average pace of growth of African economies began to slow down and by the 1980s even resulted in economic contraction.	Barrios et al. (2010)		

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: Rainfall had a significant effect on economic growth in Sub-Saharan Africa in contrast to the group of other developing countries. If rainfall in SSA had remained at its high 1955–1960 level (or at its lower average levels across 1901–1959), the gap in GDP per capita between SSA and non-SSA developing countries would have been about 40% (or 15% less) than what was observed in in actuality at the end of the 19th century (1997).	Barrios et al. (2010)	Decline in long-term rainfall trends in SSA caused a strong increase of inequality between SSA countries and other developing countries *low confidence* (*) (hypothesis needs support by independent studies)	Agriculture and hydro-energy supply are considered the main channels through which rainfall is likely to have reduced GDP growth in SSA countries.
Asia:	**Observations:** **Attribution:** No studies.		No assessment	
Australasia	**Observations:** **Attribution:** No studies.		No assessment	
Central and South America	**Observations:** **Attribution:** No studies.		No assessment	
Europe	**Observations:** **Attribution:** no studies		No assessment	
North America	**Observations:** **Attribution:** No studies.		No assessment	
Small Islands	**Observations:** **Attribution:**		No assessment	
S30	Other societal impacts—Within-country inequality			
Global	**Observations:** **Attribution:** No studies.		No assessment	
Africa	**Observations:** **Attribution:**		No assessment	
Asia	**Observations:** **Attribution:**		No assessment	
Central and South America	**Observations:** **Attribution:**		No assessment	
Europe	**Observations:** **Attribution:**		No assessment	
North America	**Observations:** **Attribution:**		No assessment	
Small Islands	**Observations:** **Attribution:**		No assessment	
S26	Other societal impacts—Social conflict			
Global	**Observations:** **Attribution:**		No assessment on global scale	

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
Africa	**Observations:**			
	Attribution: Long-term local temperature growth is associated with increased prevalence of conflict events across Africa, 2003–2017. Effect is nonlinear with declining conflict likelihood at high end of temperature change.	van Weezel (2020)	Moderate increase and decrease (nonlinear response) in occurrence of armed conflict events induced by temperature rise, *low confidence* (*) (inconclusive evidence, limited number of independent studies)	High temperature (warming)
Asia	**Observation:** Persistent armed conflicts in Western and Central Asia over recent decades; a notable decline in conflict occurrence in East Asia since the 1970s. *Middle East:* Civil unrest across most countries in the Middle East and North Africa region during the winter of 2010–2011. In Syria, protest events and armed response by state security forces in March 2011 gradually escalated into a state of civil war. Outbreak of civil war in Syria in 2011 as part of the 'Arab Spring' uprisings.	Gleditsch et al. (2002), Pettersson and Öberg (2020) (UCDP data set)		
	Attribution: *Middle East:* The civil war was preceded by a long, severe drought in the north of the country which was amplified by anthropogenic global warming (see section on 'increase in drought conditions' in the climate attribution part of this table); this led to unusually large rural-to-urban migration. The role of climate-driven migration in accentuating social grievances and sparking initial protest is disputed and poorly documented (see separate case study of the Syrian civil war in the main text).	Gleick (2014), Kelley et al. (2015), Kelley et al. (2017), Werrell et al. (2015), Selby (2019), Selby et al. (2017), Ide (2018), Ash and Obradovich (2020), Eklund and Thompson (2017)	Minor contribution of climate change to occurrence of civil war in Syria, *low confidence* (*, *low agreement*); no assessments elsewhere in the modern era	
Australasia	**Observations:**			
	Attribution:		No study of climate change impact on armed conflict in the modern era	
Central and South America	**Observations:**			
	Attribution:		No study of climate change impact on armed conflict in the modern era	
Europe	**Observations:** International fisheries conflict increased between 1974 and 2016. The geographical point of gravity of these conflicts has shifted from Europe and North America to Asia. Climate change is affecting the distribution and potential yield of marine species through altered water temperatures, ocean currents and coastal upwelling patterns.	Spijkers et al. (2019), Jones and Cheung (2018), Pinsky et al. (2018)		
	Attribution: The range of the northeast Atlantic mackerel has shifted markedly in recent years, resulting in a spatial mismatch between the areas for which multi-lateral stock management policies existed, and the actual fishing grounds, which ensued ongoing dispute between the countries involved. The contributions of climate variability and climate change to the range shift are not yet understood.	Spijkers and Boonstra (2017), Gänsbauer et al. (2016)	Moderate contribution of climate change to occurrence of fishing disputes, *low confidence* (*)	Ocean warming
North America	**Observations:**			
	Attribution:		No study of climate change impact on armed conflict in the modern era	
Small Islands	**Observations:**			
	Attribution:		No study of climate change impact on armed conflict in the modern era	
S29	Other societal impacts—Displacement and migration			
Global	**Observations:**			

Attribution of observed changes in natural, human or managed systems to long-term changes in climate-related systems ('Impact Attribution')				
Region	**Observed change in natural, human and managed system + attribution to long-term changes in climate-related systems**	**Reference**	**Synthesis statement: direction (and strength) of impact induced by changes in climate-related systems, level of confidence**	**Underlying mechanism**
	Attribution: There is no attribution of changes in displacement and migration to climate change but only a 'detection of weather sensitivity' (see part 3 of this table).		No assessment	
Asia	**Observations:**			
	Attribution:		No assessment	
North America	**Observations:** From 184, Alaska Native communities generally affected, 31 face imminent threats from flooding and erosion and three of them (Shishmaref, Newtok and Kivalina) are forced to relocate. Shishmaref experienced 10 flooding events between 1973 and 2013, 7 of them declared state emergencies and 3 federal emergencies. Since 1969, Sarichef, the island where Shishmaref is located, has lost about 60 m of land (AECOM Technical Services 2016). Erosion has undermined buildings and infrastructure, causing several structures to collapse into the sea. As protection measures have turned out to be ineffective, the community has voted for relocation in 2002, 2007 and 2016, which, however, has not been realised so far.	Smith and Sattineni (2016), Albert et al. (2018)		
	Within Louisiana's coastal parishes, only a small part of the population moved landward since 1940 compared with seaward population movements in the same period.	Hauer et al. (2019)		
	Attribution: *Alaska:* Relative sea level rise, permafrost thawing and loss of coastal protection against storms due to sea ice loss are considered possible drivers of the observed erosion. Permafrost thawing and sea ice retreat are mainly driven by anthropogenic climate forcing (see 'permafrost' and 'sea ice' section in Table SM16.21). Relative sea level rise is partly induced by vertical land movement not related to anthropogenic climate forcing, but its influence has been decreasing over time. A detailed study in *Kivalina* indicates that sea ice retreat may be a critical climate-related driver: while there is no significant trend in the timing of the first day of the open-water season, the autumn freeze-up has been delayed by 4.7 d per decade 1979–2015 (>2 weeks over the entire observation period). Each high-damage storm event occurred during the open water season for that year.	Smith and Sattineni (2016), Fang et al. (2017a) (Kivalina), Albert et al. (2018)	Minor impact of relative sea level rise on population distribution in Louisiana, *low confidence* (*), to strong impact of observed relative sea level rise, permafrost thawing and sea ice retreat on decision for relocation, *medium confidence* (**) Relative sea level rise is partly induced by subsidence from glacial isostatic adjustment, but its influence is decreasing over time such that an increasing fraction is related to sea level contributors driven by anthropogenic climate change (See Section 'S08b Coastal systems – Mean sea level rise' of Table SM16.21) Changes in sea ice retreat and permafrost thawing are dominated by anthropogenic climate forcing (see part 1 of this table) No assessment elsewhere	
	Louisiana: The lack of landward population movement within coastal parishes suggests that observed shoreline encroachment since 1940 due to relative sea level rise does not translate into a movement of the population yet.	Hauer et al. (2019)		
Small Islands	**Observations:** *Solomon Islands:* Shoreline recession at two sites has destroyed villages that have existed since at least 1935, leading to community relocation. *Fiji:* Vunidogoloa village relocated in early 2014 to reduce their vulnerability to encroaching sea level and inundation events that regularly devastated the community. *Micronesia:* Reef-edge islands around Pohnpei have disappeared within living memory or drastically reduced in size in the past decade.	Albert et al. (2018), Albert et al. (2016), McNamara and Jacot Des Combes (2015), Nunn et al. (2017)		
	Attribution: The observed displacement in Solomon Islands and Fiji is driven by relative sea level rise. In the Solomon Islands, this can be traced back to anthropogenic climate forcing as the influence of non-climate driven vertical land movement is minor and absolute sea level rise in the Indo Pacific is majorly induced by anthropogenic climate change (See Section 'S08b Coastal systems – Mean sea level rise' of Table SM16.21). Fiji: For the observed displacement in Fiji, there is no assessment of the potential local contributions of non-climate-driven vertical land movement. *Micronesia:* Reef-edge island erosion around Pohnpei over the last few decades can mostly be explained by recent sea level rise.	Albert et al. (2016), McNamara and Jacot Des Combes (2015), Nunn et al. (2017)	Strong contribution of relative sea level rise to observed displacement on Fiji and combined with wave dynamics on Solomon Islands, *medium confidence* (**) In the Solomon Islands, this is dominated by anthropogenic climate forcing (*medium confidence*) No assessment elsewhere	

SM16.7.3 Details of Studies on Sensitivity of Natural, Human and Managed Systems to Climate

Table SM16.23 | Attribution of variations and disturbances in natural, human, and managed systems to fluctuations or extremes in the climate-related systems (blue symbols in Figure 16.2) Assessment statements relate to 'identification of weather-sensitivity' i.e. the identification and quantification of the contribution of short-term fluctuations and extremes in the climate-related systems to the observed fluctuations in the natural, human, and managed systems. The titles of the blue symbols in Figure 16.2 and associated numbers can be found here as titles of associated sections. Each section provides the background information (references and associated evidence) behind the ratings in the Figure (strength of influence and level of confidence). The summary statements in the orange cells of the table are displayed in Figure 16.2.

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
S16	Water distribution—Reductions in water availability + induced damages and fatalities			
Global	**Observations:**			
	Attribution: EM-DAT attributes $247.8 billion (2010 USD) in direct economic damages and 2.2 million fatalities to droughts between 1960 and 2020. Droughts cause ~60% of all fatalities from all meteorological, climatological and hydrological hazards, making them the deadliest category of weather-related disasters in the database. On the other hand, only about 7% of global direct damages induced by all meteorological, climatological and hydrological disasters are due to droughts.	CRED and Guda-Sapir (2021)	High sensitivity, *medium confidence* (**) We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of droughts on, e.g., wildfires, conflict, displacement and migration, crop yields and malnutrition are addressed in other individual sections.	Our assessment largely builds on direct economic losses and fatalities reported in 'The International Disaster Database' (EM-DAT; CRED and Guda-Sapir, 2021). The damages considered here refer to the amount of damage to property, crops and livestock. For each disaster, the registered figure corresponds to the direct damage value at the moment of the event and does not include damages that unfold over following years. The database is made up of information from various sources, including UN agencies, non-governmental organisations, insurance companies, research institutes and press agencies, with priority given to data from UN agencies, governments and the International Federation of Red Cross and Red Crescent Societies. The entries are constantly reviewed for inconsistencies, redundancy and incompleteness. However, there may be differences in estimated damages across sources (see, e.g., estimated damages induced by the 2012 US drought in the North America section). We uniformly assume a '*medium confidence*' associated with the drought assessments based on EM-DAT assuming a more difficult assignment of damages and fatalities to droughts than to tropical cyclones.
	Globally, for the period 1981–2010, the utilisation rate of hydropower and thermoelectric power was reduced by 5.2% and 3.8% respectively, during drought years compared with the long-term average values.	Van Vliet et al. (2016)		
Africa	**Observations:**			
	Attribution: EM-DAT attributes $10.2 billion (2010 USD) in direct economic damages and ~697,000 fatalities to droughts between 1960 and 2020. According to the EM-DAT numbers, 95% of all deaths induced by meteorological, climatological and hydrological hazards (1960–2010) have been induced by droughts, a share far higher than for any other category. Even though the drought-induced economic damages, given in 2010 USD, are lower than in any other region, they still make up 27% of all damages due to meteorological, climatological and hydrological extreme events.	CRED and Guda-Sapir (2021)	High sensitivity, *medium confidence* (**) We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of droughts on, e.g., wildfires, conflict, displacement and migration, crop yields and malnutrition are addressed in other individual sections.	See discussion of EM-DAT data in the global section.
Asia	**Observations:**			

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
	Attribution: EM-DAT attributes $27.3 billion (2010 USD) in direct economic damages and 1.5 million fatalities to droughts between 1960 and 2020. More than half (56%) of all fatalities induced by weather-related extreme events in Asia stem from drought, while drought-induced economic damages have a share of about 6% of overall damages from weather-related disasters in the region.	CRED and Guda-Sapir (2021)	High sensitivity, *medium confidence* (**) We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of droughts on, e.g., wildfires, conflict, displacement and migration, crop yields and malnutrition are addressed in other individual sections.	See discussion of EM-DAT data in the global section.
Australasia	**Observations:**			
	Attribution: EM-DAT attributes $27 billion (2010 USD) in direct economic damages and 600 fatalities to droughts between 1960 and 2020. 28% of all fatalities induced by weather related extreme events in Australasia (1960–2010) stem from droughts. In terms of damages, however, droughts have the highest share compared to the other world regions: Drought damages in Australasia make up 30% of all damages induced by weather-related disasters in the region (1960–2010).	CRED and Guda-Sapir (2021)	High sensitivity, *medium confidence* (**) We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of wildfires, droughts on, e.g., conflict, displacement and migration, crop yields and malnutrition are addressed in other individual sections.	See discussion of EM-DAT data in the global section.
Central and South America	**Observations:** *São Paulo water crisis in 2015:* In January 2015, the metropolitan region of São Paulo, the largest megacity in South America, experienced a severe water shortage, with main reservoirs reaching storage levels of only 5% of their capacity. To reduce leakages from the pipes, amounting to 30–40% of the water, SABESP reduced the water pressure, which left millions 'for hours and even days' without water.	Otto et al. (2015a), Nobre et al. (2016)		
	Brazil, 2016: Três Marias, Sobradinho and Itaparica reservoirs reached 5% of volume capacity. In Ceará, 39 (of 153) reservoirs were registered as empty, while another 42 reached inactive volume, and 96 (of 184) Ceará municipalities experienced water supply interruption.	Chapter 4, Section 4.2.5, Table 4.4		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: EM-DAT attributes $31.5 billion (2010 USD) in direct economic damages and 85 fatalities to droughts between 1960 and 2020. The number of fatalities represents a share of 0.7‰ of all fatalities from all meteorological, climatological and hydrological hazards. Of all damages induced by weather-related disasters in the region, 18% were due to drought.	CRED and Guda-Sapir (2021)	Individual droughts can have severe consequences However, measured in terms of economic damages and fatalities, the influence of weather extremes on water availability is relatively small compared with the impact of weather extremes through infrastructure destruction and injuries as, e.g., induced by flooding or tropical cyclones and mortality induced by heat Therefore, the sensitivity is rated moderate, *medium confidence* (**) here. We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of droughts on, e.g., wildfires, conflict, displacement and migration, crop yields and malnutrition are addressed in other individual sections.	See discussion of EM-DAT data in the global section.
	Drought in the Brazilian Pantanal, 2019–2020: Due to the prolonged drought, river levels reached extremely low values and transportation had to be restricted in some parts of the river. Low water levels affect mobility of people and shipping of soybeans and minerals to the Atlantic Ocean by the Paraná–Paraguay Waterway, inducing considerable economic losses.	Marengo et al. (2021)		
	São Paulo water crisis in 2015: Since the austral summer of 2014, southeastern Brazil has been experiencing one of the most severe droughts in decades. The water crisis can be partly explained by the drought but is also partly induced by growing water demand of an increasing population. There is no evidence that the drought conditions have become more prevalent as a result of anthropogenic climate forcing. However, water use may have increased not only because of population growth but also because of the warm summer. Currently, there are no model simulations comparing the influences of the different drivers.	Otto et al. (2015a), Nobre et al. (2016)		
	Water crisis, Brazil 2016: The severe water restrictions have been introduced by drought conditions that have, however, not been attributed to anthropogenic climate forcing.	Chapter 4, Section 4.2.5, Table 4.4		
Europe:	**Observations:**			
	Attribution: EM-DAT attributes $41.6 billion (2010 USD) in direct economic damages and two fatalities to droughts between 1960 and 2020. Lowest number of fatalities due to drought compared with other world regions. In terms of damages, the share remains below 10% (9%) of the total damages induced by all weather-related extreme events.	CRED and Guda-Sapir (2021)	Individual droughts can induce widespread overall losses However, measured in terms of economic damages and fatalities, the influence of weather extremes on water availability is relatively small compared with the impact of weather extremes through infrastructure destruction as, e.g., induced by flooding or mortality induced by heat. Therefore, the sensitivity is rated moderate, *medium confidence* (**) here. We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of droughts on, e.g., wildfires, conflict, displacement and migration, crop yields and malnutrition are addressed in other individual sections.	See discussion of EM-DAT data in the global section.
	UK: On extreme high-temperature days (~3 d in a year), almost 50% of freshwater thermal capacity is lost, causing losses in the range of average GBP 29–66 million yr^{-1}, and in case of ~20% of particularly vulnerable power plants, these losses could go up to GBP 66–95 million yr^{-1} annualised over a 30-year period.	Byers et al. (2020)		
	The costs of agricultural droughts in Italy 2003 are estimated to be 1.75 billion Euros (–0.1% of the GDP), 0.92 billion Euros (–0.05% GDP) in 2006 and 0.56 billion Euros (–0.03% of the GDP) in 2011.	García-León et al. (2021)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
North America	**Observations:**			
	Attribution: EM-DAT attributes $ 64.6 billion (2010 USD) in direct economic damages and 45 fatalities to droughts between 1960 and 2020. In North America, 45 fatalities due to drought were reported (1960–2020). This amounts to a low share of 2‰. Also, in terms of damages, droughts are on the lower end for the North American continent, amounting to 5% of all damages.	CRED and Guda-Sapir (2021)	Individual droughts can induce widespread overall losses However, measured in terms of economic damages and fatalities, the influence of weather extremes on water availability is relatively small compared with the impact of weather extremes by infrastructure destruction as, e.g., induced by flooding and tropical cyclones or mortality induced by heat, respectively. Therefore, the sensitivity is rated moderate, *medium confidence* (**) here. We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of droughts on, e.g., wildfires, conflict, displacement and migration, crop yields and malnutrition are addressed in other individual sections.	See discussion of EM-DAT data in the global section.
	In the USA, social costs of water scarcity between 2001 and 2012 were estimated to be USD 330,000 (at 2015 value) per month for every power plant that experienced water scarcity.	Eyer and Wichman (2018)		
	The US drought of 2012 was a multi-billion-dollar disaster. National Centers for Environmental Information (NCEI) estimate for the 2012 drought indicate that losses, largely agricultural, topped $30 billion.	Rippey (2015)		
Small Islands	**Observations:** *Marshall Islands:* In 2013, 11,000 inhabitants of the Marshall Islands suffered from water shortages. In 2016, strict water rationing had to be applied.	Barkey and Bailey (2017)		
	St. Lucia, 2010: In St. Lucia, 80% of the population had to cope with limited water supply.	Cashman (2014)		
	Attribution: EM-DAT attributes $554.6 million (2010 USD) in direct economic damages and 84 fatalities to droughts between 1960 and 2020. With 84 out of a total of ~25,000 reported fatalities (0.3%) induced by weather-related disasters, droughts are not the most dangerous threat to the inhabitants of small islands. Similarly, droughts contribute 0.4% to damages from all meteorological, climatological and hydrological hazards, the lowest number in all regions.	CRED and Guda-Sapir (2021)	Individual droughts can induce widespread overall losses However, measured in terms of associated economic damages and fatalities, the influence of weather extremes on water availability is relatively small compared with the impact of weather extremes through infrastructure destruction and injuries as, e.g., induced by flooding and tropical cyclones or mortality induced by heat, respectively. Therefore, the sensitivity is rated moderate, *medium confidence* (**) here. We explicitly note that this rating is focused on specific immediate damages induced by droughts, while other impacts of droughts on, e.g., conflict, displacement and migration, crop yields, malnutrition are addressed in other individual sections.	See discussion of EM-DAT data in the global section.
	Water rationing Marshall Islands: The water shortage in 2013 and the 2016 water rationing were induced in response to droughts. The 2016 drought was one of the strongest droughts on record. The rationing has become necessary as rainwater in rooftop catchment systems was depleted and groundwater wells were brackish.	Barkey and Bailey (2017)		
	St. Lucia: The constraints on water availability were induced by Hurricane Tomás, which caused a landslide that damaged electricity supply and pumping facilities.	Cashman (2014)		

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
S18	Food system—Crop yields			
Global	**Observations:**			
	Attribution: *General impact of weather fluctuations:* In many of the main producing countries, there is a clear signal of weather fluctuations in reported national fluctuation of maize, wheat, rice and soy yields demonstrated. However, explained variances vary from country to country reaching more than 50% in some important production countries. Missing explanatory power may be due to reporting errors, management changes, effects of diseases or pests that may be dominant in some countries. Even on sub-national level, weather fluctuations explain approximately one-third of yield variability on average with higher contribution in substantial areas of the global breadbaskets (>60%). Simple climate indicators (precipitation, maximum and minimum daily temperature averaged over the growing season) can explain about one-third and more of global annual fluctuations of wheat (41%), rice (29%), maize (47%), soy (52%), barley (65%) and sorghum (29%) yields over 1961–2002.	Müller et al. (2017) (wheat, rice, maize, soy, national); Frieler et al. (2017) (wheat, rice, maize, soy, national); Ray et al. (2015) (wheat, rice, maize, soy, sub-national, 1979–2008) Lobell and Field (2007) (global, wheat, rice, maize, soybeans, barley and sorghum, 1961–2002)	Contributions of weather fluctuations to observed fluctuations in crop yields range from strong (e.g., maize in Australia), *high confidence* (***), to minor in other regions and of other crops, *low confidence* (*). Sensitivity to heat often depends on water availability and can partly be reduced by irrigation.	Variations seem to be largely driven by water availability (Frieler et al., 2017).
	Impacts of weather extremes: Across 1964–2007, heatwaves and droughts have significantly reduced annual national cereal yields (7.6% and 5.1%, respectively). Drought-induced reductions of cereal yields were highest in the more technically developed agricultural systems of North America, Europe and Australasia (~16%, significant) and insignificant reductions (< 5%) in Asia, Africa, and Latin America + Caribbean. *Maize:* Significant annual national yield reductions by extreme heat (~12%) and drought (~3%). Global-average drought-induced yield loss estimated from gridded data reaches 7% per drought (average deviation from long-term mean across all years with positive drought index, 1983–2009). *Wheat:* Insignificant reductions in annual national yields induced by droughts and extreme heat (1964–2007). Global-average drought-induced wheat yield loss estimated from gridded data reaches 8% per drought (average deviation from long-term mean across all years with positive drought index, 1983–2009). *Soy:* Global-average drought-induced yield loss estimated from gridded data reaches 7% per drought (average deviation from long-term mean across all years with positive drought index, 1983–2009). *Rice:* Global-average drought-induced yield loss estimated from gridded data reaches only 3% per drought probably due to widespread irrigation (average deviation from long-term mean across all years with positive drought index, 1983–2009).	Lesk et al. (2016), (national yield losses induced by drought and extreme heat, 1964–2007), Kim et al. (2019) (sub-national drought-induced yield losses, 1983–2009)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Interactions between heat and drought conditions: On global level, heat was shown to be more damaging in dry than in normal conditions for maize and wheat (1961–2014). Temperature effects were not significant in wet conditions for maize, soybeans and wheat. That observed damaging effects of heat unfold through effects on water deficits is supported by a range of earlier observational and modelling studies.	Matiu et al. (2017), Schlenker and Roberts (2009) (USA, observational data), Troy et al. (2015) (USA, observational data), Jägermeyr and Frieler (2018) (global, model simulations), Lobell et al. (2013) (USA, model simulations)		
	Model simulations only forced by observational weather data confirm the assumption that the observed yield losses are indeed induced by the underlying weather conditions. Extreme events such as droughts and heatwaves significantly contribute to yield variations, with 18–43% of the observed sub-national variations in maize, soy, rice and spring wheat explained by observed variations in extreme weather indicators. A combined indicator of heat and drought conditions can explain about 40% of the observed wheat yield variations (deviations from long-term mean, 1980–2010).	Jägermeyr and Frieler (2018) (national); Vogel et al. (2019) (sub-national), Zampieri et al. (2017) (wheat, 1980–2010)		Even under heatwave conditions, the losses appear to be primarily driven by water deficits (Lobell et al., 2013; Jägermeyr and Frieler, 2018; Schlenker and Roberts 2009, Schauberger et al., 2016).
Africa	**Observations:**			
	Attribution: *Maize:* In South Africa, more than 50% of the variance of national annual maize yields can be explained by observed weather fluctuations. High sensitivity of maize yields to droughts (in terms of correlation between drought indicator and yield variations) in particular in southeast Africa. *Rice:* Low sensitivity of rice yields to droughts. *Wheat:* Mostly low sensitivity of wheat yields to droughts except for Kenya. *Soy:* Mostly low sensitivity of soy yields to droughts except for South Africa.	Frieler et al. (2017) (maize, wheat, rice, soy, 1980–2010), Kim et al. (2019) (sub-national drought-induced yield losses)	Low (rice and wheat) to high (maize) contribution of weather fluctuations to reported crop yield fluctuations, *low confidence* (*)	
Asia	**Observations:**			
	Attribution: *Maize:* Mostly low sensitivity of maize yields to drought except for parts of Indonesia and northeast China (in terms of correlation between drought indicator and yields). A separate study of Liaoning Province in northeast China shows maize yield losses up to 25.8% when severe drought occurred in June–July. Under the 10 main producers, India shows the highest risk of maize yield reduction under droughts (~88% probability that maize production falls below its long-term average when experiencing an exceptional drought).	Kim et al. (2019) (sub-national correlation of yields to drought indicator, maize, rice, soy and wheat from 1983 to 2009), Leng and Hall (2019) (probability of below average yields under drought conditions, wheat, maize, rice and soybeans, 1961–2016); Frieler et al. (2017) (maize, wheat, rice, soy, 1980–2010), Chen et al. (2016) (drought effects on maize, rice, sorghum, soybean and millet in Liaoning Province, China, 1960–2015) Bhatt et al. (2014) (rice, maize, wheat, Nepal, 1967–2008)	Major contribution of weather fluctuations to annual fluctuation of rice yields, mostly low sensitivity elsewhere; regionally, the sensitivity to droughts shows an opposite pattern, with lower sensitivities of rice yields because of irrigation and higher sensitivities of other crops, *low confidence* (*)	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Wheat: Under the main producers globally, Syria and Iran are the Asian countries where a relatively large part of the variance of annual wheat yields could be explained by weather fluctuations (~35–50%). Mostly low sensitivity of wheat yields to droughts except for parts of Kazakhstan, Turkey, Iran and Syria. Under the 10 main producers globally, Russia shows a relatively high risk of wheat yield reduction under droughts (~75% probability that wheat production falls below its long-term average when experiencing an exceptional drought). In Nepal, Koshi River basin, a unit change in growing season maximum, minimum and mean temperatures is estimated to induce yield changes (compared with 2008 yields) of –5% to 10%, –5% to 2% and –4% to 11%, respectively, depending on the locations and elevations of the area.			
	Rice: In Japan and South Korea, more than 50% of the variance of annual national rice yields can be explained by observed weather fluctuations. Mostly low sensitivity of rice yields to droughts (e.g., in Liaoning Province, China) except Indochina (measured by correlation between drought index and yields in dry years). Among the 10 main producers, rice yields are most vulnerable to droughts in Vietnam and Thailand when measured as the probability of below long-term average yields under exceptional drought (86% and 76%, respectively). Climatic variations are estimated to have accounted for 40.04% and 29.72% of yield variability for early and late rice, respectively (1980–2012, southern China). In Nepal, Koshi River basin, a unit change in growing season maximum, minimum and mean temperatures is estimated to induce a yield changes (compared with 2008 yields) of –7% to 4%, –9% to 11% and –6% to 16%, respectively, depending on the locations and elevations of the area.	Liu et al. (2016b) (rice, southern China, 1980–2012)		
	Soy: Under the main producers, less than 20% of the variance of annual national soy yields in China and India can be explained by observed weather fluctuations. Mostly low sensitivity of soy yields to droughts except for in northeast China when measured by correlation between national yields and a drought index in dry years. However, under the 10 main producers, India and Russia belong to the five most vulnerable ones to drought when measured by the probability of below long-term average yields under exceptional drought conditions (75% and 80%, respectively). In Nepal, Koshi River basin, a unit change in growing season maximum, minimum and mean temperatures is estimated to induce yield changes (compared with 2008 yields) of –9% to 4%, –12% to 1% and –12% to 3%, respectively, depending on the locations and elevations of the area. Most consistent negative correlation compared with maize and rice.			

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
Australasia	**Observations:** *Wheat:* Australian wheat yield is highly variable from year to year across major production regions. For example, in New South Wales (NSW), annual wheat production ranged between 2477 and 10,488 kt across 2003–2013, where harvested area varied from 2995 to 4322 kha and yields from 0.62 to 2.75 t ha^{-1}.	Wang et al. (2015), ABARES (2021)		
	Attribution: *Maize:* Partly high sensitivity of maize yields to droughts in eastern Australia. *Wheat:* More than 50% of the variance of annual Australian wheat yields can be explained by observed weather fluctuations. In New South Wales, explained variance reaches 40%. High sensitivity of wheat yields to droughts in southeast Australia and southwest Australia. *Soy*: Low sensitivity of soy yields to droughts in Australia. *Rice:* Low sensitivity of rice yields to weather fluctuations in Australia.	Kim et al. (2019) (sub-national drought-induced yield losses), Frieler et al. (2017) Wang et al. (2015) (wheat in New South Wales)	Major contribution of weather fluctuations (in particular, variations in rainfall) to annual fluctuation of wheat yields, *high confidence* (***) Low sensitivity of reported rice and soy yields to weather fluctuations, *low confidence* (*)	
Central and South America	**Observations:**			
	Attribution: *Maize:* Mostly minor sensitivity of maize yields to droughts except for high sensitivity in the Pampas of South America. In this region, annual fluctuations of growing season average temperatures, diurnal temperature ranges, and growing season total precipitation can explain about 40% of the variance of maize yields reported for 33 counties (1971–2012). *Wheat:* Mostly minor sensitivity of wheat yields to droughts except for higher sensitivities found in some parts of the Pampas of South America (sub-region with significant drought-induced yield losses smaller than for maize). In the Pampas, annual fluctuations of growing season average temperatures, diurnal temperature ranges, and growing season total precipitation can explain about 30% of the variance of wheat yields reported for 33 counties (1971–2012). *Soy:* In Japan and South Korea, more than 50% of the variance of annual national soy yields can be explained by observed weather fluctuations. Mostly minor sensitivity of soy yields to droughts except for high sensitivities found in the Pampas of South America. In the Pampas, annual fluctuations of growing season average temperatures, diurnal temperature ranges, and growing season total precipitation can explain about 47% of the variance of soy yields reported for 33 counties (1971–2012). *Rice:* Mostly low sensitivity to droughts except for high sensitivities in some parts of northeast Brazil.	Kim et al. (2019) (sub-national drought induced yields losses), Frieler et al. (2017) Verón et al. (2015) (wheat, maize and soy yields at the county level in the Pampas region of Argentina, 1971–2012)	Major contribution of weather fluctuations to annual fluctuation of soy yields, *low confidence* (*) Minor sensitivity of reported wheat, maize and rice yields to weather fluctuations, *low confidence* (*)	

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems (‘Identification of weather sensitivity’)

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Europe	**Observations:**			
	Attribution: *Wheat:* In Spain, Hungary and Romania, more than 50% of the variance of annual national wheat yields can be explained by observed weather fluctuations. High sensitivity of wheat yields to droughts found in South and Eastern Europe; no sensitivities detected elsewhere. A separate spatial explicit analysis of wheat yields dependence on a combined drought + heat indicator in France shows that the index can explain about 25% of the observed yields variability, especially in the central-northern part where the main wheat-producing areas are located. A more detailed assessment of the sign of the scaling coefficient shows that wheat yield in Mediterranean France is more sensitive to drought, while the northern part is more sensitive to water excess. *Maize:* In Romania, France, Hungary, Germany and Italy, more than 50% of the variance of annual national maize yields can be explained by observed weather fluctuations. High sensitivity of maize yields to droughts found in Southern Europe; no detection of sensitivities elsewhere. *Rice:* No detection of sensitivity of rice yields to droughts. Soy: No detection of sensitivity of soy yields to droughts.	Kim et al. (2019) (sub-national drought induced yields losses), Frieler et al. (2017), Zampieri et al. (2017) (France, wheat, 1986–2014)	Major contribution of weather fluctuations to annual fluctuation of wheat and maize yields in some European countries, *moderate confidence* (**) Minor contributions in other regions and of soy and rice yields, *low confidence* (*)	
North America	**Observations:**			
	Attribution: *Wheat:* In Canada, more than 50% of the variance of annual national wheat yields can be explained by observed weather fluctuations. High sensitivity of wheat yields to droughts in the Great Plains of North America; low sensitivities found elsewhere. Observed national crop yields show that there is an 80% probability that wheat production falls below its long-term average when experiencing an exceptional drought, especially in the USA and Canada. Analysis of wheat variety field trial outcomes (Kansas, 1985–2013) shows highest sensitivities of wheat yields to freezing temperatures in autumn and extreme heat events in the spring (negative effects of exposure). *Maize:* In the USA, more than 50% of the variance of annual national maize yields can be explained by observed weather fluctuations. Effects of excessive rainfall on US maize yields has been shown to be comparable to the effects of droughts. High sensitivity of maize yields to droughts in the Great Plains of North America; low sensitivities found elsewhere. *Soy:* High sensitivity of soy yields to droughts in the Great Plains of North America; low sensitivities found elsewhere. Also, under the 10 main producers, the USA belongs to the three ones most vulnerable to droughts when measured by the probability of below long-term average yields under exceptional drought conditions (75%). *Rice:* No sensitivity of rice yields to droughts found in North America.	Kim et al. (2019) (sub-national drought-induced yield losses), Leng and Hall (2019) (probabilistic drought effects), Frieler et al. (2017), Li et al. (2019b) (effects of excessive precipitation on maize yields in the USA), Tack et al. (2015) (wheat, field trial data)	Major contribution of weather fluctuations to annual fluctuation of wheat and maize yields in Canada and the USA, respectively, *high confidence* (***) Minor sensitivity of rice yields in general and soy yields in specific regions, *low confidence* (*)	
Small Islands	**Observations:**			
	Attribution:		No assessment	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
S19	Food system—Food prices			
Global	**Observations:** International food prices spiked in 2007–2008 and 2010–2011, and domestic food prices increased substantially in most countries during these periods.	FAO et al. (2011)	*High confidence*	
	Attribution: Research on the identification of drivers of food price peaks in 2007/2008 and 2010/2011 is still debated. Different effects have been suggested as the main drivers for the recent price spikes. These include biofuel production and oil price, speculation and ethanol production, supply–demand dynamics in combination to trade policies, and export restrictions. Dependence on internal supply–demand dynamics in principle allows for weather conditions being responsible for the price peaks to the extent weather affects production. The pure effect of weather extremes on supply and associated price responses compared with a counterfactual 'regular' situation has not been estimated so far. However, given the explanatory power of the alternative drivers, the impact is estimated to be minor.	Headey (2011) (export restrictions), Schewe et al. (2017) (supply–demand dynamics), Lagi et al. (2015) (speculation and ethanol production), To and Grafton (2015) (biofuel production and oil price), Bren d'Amour et al. (2016) (teleconnected supply-shocks)	Minor influence of weather conditions on observed price peaks on the global market, *low confidence* (*) Minor sensitivity of domestic price levels to ENSO events, *medium confidence* (**) In some cases, the sensitivity of prices to ENSO may have been higher, but as there is *low confidence* in this finding, we decided for the above synthesis	
	Both extreme events, El Niño and La Niña, have been shown to increase international food price volatility of maize during spring–summer and autumn–winter seasons and, of soybean, during the spring–summer.	Peri (2017)	Moderate sensitivity of wheat, maize and soy price to ENSO events (soy price sensitivity is slightly lower), *low confidence* (*)	
	Statistically significant linkages between ENSO events in the Niño 3.4 region and agricultural commodity price levels have been revealed. For instance, the relationship with regard to wheat prices is nonlinear. Wheat prices increase (by up to 6%) after La Niña events, and decrease after El Niño events.	Ubilava (2018) (prices of agricultural commodities), Ubilava (2017) (wheat prices), Ubilava and Holt (2013)		
Africa	**Attribution:** *Developing countries in general:* During the recent period of food price spikes, external international grain prices have been found to only weakly influence the domestic price movements, when internal drivers are also considered. Domestic weather anomalies and variation in agricultural productions are identified as important driver for domestic price movements. Across all developing countries, 20% of markets are affected by domestic weather and only 9% of markets are affected by changes in international prices. *East Africa:* In Tanzania, two-thirds of local price variations come from domestic influences including weather but also harvest cycles and trade policies. In Uganda, variations in demand seem to have a stronger effect on food prices than supply shocks, but potentially weather-driven variations in production are estimated to have a stronger effect than the pass-through of international price.	Brown and Kshirsagar (2015) (developing countries), Baffes et al. (2019) (Tanzania), Mawejje (2016) (Uganda), Hill and Fuje (2020) (Ethiopia), Nsabimana and Habimana (2017) (Rwanda)	Moderate sensitivity of food prices to weather variations in East Africa, *medium confidence* (**) No assessment elsewhere	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Asia	**Observations:** *Russia:* Grain production in Russia was characterised by extreme weather events in 2010/2011 and 2012/2013, with grain production falling 30% below the average of the three preceding years in both years (even more than 60% below average in some regions). While in 2010/11 an export ban was implemented, trade stayed freely possible in 2012/2013. In addition, in 2007/2008, export restrictions were implemented in response to raising global grain prices without Russia being explicitly affected by production shortages (wheat production 7% higher than in the average across the three preceding years). Domestic (and global) wheat prices rose in all three cases but stayed lowest in 2010/2011 compared with 2012/2013 (highest level) and 2007/2008.	Götz et al. (2016) (Russia)		
	Malaysia: Food prices have been increasing steadily over the recent years (2010–2017).	Wong et al. (2019) (Malaysia)		
	Attribution: *Russia:* A comparison of the three situations allowed estimation of the impact of weather-induced production shortages on domestic prices and the role of export restrictions in dampening associated price peaks induced by supply shortages and/or global grain prices. The analysis indicates an influence of domestic supply shortages on domestic prices that are not only following global prices and a strong dampening of this effect by export restrictions.	Götz et al. (2016) (Russia)	Moderate sensitivity of domestic prices to extreme weather condition, *low confidence* (*), *limited evidence* No assessment elsewhere	
	Malaysia: Further, when La Niña and El Niño events occur in a given year, crude palm oil production decreases by 3.37%, and palm oil stock level decreases by 2.5%, leading to an increase in crude palm oil price by 10.2%.	Rahman et al. (2013)		
Australasia	**Observations:**			
	Attribution: No dedicated studies.		No assessment	
Central and South America	**Observations:**			
	Attribution: Weather has been shown to have affected the Colombian consumer food inflation growth (i.e., an increase in the food price index) during *El Niño*. On the contrary, there are reductions in the inflation in the *La Niña* phase.	Abril-Salcedo et al. (2016), Abril-Salcedo et al. (2020)	Moderate sensitivity of ENSO on food prices in Colombia, *low confidence* (*), no assessment elsewhere	
Europe	**Observations:** *Ukraine:* The Ukraine implemented direct or indirect export restrictions during all three recent peaks of global wheat prices (2007/2008, 2010/2011 and 2012/2013), and domestic grain production was about 20% lower than 2005–2013 average in all three years 2007, 2010 and 2012.	Götz et al. (2016) (Ukraine)		
	Attribution: *Ukraine:* As in contrast to the Russian situation (see above) there was no period of domestic supply shortages but no trade restriction, the impacts of supply shortages on domestic prices could not be quantified separately.	Götz et al. (2016) (Ukraine)	No assessment	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
North America	**Observations:** No dedicated studies. **Attribution:**		No assessment	
Small Islands	**Observations:** No dedicated studies. **Attribution:**		No assessment	
S25	Terrestrial ecosystems—Burned areas Note: This is exclusively about the sensitivity of **burned areas** to weather fluctuations.			
Global	**Observations:** Strong year-to-year fluctuations in areas burned by wildfires by orders of magnitude.	Jolly et al. (2015) (global)		
	Attribution: In forested lands, fluctuation in purely weather-based measures of fuel aridity can explain large amounts of variations in annual burned areas, with weaker correlations in drier regions. By contrast, in non-forested regions, cumulative precipitation antecedent to the fire season shows positive correlations with annual burned areas. Here, correlations are stronger in drier regions. Overall, climate variability explains about one-third of the inter-annual variability in burned areas. Spatial analysis of monthly burned areas shows highly significant decreases in burnt area with soil moisture, increases with dry days and maximum temperature while controlling for spatial variations in NPP, diurnal temperature range, grazing land, grass/shrub cover, cropland area and human population.	Abatzoglou et al. (2018), Bistinas et al. (2014) (spatial analysis of monthly burned areas from 2000 to 2005)	Mostly strong to moderate sensitivity of burned areas to weather fluctuations, *medium confidence* (**)	
	A spatial empirical analysis of gridded satellite products of the fractional area burned per year and monthly burned areas indicates that increasing population density (comparison across grid cells not time) mainly reduces burned areas.	Knorr et al. (2014) (annual data), Bistinas et al. (2014) (monthly data)		
Africa	**Attribution:** Seasonally anomalous weather had a statistically demonstrable impact on fire probability, with warmer/drier seasons showing higher fire probability. The state of the Antarctic Ocean Oscillation (AAO) is an important large-scale influence linked to global circulation. Fire probability increases when AAO is in positive phases. However, accumulated precipitation ending 14 months prior to the fire season, 12-month accumulated precipitation ending 2 months prior to the fire season, a Fire Weather Index, and climatic water deficit over the fire season individually only explain relatively small fractions of the annual variation in burned area.	Abatzoglou et al. (2018)	Mostly minor to moderate sensitivity of observed area burned to weather fluctuations, *low confidence* (*)	Anomalously dry and warm weather enhances vegetation dryness, flammability and wildfire risk.
	In arid regions of southern Africa, large fires typically followed La Niña periods (e.g., 2011 and 2012), when increased rainfall and productivity increase fuel connectivity. Significant reductions in burned areas in southern Africa during El Niño years compared with La Niña year but relatively small effect when normalised by all year mean differences (1997–2016).	Andela et al. (2019), Chen et al. (2017)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Asia	**Attribution:** Within-season weather-based fuel-aridity measures and annual precipitation prior to the fire season can independently explain 30% to more than 50% of the observed variance in burned forest areas in maritime Southeast Asia. Similar levels are reached by within-season weather-based fuel-aridity measures in forested North Asia. *Siberian Larch forests:* Inter-annual variations in burned areas (1996–2015) are moderately to highly correlated with variations in drought intensity measured by the Standardized Precipitation Evapotranspiration Index, (SPEI, $r = -0.4$) and temperatures ($r = 0.5$ for the entire fire season to 0.7 in June–July). Results are supported by similar studies summarised in the review paper. Starting from an El Niño phase in the Pacific Ocean, atmospheric blocking in summer 2019 led to highest recorded temperatures and low precipitation over Siberia, and causing burned area 4× above the 2001–2019 average burned area.	Ponomarev et al. (2016), Abatzoglou et al. (2018) (Siberian Larch forests), Kharuk et al. (2021) (Siberia, review), Bondur et al. (2020) (2019 wildfire in Siberia)	Strong sensitivity of burned areas to weather fluctuations in parts of Asia, *medium confidence* (**) No assessment elsewhere	
Australasia	**Attribution:** High correlations between fire season fuel-aridity measures and burned forest areas in southeastern Australia on ecoregion level; depending on the measure, explained variance can reach more than 50%. Forests in the Australian Alps in Southeastern Australia may be subject to positive feedback of fire, i.e., post-fire stands are more likely to burn than mature stands.	Abatzoglou et al. (2018), van Oldenborgh et al. (2021), Zylstra (2018)	Strong sensitivity of burned areas to weather fluctuations in Southeastern Australia, *medium confidence* (**), mostly strong sensitivity in other regions, too; *low confidence* (*)	
Central and South America	**Observations:** In January and February 2017, over 500,000 ha were burned in Central Chile, the largest burned area across the previous 40 years.			
	Attribution: Variations in a fire weather and water deficit index can individually explain 50% and more of the variation in burned areas in parts of the forested land; in most other forested regions, it is 30–50%. On most not forested lands, at least one of both indicators reaches an explained variance of 50% or more.	Abatzoglou et al. (2018)	Moderate to strong sensitivity of burned areas to weather fluctuations in forested land, strong sensitivity of burned areas to fire weather and water deficits in non-forested land, *low confidence* (*)	
	Amazonia: Extreme droughts that occur during warm phases of the El Niño-Southern Oscillation and the Atlantic Multidecadal Oscillation can drive extreme fire years. The impacts of deforestation are greater under drought conditions, as fires set for forest clearance can become uncontrollable and burn larger areas, especially forests that have been previously logged.	Aragão et al. (2018), Silva et al. (2018), Alencar et al. (2015), Marengo et al. (2018), Chen et al. (2011)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Central Chile: Fire activity in central Chile was mainly associated with above-average precipitation during winter of the previous year and with dry conditions during spring to summer. In addition, burned areas are correlated with maximum temperature. R^2 between climate indicators and burned areas reaches about 20–50%. The central Chile mega-fire in January 2017 occurred during the warmest summer ever recorded in Central Chile but was also preceded by a relatively warm and dry spring identified as increasing fire risk in the correlation analysis. More than half of the area burnt in Chile was forest plantations with fast growing, high-density forest stands that are highly flammable and favour the development of large and severe wildfires.	Urrutia-Jalabert et al. (2018) (Central and south-central Chile, 1976–2013), De la Barrera et al. (2018), Holz et al., 2017 ('fire activity' measured by tree ring data not necessarily having a direct translation into 'burned areas'), Gómez-González, (2018) (2017 megafires in Chile)		
Europe	**Attribution:** Within-season weather-based fuel-aridity measures can explain 30% to more than 50% of the observed variance in burned forest areas in Southeastern and Northern Europe. Summer droughts and high temperatures are primary determinants of the inter-annual variability of fires in Southern Europe. Averaged across Mediterranean Europe, drought indices can explain about 40% of the observed variations in burned areas. In Spain, Portugal and Latvia, fire weather season length can explain about 50% of the annual variability in observed burned areas, with even slightly higher values in Italy and lower but still significant values >20% in Greece and France (1980–2013).	Abatzoglou et al. (2018), Turco et al. (2017), Trigo et al. (2016), Jolly et al. (2015) (fire weather season length)	Moderate to strong sensitivity of burned area to weather conditions, *medium confidence* (**)	
North America	**Observations:** Anaktuvuk River Fire in Arctic tundra in 2007: Single fire burned a 1039 km^2 area, more than doubling the total area burned during the previous 60 years in the region.	Hu et al. (2010a), Chipman et al. 2015		
	Attribution: *USA:* In forested (primarily flammability limited) regions, at least 30% of the variance in annual fluctuations in macroscale-burned areas can be explained by variations in purely weather-based within-season fire risk indicators, with more than 60% reached in Pacific Northwest, Northern Rockies, the Eastern Great Basin, Rocky Mountains and Southwest. Climate-driven increases in lightning ignitions and meteorological conditions favouring high fire spread led to extreme fires in the northern treeline ecotone. Explained variances in non-forested regions are usually lower but still reach 30% and more when antecedent fire risk indicators are included. Fire weather season lengths can explain about 50% of the variations in burned areas in the USA (1979–2013, 1992–2013); correlations are low in Canada.	Seager et al. (2015) (USA), Abatzoglou and Kolden (2013) and others also used for 'impact attribution' (Table 16.2), Jolly et al. (2015) (fire weather season length), Veraverbeke et al. (2017)	Within-season weather conditions have a strong influence on inter-annual variability in burned areas in forested land and Arctic tundra, *high confidence* in forested land (***)	Weather conditions regulate vegetation productivity and fuel moisture. While rainfall during the dry season suppresses fire activity, vegetation buildup during wet years in more fuel-limited arid areas can increase burned area in subsequent years. Burned area is mostly limited by a combination of above-average air temperatures and drought, often caused by lightning in high-northern latitudes.
	Arctic tundra, Alaska: Average temperature and total precipitation in June–August alone can explain ~90% of the variance in annual area burned from 1950–2009 in Alaska, with thresholds at ~11°C and ~150 mm (minimal sensitivities below the temperature and above the precipitation threshold, but strong increases in burned areas when crossing the thresholds). Exceptionally warm and dry conditions facilitated the Anaktuvuk River Fire in 2007.	Hu et al. (2010a), Hu et al. (2015), Jones et al. (2009) (Anaktuvuk River Fire)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Small Islands	**Attribution:** *Pacific, Big Island Hawaii*: Excess rainfall for the year prior to fire occurrence increases vegetation productivity across grasslands and, thus, overall fire probability, more so than drought the year that fire occurred. Prior-year rainfall anomalies can explain about 14% of the variations in the observed probability of fire, but the effect on burned areas is not explicitly quantified.	Trauernicht (2019)	Moderate sensitivity of burned areas to weather fluctuations in individual Island in the Caribbean and Pacific, *low confidence* (*) because of limited number of studies, no assessment elsewhere	
	Caribbean, Puerto Rico: Relative weather indicators (average across a certain number of days before the event divided by the long-term average) are shown to have a high predictive power when classifying local units into fire occurrence versus no fire occurrence. Absolute weather indicators (average across a certain number of days before the event) were most important for the classification of large versus small fires. The classification of the extent is more difficult, but the climate indicator still provided substantially better performance than random assignment. For the occurrence problem, precipitation and minimum temperatures were most important, while in the extent problem, after precipitation, maximum temperature and wind speed were most important.	Van Beusekom et al. (2018)		
S20	Other societal impacts—Malnutrition			
Global	**Observations:** More than one in three children in many developing countries are affected by stunting, a result of long-term nutritional deprivation. Moreover, as of 2019, more than 750 million people worldwide (i.e., almost 1 in 10) were severely food insecure.	UNICEF WHO (2019) Joint child malnutrition estimates, FAO et al. (2020)		
	Attribution: *53 developing countries:* In the recent past, periods of drought were associated with lower body height in children under 5 years old, in the study countries. The severity of stunting increased monotonically with drought severity.	Cooper et al. (2019)	Moderate (as partly hard to quantify) sensitivity of stunting to weather fluctuations (in particular, droughts) in developing countries and in context of subsidence farming, *medium confidence* (**) No assessment elsewhere	Drought (measured by 24-month SPEI)
	Subsistence farmers in low- and middle-income countries: Significant but variable link between weather variables, e.g., rainfall, extreme weather events (floods/droughts), seasonality, and temperature, and childhood stunting at the household level (12 of 15 studies, 80%).	Phalkey et al. (2015) (review)		Rainfall variability and intensity, droughts, floods
	Evidence from 19 low- and middle-income countries and more than 107,000 children shows that long-term (over 30 years) temperature levels and low precipitation in the year prior to the surveys are associated with decreases in overall child diet diversity.	Niles et al. (2021)		
Africa	**Observations:** Sub-Saharan Africa contained 17% of the world's children under 5 but a third of all undernourished children in 2015.	UN (2015)		

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
	Attribution: In *Sub-Saharan* Africa, high temperatures and low precipitation have been shown to reduce child weight. High temperatures are also shown to lead to wasting. The largest weight loss is monitored in rural areas, likely due to a loss of agricultural yields caused by excess heating during the growing season.	Baker and Anttila-Hughes (2020), Thiede and Strube (2020), Davenport et al. (2020), Grace et al. (2015), Randell et al. (2020), Saronga et al. (2016)	Major sensitivity of malnutrition to weather in Sub-Saharan Africa, *high confidence* (***)	
	In rural *Nigeria*, a negative rainfall shock has been shown to decrease agricultural productivity and hence decrease household consumption by 37%.	Amare et al. (2018)		
	Ethiopia: Greater rainfall during the rainy seasons in early life is linked to greater height for age. Higher temperatures *in utero* and more rainfall are positively associated with severe stunting.	Randell et al. (2020)		
	Tanzania: Droughts and floods have been shown to lead to food shortages in rural Tanzania.	Saronga et al. (2016) (qualitative)		
Asia	**Observations:** *Bangladesh:* Bangladesh was hit by the worst flood in over a century in the summer of 1998.	del Ninno and Lundberg (2005)		
	Mongolia: The severe winter in 2009–2010 caused catastrophic damage and resulted in the death of 10.3 million livestock.	Groppo and Kraehnert (2016)		
	Indonesia: In Indonesia, about a third of children under age 5 are stunted—among the highest rates in Asia and the Pacific.	UNICEF (2019)		
	India: The prevalence of underweight among children in India is the highest worldwide.	Kumar et al. (2016)		
	Japan: The mean national height-for-age *z*-scores of Japanese primary school children in the 1930s, the period that Ogasawara and Yumitori (2019) examine (see below), were close to the scores in rural areas in low- and middle-income countries today.	Ogasawara and Yumitori (2019)		
	Attribution: *Bangladesh:* The nutritional status of children in households that were more severely exposed to the flood deteriorated. Evidence from three-round panel data suggests that children exposed to the flood were adversely affected by the shock to their health and did not recover within the survey period.	del Ninno and Lundberg (2005)	Moderate sensitivity of nutrition status (of children) and consumption to weather conditions in Bangladesh, China, Japan, India, Indonesia and Mongolia, *medium confidence* in India (**) and in remaining countries *low confidence* as based on individual studies (*)	
	Mongolia: Identification of a causal impact of the weather shock on children's height by exploiting exogenous variation in the intensity of the shock across time and space by two waves of a panel survey. The shock significantly slowed the growth trajectory of exposed children from herding households. This negative effect is persistent, remaining observable in both panel waves, 3 and 4 years after the shock. The effect is driven by children who experienced the shock *in utero*.	Groppo and Kraehnert (2016)		

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Indonesia: Evidence from panel data regression analyses shows that delays in the monsoon are systematically associated with poor child health outcomes in Indonesia. Delays in monsoon onset during the prenatal period are linked to a reduced child height among children aged 2–4 years. Delays in the most recent monsoon season adversely affect weight of young (<2 years) children.	Thiede and Gray (2020)		
	India: Evidence from rural India shows that children exposed to a drought *in utero* or at birth have a lower weight-for-age *z*-score, a higher probability of being underweight and severely underweight, and a higher probability of dying before age 1. Further, adverse weather events have been shown to aggravate inequality by reducing consumption of poor farming households.	Kumar et al. (2016) (drought impacts), Sedova and Kalkuhl (2020) (farming households)		
	Dry shocks (absolute deviation of rainfall below its long-run mean) have been shown to have a statistically significant and negative effect on household nutrition. A median dry shock corresponds to a drop in households spending by 1% per capita per month on food and a drop in calories, protein and fat consumption by up to 1.4%.	Carpena (2019)		
	In rural Eastern India, flooding is associated with child undernutrition.	Rodriguez-Llanes et al. (2016)		
	Japan: In Japan, exposure to cold waves in early life was associated with stunting. In the coldest regions, the stunting effects of cold weather shocks on the boys and girls are estimated to be approximately 0.8 and 0.6 cm, respectively.	Ogasawara and Yumitori (2019)		
	China: The prenatal exposure to heatwaves has been shown to have stronger negative effects than exposure to cold spells on surviving births. Between the 1980s and the 1990s, the population-weighted total number of days with a mean temperature above 28°C increased from 233 d to 261 d and on average caused 1.4% (46.5 g) additional damage to birth weight.	Chen et al. (2020b)		
Australasia	**Observations:**			
	Attribution:		No assessment	
Central and South America	**Observations:** *Brazil:* Amazonian societies in Brazil were exposed to severe floods between 2009 and 2014 and major droughts in 2005, 2010 and 2015, leading to disruption to flows of essential goods and public services.	de Oliveira et al. (2021)		
	Ecuador: Severe floods hit Ecuador during the 1997–1998 El Niño phenomenon, leading to socioeconomic losses that reached 13% of Ecuador's GDP in 1996. Losses in agriculture accounted for approximately 6% of the GDP, whereby approximately 30% of Ecuador's crops were destroyed. Damages in Ecuador's infrastructure and transportation corresponded to 3.7% of the GDP.	Rosales-Rueda (2018)		
	Peru: Peru experiences one of the highest rates of stunting in Latin America, affecting roughly one in four children.	Nicholas et al. (2021)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems (‘Identification of weather sensitivity’)

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: *Brazil:* Focusing on Amazonian populations in Brazil, a study shows that prenatal exposure to extremely intense rainfall is associated with preterm birth, restricted intra-uterine growth and lower mean birth weight (≤–183 g). Adverse birth outcomes are also a consequence of non-extreme intense rainfall (40% higher odds of low birth weight), drier conditions than seasonal averages (–39 g mean birth weight) and conception in the rising-water season (–13 g mean birth weight).	Chacón-Montalván et al. (2021)	Strong sensitivity of nutrition status of children to weather in Brazil, Columbia, Ecuador and Peru; *medium confidence* in Brazil (**), in remaining countries, *low confidence* as based on individual studies (*)	Rainfall variability
	Another study on impacts of *in utero* exposure to Hurricane Catarina in Brazil finds that the adverse effects of the exposure are concentrated among babies born to mothers aged 15–24: birth weight decreased by 82 g, the probability of being born with low birth weight increased by 3.4 pp, and foetal deaths increased by about 17 per 1000 live births and foetal deaths.	de Oliveira et al. (2021)		Extreme events (Hurricane Catarina)
	Negative rainfall shocks in the Brazilian semiarid are correlated with higher infant mortality, lower birth weight and shorter gestation periods.	Rocha and Soares (2015)		Rainfall variation
	Colombia: Exposure to moderate heatwaves during the third trimester of pregnancy leads to a reduction in infants’ birth weight by about 4.1 g. Exposure to moderate cold shocks during the first and second trimesters of pregnancy leads to a reduction in the length at birth by 0.014–0.018 cm.	Andalón et al. (2016)		Extreme heat and cold
	Ecuador: An analysis of extreme floods in Ecuador during the 1997–1998 El Niño shows that children exposed to severe floods *in utero*, in particular during the third trimester, were more likely to be born with low birth weight and are shorter in stature 5 and 7 years later. The mechanisms behind this can be attributed to households’ decline in income, total consumption and food consumption in the aftermath of the shock.	Rosales-Rueda (2018)		Extreme events (El Niño-related floods)
	Peru: Rural, Indigenous children at age 0–1 experience a reduction in height-for-age associated with prenatal excess rainfall, which can also be observed at age 4–5.	Nicholas et al. (2021)		Rainfall variation
Europe	**Observations:**			
	Attribution:		No assessment	
North America	**Observations:** An estimated 10.5% of households in the USA were food insecure at least some time during 2019, i.e., they lacked access to food sufficient for an active, healthy life for all household members.	U.S. Department of Agriculture Coleman-Jensen et al. (2020)		
	Attribution: Following disasters (i.e., Hurricane Katrina, Hurricane Harvey), socioeconomically vulnerable groups were more at risk to be food insecure.	Clay et al. (2018) (Hurricane Katrina), Fitzpatrick et al. (2020) (Hurricane Harvey)	Moderate sensitivity of nutrition status to weather events, *medium confidence* (**)	
	In the USA, exposure to cold and hot exposure during pregnancy increased low birth weight risk.	Ha et al. (2017); Molina and Saldarriaga (2017)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Small Islands	**Observations:** The reliance on food imports and processed foods as well as a decline in consumption of locally produced foods—all of which are linked to malnutrition—have an increasing trend in Pacific Island Countries.	Iese et al. (2021)		
	Attribution: In the aftermath of the Tropical Cyclone (TC) Harold in April 2020, crops were destroyed and livestock killed in Tonga, Solomon Islands, Vanuatu and Fiji. This led to increased hardships by reducing production, income and food for households in the affected countries.	Iese et al. (2021)	No assessment because of missing additional studies	
S14	Coastal systems—Damages			
Global	**Observations:** *Coastal erosion:* The surface of eroded land in 1984–2015 is approximately 28,000 km² according to satellite imagery, twice the surface of gained land.	Mentaschi et al. (2018)		
	Salinisation: An estimated 500 million people worldwide are adversely affected by the salinisation of freshwater and soils. This includes impacts on food and water security, agricultural livelihoods and human health.	Rahman et al. (2019)		
	Attribution: *Coastal erosion:* While the dominant cause for land loss is planned exploitation of coastal resources, the instalment of dams or the clearing of mangrove forests, another important driver of coastal erosion is natural disasters such as extreme storms, as well as relative sea level rise.	Mentaschi et al. (2018)	High sensitivity to tropical cyclones, *high confidence* (***)	
	Salinisation: Local drivers such as groundwater abstraction, improper maintenance of sea defence infrastructure, and saline aquaculture are compounded with global sea level rise and changes in storm surge.	Rahman et al. (2019), Bayabil et al. (2020), Eswar et al. (2021), Mukhopadhyay et al. (2021)		
	Tropical cyclones: Between 1960 and 2020, more than 2000 landfalling TCs caused almost $1.4 trillion (2010 USD) in direct economic damages and approximately 910,000 fatalities, the most destructive being Hurricane Katrina (2005) with USD 150 billion in direct economic damages. The single most fatal TC was the 1970 Bhola cyclone with 300,000 reported fatalities. *Coastal floods:* Apart from TC-related flooding, EM-DAT attributes $14.6 billion (2010 USD) in direct economic damages and 3269 fatalities to the remaining types of coastal flood disasters between 1960 and 2020 (hydrological disasters, not including tsunamis). Even though coastal areas make up only a small fraction of global land area, 40% of all damages and 25% of all fatalities in the EM-DAT disaster groups of meteorological, climatological and hydrological disasters are due to coastal disasters (TCs and coastal floods).	CRED and Guda-Sapir (2021)		The considered data from 'The International Disaster Database' (EM-DAT; CRED and Guda-Sapir, 2021) refer to the amount of damage to property, crops and livestock at the moment of the event and do not include damages that unfold over following years. The database is made up of information from various sources, including UN agencies, non-governmental organisations, insurance companies, research institutes and press agencies, with priority given to data from UN agencies, governments and the International Federation of Red Cross and Red Crescent Societies. Entries are constantly reviewed for inconsistencies, redundancy and incompleteness. We uniformly assume '*high confidence*' associated with the tropical cyclone assessments based on EM-DAT assuming an easier assignment of damages and fatalities to tropical cyclones than to droughts.

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Africa	**Observations:**			
	Attribution: *Cyclone Idai:* Reported 602 deaths, 1600 injuries, 1.85 million people in need, damages and losses of USD 3.2 billion in Mozambique. Total damages between USD 548 million and USD 622 million in Zimbabwe. Between 1900 and 2018, at least 334 major flood events occurred in the Western Cape, South Africa, with the number of flooding events per year increasing over time.	Nhamo and Chikodzi (2021), Charrua et al. (2021), Dube et al. (2021)	High sensitivity to tropical cyclones, *high confidence* (***)	
	Total TC impacts: Over the period 1960–2020, more than 5500 fatalities and almost \$10 billion (2010 USD) in direct economic damages are associated with TCs in Africa (EM-DAT). The *share of economic damages due to coastal hazards* among all meteorological, climatological and hydrological hazards (according to EM-DAT) in Africa is 25%, which is lower than the global average, but still high for a region with generally low TC activity.	CRED and Guda-Sapir (2021)		See discussion of EM-DAT data in the global section.
Asia	**Observations:**			
	Attribution: *Tropical cyclones:* According to EM-DAT, of the 910,000 recorded deaths due to TCs worldwide between 1960 and 2020, a total of 847,000 were due to TCs in Asia, while only \$385 of the total \$1402 billion (2010 USD) in direct economic damages are associated with TCs in Asia. *Coastal floods:* Apart from TC-related flooding, EM-DAT attributes \$12.3 billion (2010 USD) in direct economic damages and 2060 fatalities to the remaining types of coastal flood disasters between 1960 and 2020 in Asia (hydrological disasters, not including tsunamis). Within Asia, the *share of economic damages as well as fatalities due to coastal hazards* among all meteorological, climatological and hydrological hazards (according to EM-DAT) is more than 31% each, which is lower than the global average for economic damages, but higher in terms of deaths.	CRED and Guda-Sapir (2021)	High sensitivity to tropical cyclones, *high confidence* (***)	See discussion of EM-DAT data in the global section.
	Cyclones Sidr (2007) and Aila (2009): The prevalence of diarrhoea, skin diseases, hepatitis and other infectious diseases has increased after the events, and the mental health of people in coastal areas of Bangladesh has degraded.	Kabir (2014)		
	Saline contamination of soils: Extreme coastal water levels lead to saline intrusion and subsequent agricultural income losses in Bangladesh.	Chen and Mueller (2018), Sherin et al. (2020)		
Australasia	**Observations:**			
	Attribution: Damages were recorded for 38 of all 154 landfalling tropical cyclones in Australia since 1970. On average, each landfalling TC (i.e., including the ones not inducing damages) caused damages of about 11 million Australian dollars in the last two decades of the 20th century. *Cyclone Tracy (1974)* caused insured damages of USD 4090 million (normalised to 2012). *Cyclone Yasi (2011)* caused a USD 300 million loss to agricultural production in Queensland and insured damages of \$1412 million.	Seo (2014) Handmer et al. (2018)	Coastal damages induced by individual tropical cyclones can be very high, but overall they were lower than in other regions, which has led us to the assessment: moderate sensitivity, *high confidence* (***)	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
	Total TC impacts: Over the period 1960–2020, 236 fatalities and more than $20 billion (2010 USD) in direct economic damages are associated with TCs in Australasia (EM-DAT). The *share of economic damages due to coastal hazards* among all meteorological, climatological and hydrological hazards (according to EM-DAT) in Australasia is 22%, which is lower than the global average.	CRED and Guda-Sapir (2021)		See discussion of EM-DAT data in the global section.
Central and South America	**Observations**			
	Attribution: *Hurricanes Eta and Iota (2020)* caused more than 400 deaths and damages above $6 billion (2010 USD) in Central America, mainly due to extreme rainfall. *Hurricane Mitch (1998):* According to EM-DAT, 3.2 million people from eight countries were affected by this storm; almost 19,000 lost their lives. The direct economic damages amounted to $8.88 billion (2010 USD). *Total hurricane impacts:* Over the period 1960–2020, more than 35,000 fatalities and almost $64 billion (2010 USD) in direct economic damages are associated with hurricanes in Central and South America (EM-DAT). The *share of economic damages due to coastal hazards* among all meteorological, climatological and hydrological hazards (according to EM-DAT) in Central and South America is 36%, which is slightly lower than the global average, but still high for a region with generally low TC activity. For fatalities, the share of 33% is clearly above average.	CRED and Guda-Sapir (2021)	High sensitivity to tropical cyclones, *high confidence* (***)	See discussion of EM-DAT data in the global section.
	Hurricanes in Mexico: Between 1990 and 2011, hurricanes caused an estimated 1600 deaths in terms of mortality displacement. Due to underreporting, this exceeds the number of 989 officially reported deaths in EM-DAT.	Pugatch (2019)		
Europe	**Observations:**			
	Attribution: The storm-induced North Sea flood of 1953 caused damages of 0.5 billion in Belgium, more than 1 billion in the UK and almost 5 billion in the Netherlands, inflation-adjusted to 2011 EUR. Flooding from the Vincinette winter storm caused damages of almost 5 billion in Hamburg in 1962, inflation-adjusted to 2011 EUR. Flooding from cyclone Xynthia 2010 caused damages of 1.3 billion in coastal France, inflation-adjusted to 2011 EUR.	Paprotny et al. (2018a)	Coastal damages induced by individual storms can be high, but overall events were rare and the overall damage much lower that in other regions, which has led us to the assessment: moderate sensitivity, *high confidence* (***).	
	Winter storm Xaver (2013): The financial impact of the coastal flooding was estimated to be more than EUR 1.5 billion.	Horsburgh et al. (2017)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Hurricanes: Even though Europe is clearly outside the typical realm of TC activities, remnants of North Atlantic hurricanes occasionally hit European coastlines, as in the case of Hurricane Charley (1986). EM-DAT associates 176 deaths and $3.7 billion (2010 USD) in economic damages to hurricanes that reached European countries 22 times between 1960 and 2020. Clearly, this is not a major disaster type in Europe, where economic damages from other weather-related disasters amount to almost USD 450 billion.	CRED and Guda-Sapir (2021)		see discussion of EM-DAT data in the global section.
North America	**Observations:**			
	Attribution: *Total hurricane impacts:* Over the period 1960–2020, more than 4300 fatalities and $770 billion (2010 USD) in direct economic damages are associated with hurricanes along the western and eastern coasts of North America (EM-DAT). For North America, hurricanes are clearly the single most devastating disaster category. The *share of economic damages due to hurricanes* among all meteorological, climatological and hydrological hazards (according to EM-DAT) in North America is almost 55%.	CRED and Guda-Sapir (2021)	High sensitivity to hurricanes, *high confidence* (***)	See discussion of EM-DAT data in the global section.
Small Islands	**Observations:** *Exemplary damages induced by individual tropical cyclones (TC):* *TC Pam 2015*: The destruction induced by TC Pam 2015 is considered one of the worst natural disasters in the history of Vanuatu. The cumulative reduction in economic activity in affected Pacific islands within the first 5 months following the event (as indicated by nightlight activity) amounted to as much as 111%. *TC Fantala 2016:* In addition to land loss in uninhabited islets, up to 28% of land area, the category 5 storm spared only 4 of the 50 buildings in the Farquhar Atoll (Seychelles) from severe damages, leaving 19 buildings completely destroyed. *TC Winston 2016:* USD 0.9 billion destruction in Fiji equivalent to 20% of GDP. *Damages to agriculture:* USD 56.5 million through TC Pam in Vanuatu and 255 million through TC Winston in Fiji.	Magee et al. (2016) (TC Pam), Mohan and Strobl (2017) (TC Pam), UNITAR (2016), Duvat et al. (2017) (TC Fantala), Shultz et al. (2019) (TCs in 2017), Mansur et al. (2017) (TC Winston)		
	During 2017, 22 of the 29 Caribbean SIDS were affected by at least one named storm, and multiple SIDS experienced extreme damage. Mangrove habitats throughout the Caribbean severely damaged by hurricanes.	Taillie et al. (2020), Walcker et al. (2019)		
	Major floods in the Maldives led to serious damage to the entire Archipelago (1987) and affected 1650 people and more than 500 housing units (2007). The giant swell 1996 from major floods affected a large area in French Polynesia (>20% flooded or destroyed homes). A stronger but shorter event in 2011 caused less damage.	Wadey et al. (2017), Canavesio (2019)		

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: The damages are clearly associated with the cyclones (wind speed, rainfall, coastal flooding). In several cases, the intensity of the extremes (rainfall associated with the tropical cyclones) could be attributed to anthropogenic climate forcing. However, as there is no translation of the attributable increase in intensity to the associated increase in damage, the description of the total damages induced by the TCs only documents a sensitivity to weather extremes but does not represent an attribution of damages to climate change.		High sensitivity to tropical cyclones, *high confidence* (***)	
	For SIDS, TCs are very clearly the single most devastating disaster category: The *share of economic damages due to TCs* among all meteorological, climatological and hydrological hazards (according to EM-DAT) in SIDS is more than 97%.	CRED and Guda-Sapir (2021)		See discussion of EM-DAT data in the global section.
	Swells from Southern Ocean storms were a main driver of flood damages in the Maldives for 1987 and 2007 events. Relation to climate change is unclear. Similar swells drove the flood events in French Polynesia in 1996 and 2011. The role of climate change for such swell-driven floods is not quantified.	Wadey et al. (2017), Canavesio (2019)		
S26	Other societal impacts—Social conflict			
Global	**Observation:** Armed conflict (measured as outbreak or incidence of militarised conflict between organised actors over political incompatibilities that causes at least 25 battle fatalities per calendar year) exhibits considerable inter-annual, inter-decadal and inter-regional variation in frequency and trends. Global frequency of armed conflict 2014–2019 has been at the highest level since the early 1990s. Almost all contemporary armed conflicts are intra-state (civil) conflicts. In 2019, 50 of the 54 active state-based armed conflicts were located in Africa or Asia. Global severity of armed conflict (measured as battle-related deaths) has declined steeply on average since 1950, despite an uptick in recent years. Around 51,000 were killed in state-based armed conflict in 2019, only around 200 of whom were casualties of interstate conflicts. Non-state (inter-group) conflict has increased markedly since 1989 and caused around 20,000 deaths in 2019. One-sided violence including terrorism shows a downward trend. Uppsala Conflict Data Program (UCDP) estimates that around 5000 civilians were killed in one-sided events in 2019. Other data sources (e.g., Correlates of War, ACLED) corroborate these trends.	Gleditsch et al. (2002), Pettersson and Öberg (2020) (UCDP data set)	*Very likely*	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
	Attribution: Climate (variability, hazards, trends) affects prevalence of armed conflict within states, primarily in countries that harbour multiple non-climatic risk factors. The climate effect is judged to be small relative to leading non-climatic factors.	Mach et al. (2019), Buhaug et al. (2014), Hsiang and Burke (2014), Theisen (2017), Koubi (2019), von Uexkull and Buhaug (2021)	Sensitivity of armed conflict to climate conditions increases from low to moderate conditional on non-climate risk factors such as high population, ethnopolitical exclusion, agricultural dependence or socioeconomic development, *medium confidence* (**)	All relevant dimensions of the climate system
	Weather- and climate-related disasters and extremes increase prevalence of social unrest and civil conflict in countries marked by high populations, ethnopolitical exclusion, agricultural dependence and low socioeconomic development.	Eastin (2016), Schleussner et al. (2016), Ide et al. (2020) Abel et al. (2019), Buhaug et al. (2020), Ghimire and Ferreira (2016), Ide et al. (2021)		Drought; meteorological, climatological, and hydrological disasters
	Climatic hazards increase the prevalence of armed conflict via forced migration and human displacement.	Abel et al. (2019), Bhavnani and Lacina (2015), Bosetti et al. (2020), Ghimire et al. (2015), Burrows and Kinney (2016), AR6 WGII Section 7.4.	Minor sensitivity of armed conflict to weather-induced migration, *low confidence*	Forced migration in response to climatic hazards
	Climate-induced variation in transboundary freshwater resources increases international cooperation, although effect is sensitive to the institutional context. Some evidence also suggests that weather anomalies increase prevalence of water-related interstate disputes.	Bernauer and Böhmelt (2020), Dinar et al. (2015), Dinar et al. (2019), Link et al. (2016), Petersen-Perlman et al. (2017), Schmidt et al. (2021)	Minor to moderate sensitivity of international water cooperation to weather conditions, depending on context, *low confidence* (some concerns about data quality)	Variation in transboundary river flows
Africa	**Attribution:** Drought and rainfall loss increase the prevalence of civil conflict through loss of livelihood and income, notably for agriculturally dependent and politically excluded social groups (*medium confidence*). Some concerns about sample selection bias in the literature.	Bell and Keys (2018), Buhaug et al. (2015), Harari and Ferrara (2018), Owain and Maslin (2018), von Uexkull (2014), Von Uexkull et al. (2016)	Sensitivity of violent conflict to weather fluctuations (including extreme events) increases from minor to moderate (e.g., social unrest to weather-affected food price shocks) depending on societal context (e.g., political exclusion, agricultural dependence), *medium confidence* (**, some concerns about sample selection bias in the literature)	Precipitation deficit and drought
	Drought and rainfall loss increase prevalence of non-state (communal) violence and individual support for use of violence, especially among marginalised and agriculturally dependent groups (*medium confidence*). Some concerns about sample selection bias in the literature.	Bagozzi et al. (2017), Detges (2017), Linke et al. (2018), Nordkvelle et al. (2017), van Weezel (2019), Vestby (2019), von Uexkull et al. (2020), Yeeles (2015)		Precipitation deficit and drought
	High temperature anomalies increase prevalence of civil and non-state conflict (*low confidence*, *low agreement*); some concerns about sample selection bias in the literature.	Bollfrass and Shaver (2015), Landis (2014), Maystadt et al. (2015), O'Loughlin et al. (2014), Yeeles (2015)		High temperature
	Weather-affected rising food prices or food insecurity increase the likelihood of social unrest, especially in states marked by poor governance and inefficient markets. Moderate to strong sensitivity of social unrest to weather-affected food price shocks, depending on context, (*low confidence*). Limited quantification of weather effect.	Smith (2014), Raleigh et al. (2015), Jones et al. (2017), McGuirk and Burke (2020), Koren et al. (2021)		Rising food prices in response to drought

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Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Asia	**Attribution:** Drought increases the prevalence of civil conflict for agriculturally dependent and politically excluded social groups in poor countries (*low confidence*, limited number of independent studies). Drought effects on lower levels of water-related conflict (in Middle East and North Africa [MENA] region) are similarly highly context dependent.	Von Uexkull et al. (2016) Wischnath and Buhaug (2014); Ide et al. (2021)	Minor to moderate sensitivity of violent conflict to weather conditions (particularly drought) depending on social context (e.g., exclusion and agricultural dependence), *medium confidence* (**)	Drought
	Drought and rainfall loss increase prevalence of non-state (communal) violence and individual support for use of violence, especially among marginalised and agriculturally dependent groups in poor countries (*medium confidence*; some concerns about sample selection bias in the literature).	Bagozzi et al. (2017), Nordkvelle et al. (2017), Yeeles (2015)		Precipitation deficit and drought
	High temperature anomalies increase prevalence of civil and non-state conflict (*medium confidence*; some concerns about sample selection bias in the literature).	Bollfrass and Shaver (2015), Caruso et al. (2016), Landis (2014), Yeeles (2015)		High temperature
Australasia	**Observations:**			
	Attribution:		No study of weather sensitivity of armed conflict	
Europe	**Observations:**			
	Attribution:		No study of weather sensitivity of armed conflict	
Central and South America	**Observations:**			
	Attribution:		No study of weather sensitivity of armed conflict	
North America	**Observations:**			
	Attribution:		No study of weather sensitivity of armed conflict	
Small Islands	**Observations:**			
	Attribution:		No study of weather sensitivity of armed conflict	
S29	Other societal impacts—Displacement and migration			
Global	**Observations:** *Internal displacement:* Since reporting started in 2008, every year, between 15 million and 42 million people worldwide were displaced within their countries in relation to disasters.	IDMC, Global Report on Internal Displacement, IDMC (2020)		
	International migration: Millions of people emigrate from their countries of origin each year, becoming international migrants as reported by the UN's International Organization for Migration. Migrants make up roughly 3% of the global population.	IOM Global Migration Indicators 2018, Abel and Sander (2014), Abel (2018)		
	Internal migration/urbanisation: Increasing urban population: in 2000, there were 371 cities with 1 million inhabitants or more worldwide. By 2018, this figure increased to 548 cities.	UN (2018)		

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Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	International refugees: Millions of people every year flee their countries of origin, becoming international refugees or asylum seekers as reported by the United Nations High Commissioner for Refugees (UNHCR). Global trend in forced displacement has been rising every year since 2011.	UNHCR Global Trends in Forced Displacement 2020 UNHCR (2020)		
	Attribution: Sensitivity of internal displacement and international migration to (extreme) weather is different (see below). For the figure, we summarised the finding as described in the orange cell.		Sensitivity assessments range from *high confidence* (***) in strong sensitivity of displacement to *high confidence* (***) in minor sensitivity of migration in low- and high-income groups.	
	Internal displacement: Weather extremes are the dominant driver of internal displacement. On average, 87% of disaster-induced displacement is due to weather-related disasters, mainly floods (51%) and storms (35%); only 13% are due to geophysical hazards such as earthquakes. The close temporal and spatial proximity between disaster and displacement occurrence allows a simple attribution of displacement to disasters; however, vulnerability to weather-induced displacement is not uniform and not well understood.	IDMC, Global Report on Internal Displacement; IDMC, Disaster displacement: a global review, 2008–2018, (IDMC, 2019), IDMC (2020), Kakinuma et al. (2020)	Strong sensitivity of displacement to weather fluctuations, *high confidence* (***)	Primary drivers: fluvial, pluvial and coastal flooding; tropical cyclones; and other storms. Other drivers: droughts, wildfires, landslides, extreme temperatures.
	International migration: Effects of temperature or precipitation anomalies on international migration have been found in multiple studies using panel data sets including large numbers of countries. The sign and magnitude of the effect are not universal but depend on factors such as income levels in the country of origin. Generally, positive temperature anomalies and both negative and strongly positive precipitation anomalies have been found to increase emigration from middle-income countries. In poor countries, such anomalies may have no effect or even suppress migration, as people cannot afford to migrate (poverty traps).	Coniglio and Pesce (2015) (migration to rich Organisation for Economic Co-operation and Development [OECD] countries), Cattaneo and Peri (2016) (low-income countries, poverty traps), Beine and Parsons (2017) (poverty traps), Nawrotzki and DeWaard (2016)	Moderate to minor sensitivity, depending on income levels and the importance of the agriculture sector; *high confidence* (***)	Inter-annual or inter-decadal anomalies in temperature or precipitation
	Climate (temperature, precipitation) anomalies influence international out-migration via agricultural productivity and employment in the agricultural sector. This effect was found for countries such as Mexico or India, and generally for countries with large importance of the agricultural sector. The effect is mediated by the income in the origin country: no climate effect was found in the poorest countries—likely because of poverty constraining migration—and in rich countries.	Cai et al. (2016), Nawrotzki et al. (2015), Viswanathan and Kavi Kumar (2015), Falco et al. (2019)		Weather-induced variations in agricultural productivity
	Internal migration/urbanisation: Multi-stage regression analyses as well as recent meta-regression analyses provide further evidence of an indirect effect of climate variability on migration, operating through urbanisation: greater variability in temperature and rainfall is associated with increased rural–urban movement, particularly within middle-income countries; and increased urbanisation in turn is associated with higher out-migration rates to international destinations.	Šedová et al. (2021), Marchiori et al. (2012), Maurel and Tuccio (2016), Castells-Quintana et al. (2020), Peri and Sasahara (2019), Hoffmann et al. (2020)		

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Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Natural hazards are found to affect out-migration particularly from middle-income countries; however, studies combine weather-related and geophysical hazards into composite indices, making it impossible to discern the effects of weather events alone.	Beine and Parsons (2017), Gröschl and Steinwachs (2017)		Natural hazards (both weather-related and geophysical)
	International refugees: Drought and temperature anomalies in countries of origin are overall weakly associated with increased flows of irregular international migrants and asylum seekers, with direction, shape and strength of relationship varying between studies and regions and over time.	Missirian and Schlenker (2017), Abel et al. (2019), Cottier and Salehyan (2021), Schutte et al. (2021)	Mostly minor sensitivity (moderate for some countries and periods); *medium confidence* (**)	Drought, measured by Standardized Precipitation Evaporation Index (SPEI); temperature anomaly
Africa	**Observation:** Displaced people in East Africa crossing borders and becoming refugees/increasing urbanisation rates in Sub-Saharan Africa.	Owain and Maslin (2018)		
	Attribution: During 1963–2014 in East Africa, severe droughts contributed to refugees crossing international borders.	Owain and Maslin (2018)	Magnitude of sensitivity cannot be assessed with study design and therefore rated moderate; *medium confidence* (**) Locally high sensitivity to flood-induced displacement	
	In Sub-Saharan Africa, regions where cities are likely to be manufacturing centres, drier conditions increase urbanisation.	Henderson et al. (2017)		
	Flood-induced displacement is high under low to moderate exposure to flooding in low-income countries such as Nigeria and Zimbabwe.	Kakinuma et al. (2020)		
Asia	**Observations:** Internal migration/urbanisation/rural-to-urban migration in Indonesia, India, Bangladesh, Vietnam and other countries.			
	Attribution: Temperature had a nonlinear effect on migration within Indonesia.	Bohra-Mishra et al. (2014)	Moderate sensitivity in Indonesia and India and Vietnam, *low confidence* (*) in India and Indonesia as only based on one study, *moderate confidence* in Vietnam (**) No assessment elsewhere	Annual temperature anomalies
	Natural disasters, notably flood hazards, increase urbanisation, i.e., domestic rural-to-urban migration in Bangladesh and Vietnam, whereas drought reduces migration (Vietnam).	Petrova (2021); Koubi et al. (2016)		Natural hazards (floods, drought)
	An analysis of household-level permanent migration (internal and international) in coastal Bangladesh (populations surveys, 2003–2011) establishes a link from soil salinity to crop production and then to migration, indicating that soil salinity may be a more important driver of migration than direct flooding. However, salinity is only measured at two times, 2000 and 2009. Changes in sea levels are a plausible driver of salinity changes, but the paper does not explicitly establish this connection.	Chen and Mueller (2018) (Bangladesh)		
	Adverse weather shocks drive rural–urban migration to different states in India. Approximately 8% of urbanisation between 2005 and 2012 can be attributed to weather.	Sedova and Kalkuhl (2020)		Temperature and precipitation anomalies
	Several studies using econometric analyses show that, in Vietnam, sudden-onset events such as typhoons or floods can be attributed to migration to urban areas.	Gröger and Zylberberg (2016), Koubi et al. (2016), Nguyen et al. (2015)		Weather-related natural hazards

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Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Australasia	**Observations:** Migration and temporary relocation in Australia.			
	Attribution: In Australia, sudden-onset hazards (e.g., floods, cyclones and wildfires) have been shown to lead to temporary relocation. Slow-onset climate change impacts (sea level rise, temperature or precipitation extremes) have more sustained effects on long-term mobility.	Bakar and Jin (2018) (case study in the Murray–Darling Basin, Australia), Zander and Garnett (2020)	Moderate sensitivity in Australia, *low confidence* (*) as conclusions only derived from studies on Australia	Weather-related natural hazards
Central and South America	**Observations:** An increase in migration in Central and South America.			
	Attribution: Droughts and hurricanes have driven migration in northern Latin America, Central America and the Caribbean. For instance, an estimated 4 more residents aged 15–25 per 1000 will move outside of the province capital as a result of a one-standard-deviation increase in drought intensity.	Baez et al. (2017) (Northern Latin America and the Caribbean), Chort and de la Rupelle (2016) (Mexico), Spencer and Urquhart (2018) (migration from Central American and Caribbean to the USA)	Moderate to strong sensitivity, e.g., in terms of dependence on agriculture, *medium confidence* (**)	Weather-related natural hazards
	Mexico–USA migration: Emigration from Mexico (to the USA) is sensitive to Mexican climate conditions. The sensitivity seems to be transmitted through the impact of weather conditions on agriculture as it appears particularly high in rural areas. An analysis of annual migration data from 1970–2009 shows that decadal minimum precipitation is associated with particularly high emigration as soon as agriculture is broadly affected, too.	Murray-Tortarolo and Salgado (2021) (drought effects on migration, 1970–2009), Feng et al. (2010) (effect of weather-induced fluctuations of crop yields, 1995–2005), Nawrotzki et al. (2015) (comparison of urban versus rural sensitivities, 1986–1999)		
Europe	**Observations:** Internal migration in the Netherlands.			
	Attribution: Adverse climatic conditions have been shown to affect historical internal population movements in the Netherlands.	Jennings and Gray (2015)	Moderate sensitivity to weather variability in the Netherlands, *low confidence* (*) as based on one study only, no assessment elsewhere	Temperature- and precipitation-related
North America	**Observations:** An increase in migration and displacement			
	Attribution: In the USA, severe natural disasters such as tornadoes, hurricanes and floods have led to both displacement and migration. Specifically, from 1920 to 2010, severe disasters (a composite indicator capturing disasters associated with 25 or more deaths) have increased out-migration rates at the county level by 1.5 percentage points.	Raker (2020), Boustan et al. (2020)	Moderate sensitivity to weather variability, *medium confidence* (**)	Weather-related natural hazards
Small islands	**Observations**: *Puerto Rico*: After September 2017, Puerto Rico witnessed a 'depopulation' of 14% in only 2 years as a result of emigration to the US mainland.	Melendez and Hinojosa (2017)		
	Grenada: Since the end of World War II, 150–200 persons emigrated from Carriacou, Grenada per year. In sum, this is more than its current population.	Cashman and Yawson (2019)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: *Puerto Rico*: The migration appears as a direct consequence of Hurricane Maria.	Melendez and Hinojosa (2017), Alexander et al. (2019)	Strong sensitivity, *medium confidence* (**), no assessment elsewhere	
	Grenada: The significant droughts in the mid-1930s to mid-1940s, mid-1960s to mid-1970s, and recently in 2000–2001 coincided with population dips in Carriacou, Grenada after the drought events. The dips are mainly due to out-migration.	Cashman and Yawson (2019)		
S31	Other societal impacts—Macroeconomic output			
Global	**Observation:** Per capita GDP growth rates (in real as well as in nominal terms) in nearly all countries have been subject to substantial annual fluctuations, including frequent changes of sign since 1960.	World Bank's World Development Indicator Database		According to World Development Indicator database of the World bank also employed by original studies (nominal and real GDP per capita in constant 2011 USD)
	Attribution: Economic performance is shown to be sensitive to temperature fluctuations and weather extremes. The individual assessments are provided below and summarised here.		Moderate sensitivity of economic performance to temperature fluctuations but high sensitivity of output growth to extreme weather conditions, *high confidence* (***, based on *high agreement* and *robust evidence* from several independent studies)	
	Effects of temperature fluctuations: Nonlinear dependence of economic production and thus real per capita GDP growth rates on annual temperature variability. Dependence has inverse U-shape with growth rate increases and decreases below and above a critical threshold temperature, respectively. Threshold temperature not country dependent.	Burke et al. (2015), Kalkuhl and Wenz (2020), Burke and Tanutama (2019), Pretis et al. (2018)	Moderate sensitivity of GDP to annual temperature anomalies, *high confidence* based on *high agreement*, *robust evidence* from several independent studies (***)	Driver: annual temperature variability; understanding of underlying processes still lacking
	Effect of extreme weather events: Severe tropical cyclones and fluvial floods have negative short-term (immediate and up to 5 years after shock) and long-term (up to 10–15 years after shock) impacts on economic growth. Moderate floods may have positive short-term impacts on economic growth, but impacts of severe floods are always negative.	Felbermayr and Gröschl (2014), Panwar and Sen (2019) (tropical cyclones, short-term effects), Hsiang and Jina (2014), Berlemann and Wenzel (2018), Krichene et al. (2020) (tropical cyclones, long-term effects), Loayza et al. (2012), Felbermayr and Gröschl (2014), Fomby et al. (2013) (fluvial floods, short-term effects), Krichene et al. (2021) (fluvial floods, long-term effects)	Strong sensitivity of GDP to severe tropical cyclones and fluvial floods. Impact on GDP are strongly negative in the short term, *high confidence* based on *high agreement* and *robust evidence* from several independent studies (***) Long-term responses in GDP are moderately negative, *low* to *medium confidence* based on *medium agreement* and *limited evidence* (*).	
	Extreme temperature anomalies, droughts and wildfires have significant negative short-term impacts on economic growth (in the year of and in the year following the disaster); storms, floods and wet-mass movements also affect economic growth significantly negatively in the long term (more than 5 years after the disaster).	Klomp and Valckx (2014), Kousky (2014)	Strong sensitivity of economic growth to extreme events. *High confidence* (***, *high agreement* and *robust evidence* from more than 25 independent studies)	
Africa	**Observations:** Per capita GDP growth rates have been subject to substantial fluctuations including changes in sign in Sub-Saharan Africa in the period 1970–2009.	World Bank's World Development Indicators and African Development Indicators databases		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: In SSA countries, there is an inverted U-shaped relationship between annual mean temperature and economic growth. If a threshold temperature of 24.9°C is exceeded, a percentage increase in temperature significantly reduces economic performance in SSA by approximately 0.13%. Below the threshold, an increase in average temperature by one degree increases economic performance by 3%. Study is based on panel data for 1970–2009 and for 18 SSA countries.	Alagidede et al. (2016)	Strong sensitivity of GDP to annual temperature anomalies, *low confidence* (*)	
Asia	**Observations:** Chinese total factor productivity (TFP) in the manufacturing sector and per capita GDP in this sector has been growing substantially over the period 1998–2007, driving increases in total per capita GDP due to the large importance of the manufacturing sector for the Chinese economy.	Penn World Tables v. 9.1		
	Attribution: Inverse U-shaped relationship between output in the manufacturing sector and local daily mean temperatures are mainly caused by a U-shaped dependence of the firm-level TFP on temperature for labour and capital-intensive firms. A day with temperature above 90 °F decreases TFP by 0.56%, relative to a day with temperature between 50 °F and 60 °F. Uses data from a half million Chinese firms over 1998–2007.	Zhang et al. (2018a)	Strong sensitivity of GDP and TFP in the manufacturing sector to daily temperature anomalies in China, no assessment elsewhere, *low confidence* (*) (needs verification by independent studies)	
Australasia	**Observations:**			
	Attribution: No studies.		No assessment	
Central and South America	**Observations:** Per capita GDP growth rates (in real as well as in nominal terms) of countries in Central America have been subject to substantial annual fluctuations including some changes of sign since 1960.	World Bank's World Development Indicator Database		According to World Development Indicator database of the World bank also employed by original studies (nominal and real GDP per capita in constant 2011 USD)
	Attribution: Tropical cyclone strikes reduce output growth on average by 0.83 percentage points in the year of the disaster.	Strobl (2012) (Central America and Caribbean)	Strong sensitivity of output growth to hurricane strikes in the year of the event in 5 Central American countries and 26 Caribbean Small Island States, no assessment elsewhere, *low confidence* (*, needs verification by independent studies)	Destruction caused by strong winds and extreme rainfall from hurricanes.
Europe	**Observations:**			
	Attribution: No studies.		No assessment	
North America	**Observations:** Per capita GDP growth rates (in real as well as in nominal terms) of the USA have been subject to annual fluctuations 1960.	World Bank's World Development Indicator Database		According to World Development Indicator database of the World bank also employed by original studies (nominal and real GDP per capita in constant 2011 USD)
	Attribution*: Dependence on variations in global mean temperature:* The combined value of market and non-market damage across analysed sectors (agriculture, crime, coastal storms, energy, human mortality, and labour) in the USA increases quadratically in global mean temperature, costing roughly 1.2% of gross domestic product per +1°C on average. The meta-analysis is based on individual studies demonstrating the sensitivity of the individual systems to regional fluctuations in temperature and precipitation.	Carleton and Hsiang (2016), Hsiang et al. (2017) (meta-analysis based on multiple peer-reviewed studies: labour [1], mortality [2], crime [2], agriculture [3], coastal impacts [1], energy costs [1])	Strong sensitivity of economic performance to global mean temperature fluctuations in the USA, *medium confidence* (**)	

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Sensitivity to hurricanes: Hurricanes reduce annual GDP growth rates of affected coastal counties by at least 0.45 percentage points in the year of the shock; no significant longer-term impacts; negligible effect on state and national level.	Strobl (2011)	Moderate sensitivity of economic performance to hurricane strikes in affected coastal counties in the USA, *low confidence* (*, would need support from independent studies) No assessment elsewhere	Of the negative growth effects of a hurricane, 28% are due to relatively richer people moving away from affected counties in response to the hurricane.
Small Islands	**Observations:** Per capita GDP growth rates (in real as well as in nominal terms) in Small Islands States have been subject to substantial annual fluctuations including frequent changes of sign since 1960.	World Bank's World Development Indicator Database		According to World Development Indicator database of the World bank also employed by original studies (nominal and real GDP per capita in constant 2011 USD)
	Attribution: Tropical cyclone strikes substantially reduce economic activity in the 0.5–1.5 years following the disaster. Non-significant or even positive impacts are observed after this period. Strong differences in the response dynamics of the various sectors. *Immediate impacts in the year of the tropical cyclone strike:* Estimates of loss in income growth induced by hurricanes range from 0.83 (across 26 Caribbean Small Islands States + 5 Central American countries, Strobl, 2012) to 1.5 percentage points (21 Caribbean Small Islands States, Bertinelli et al., 2013) in the year of the disaster. In individual cases, the losses can reach much higher values (Mohan et al., 2017, on the impact of Cyclone Pam on South Pacific Small Island States; Ishizawa et al., 2019, on Dominican Republic). *Long-term effects:* Inconsistent findings ranging from no effects beyond the year of the strike (Bertinelli et al. 2013) to negative impacts up to 15 months after the strike (Ishizawa et al. 2019) and even longer-lasting impacts (2–3 years after the event) such as significant reduction of exports or consumption (Mohan et al., 2018). The different timing and different directions of the impacts on individual components of national GDP may hide the signal in overall GDP.	Strobl (2012) (26 Caribbean Small Islands States + 5 Central American countries), Bertinelli and Strobl (2013) (21 Caribbean Small Islands States), Ishizawa et al. (2019) (Dominican Republic), Mohan and Strobl (2017) (impact of Cyclone Pam on South Pacific Small Island States), Mohan et al. (2018) (21 Caribbean Small Islands States)	Strong sensitivity of economic activity to hurricane strikes in the Caribbean and South Pacific Islands, (*high confidence* ***, *High agreement* across studies using different methods) No assessment elsewhere	
S30	Other societal impacts—Within-country inequality			
Global	**Observation:** Since 1980, within-country income inequality has increased in nearly all countries, but at different speeds. It has increased rapidly in North America, China, India and Russia and moderately in Europe. Average inequality within developing countries has been slowly rising, though staying fairly flat since 2000.	Ravallion (2014), Alvaredo et al. (2018), UNDP (2013)		
	Attribution: Based on data for 92 countries, extreme weather events have contributed to an increase in within-country inequality because poor people suffer relatively higher well-being losses.	Chapter 8; Hallegatte and Rozenberg (2017), Hallegatte et al. (2016), Hallegatte et al. (2017)	Low to moderate sensitivity of within-country inequality to extremes, *low confidence* (*, *high agreement*, but more independent studies needed since all studies are based on World Bank's *Decomposing World Income Distribution Database* and share same Methodology)	Poorer people are more strongly exposed to climate extremes and have lower coping capacities. Their consumption losses (relative to their lost assets) are therefore larger than for richer parts of the populations
	Based on data from 86 countries from 1965 to 2004, among fluvial and flash floods and tropical cyclones, only floods have been found to negatively impact within-country income inequality. The impact is observed only in the very short term (up to 5 years after disaster) and does not persist in the long term (5–10 years after disaster).	Yamamura (2015)		As risk of extreme weather events can be predicted, rich people tend to reside in less risky areas. Moreover, poor people are less able to invest in disaster-prevention measures.

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
Africa	**Observations:** Sub-Saharan Africa has the second-highest average within-country income inequality of all world regions, although with no clear trend since 1980. North Africa has seen steadily falling inequality in this period. *Ethiopia:* Since 1980, Ethiopia has seen large increases in average income, but income inequality has prevailed. *Kenya:* Inequality in Kenya has been decreasing since 1990. However, the country remains unequal, where the top 1% of households have 15% of total income compared with 14% of total income for the bottom 50% of households.	World Inequality Database, Alvaredo et al. (2018), World Inequality Lab (2017)		
	Attribution: There is evidence that low rainfall has increased within-country inequality in Ethiopia and Kenya; see individual statements below.		Moderate sensitivity of within-country inequality to droughts in Ethiopia and Kenya, *low confidence* (*), no assessment elsewhere	
	Ethiopia: Ethiopian drought of 1998–2000 had regressive effects on household income. Poverty traps exist below a certain post-shock asset threshold.	Carter et al. (2007), (1998–2000 drought in Ethiopia), Dercon et al. (2005)	Moderate sensitivity of within-country inequality to droughts in Ethiopia, *low confidence* (*, hypothesis would need support from other independent studies)	Poorer households have less financial means to recover and a higher risk to fall below the post-shock asset threshold marking the poverty trap.
	Kenya: Negative annual rainfall anomalies have significantly reduced income of households and calorie consumption in rural Kenya, and pushed additional people into poverty.	Wineman et al. (2017)	Moderate sensitivity of income and calorie consumption to negative annual rainfall anomalies. *Low confidence* (*, needs support by other independent studies)	Among four weather extremes (high rainfall, low rainfall, heat and high winds), households in rural Kenya are mostly affected by low rainfall, as they rely on rain-fed agriculture and livestock.
Asia	**Observations:** Trends in consumption inequality between 1990 and early 2010s have been heterogeneous across the region, with pronounced inequality increases in China and India and strong inequality reductions in the Russian Federation. Individual cases for which there is research on the sensitivity of within-country inequality to variations in weather conditions:	Alvaredo et al. (2018)		
	Myanmar: In the period 2005–2010, average real household consumption expenditures remained stagnant, but measured poverty incidence and inequality both declined significantly in Myanmar.			
	India: Consumption inequality in India has been rising at a moderate pace since the early 1990s. The increase accelerated between 1993/1994 and 2004/2005, and then slowed down.	India's National Sample Surveys		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: *Myanmar after Cyclone Nargis in 2008:* Increased inequality within affected regions but decreased inequality between affected and non-affected regions. Overall measured inequality declined because between-region reduction exceeded the within-region increase. Low sensitivity of within-country consumption inequality to major cyclone Nargis in Myanmar.	Warr and Aung (2019) (Myanmar)	Sensitivity of within-country inequality to weather fluctuations ranges from low (impact of individual tropical cyclones) to high (impact of rainfall variability and drought conditions in rural areas) in Vietnam, India and Myanmar, *low confidence* (*, would need further independent studies) No assessment elsewhere (not indicated in the figure in favour of highlighting the range of findings, given that only two types of rating can be displayed)	
	India: Poor households in rural India respond more strongly to (seasonal) temperature changes: an increase in spring temperature by 1°C increases consumption of the non-poor by 6% and reduces consumption of the poor by almost 22%. In the cold rabi season, poor households profit more strongly from higher temperatures than non-poor households. Less precipitation is harmful to the poor in the monsoon kharif season and beneficial in the winter and spring seasons. Adverse weather aggravates inequality by reducing consumption of the poor farming households. Strong sensitivity of within-country consumption inequality to seasonal temperature anomalies in rural India.	Sedova and Kalkuhl (2020)		Agriculture is a main impact channel for consumption inequality.
	Vietnam: Higher rainfall variability and higher intensity of floods and meteorological droughts negatively impact growth of household consumption in Vietnam. Consumption reduction is higher among poor households, increasing within-country inequality:weather extremes increase the share of the population living under the poverty threshold in Vietnam from 18.9% to 21.6%, and cause a rise of the inequality (Gini) index by 0.2%. Estimates based on 2008 household survey. Strong sensitivity of within-country inequality to weather extremes in Vietnam. Sensitivity in both rural and urban areas, mainly to rainfall variability and meteorological droughts.	Bui et al. (2014)		Higher rainfall variability and meteorological droughts mainly impacts the consumption of poor people in rural areas, whereas floods more strongly affect urban areas.
	Vietnam: Households living in communes with steeper slope, higher annual rainfall and temperature variability and flood and drought hazards have significantly lower consumption. Poor households in communes with higher annual rainfall variability and drought hazards have significantly lower consumption growth. Household-level, three-wave, panel data 2010, 2012, 2014.	Narloch and Bangalore (2018)	Moderate sensitivity of regional consumption differences to exposure to annual rainfall and temperature variability, and flood and drought hazards	
North America	**Observations:** Since 1980, within-country income inequality has increased rapidly in the USA.	Ravallion (2014), Alvaredo et al. (2018), UNDP (2013), Alvaredo et al. (2018)		
	Attribution: Historical US hurricanes have increased inequality in affected states. For every 100 billion USD in hurricane economic damages, there is an increase in income inequality by 5.4% as measured by Gini coefficient.	Miljkovic and Miljkovic (2014) (state-level panel data 1910–200), Boustan et al. (2020) (county-level panel data 1920–2010)	Strong sensitivity of income inequality in the USA to hurricane strikes; *medium confidence* due to *high agreement* of different longitudinal studies but partially conflicting findings for individual hurricanes, e.g., Katrina (Shaughnessy, 2010) (**) No assessment elsewhere	Richer people are moving out. There are conflicting findings for individual hurricanes, e.g., Katrina (Shaughnessy et al., 2010).

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Small Islands	**Observations:**			
	Attribution: *Impact of tropical cyclone Evan on Samoan households.* Poorer households suffered higher and more persistent losses with regard to their livelihoods than middle- and high-income households.	Le De et al. (2015)	Low sensitivity of income inequality in Samoa to major tropical cyclone Evans, *low confidence* (*) No assessment elsewhere	Middle- and high-income households receive remittances which push up their recovery. The lack of remittances for the poor in Samoa increases within-country inequality.
34b	Other societal impacts—Between-country inequality			
Global	**Observation:** Annual per capita GDP growth rates were similar in developing countries and industrialised countries in the period 1960–2000. From 2000 onwards, GDP growth rates were substantially higher in developing than in industrialised countries.	World Bank's World Development Indicators		
	Attribution: Extreme weather events and temperature fluctuations dampen the convergence of economic development:		Sensitivity of between-country inequality to variations in weather conditions range from moderate (e.g., substantial impact on economic productivity in developing compared with non-significant impacts in developed countries) to low (e.g., GDP growth in developing economies where the agricultural sector is important is more strongly reduced by droughts than in developed economies where the agricultural sector is only from minor importance), *high confidence* (***, good agreement across many independent studies).	
	Positive annual temperature anomalies dampen the convergence of economic development. They lead to a stronger reduction in economic growth rates in developing countries than in industrialised countries, probably because the agricultural sector, which suffers the largest growth rate losses, is more important for developing than for industrialised countries.	Dell et al. (2012); Felbermayr and Gröschl (2014); Letta and Tol (2019)		Driver: annual temperature variability; strongest growth rate losses in agricultural sector. Poor countries have a much larger share of their GDP in this sector.
	Increases in seasonally adjusted day-to-day temperature variability reduce macro-economic growth. An extra degree of variability results in a five-percentage-point reduction in regional growth rates on average. The impact of day-to-day variability is modulated by seasonal temperature difference and income, resulting in highest vulnerability in low-latitude, low-income regions (12-percentage-point reduction).	Kotz et al. (2021)		
	Tropical cyclones have a relatively stronger adverse impact on long-term economic growth in low-income countries than in industrialised countries. Panel data 1960–2002 *(low confidence)*.	Berlemann and Wenzel (2018)		Impact channels: long-term growth losses in low-income countries increased by (i) lack of protection measures, (ii) increase in net fertility and (iii) decrease in educational efforts in disaster aftermath.
	Droughts affect short-term (year of drought or year after drought) as well as long-term (up to 5 years after disaster) GDP growth rate in poorer countries more strongly than in OECD countries (*low confidence*).	*Short term:* Panwar and Sen (2019), Fomby et al. (2013) *Long-term* (up to 5 years after disaster): Berlemann and Wenzel (2016)		Impact channels: long-term growth losses due to (i) lower education levels, (ii) lower saving rates and (iii) higher fertility in aftermath of droughts.
	Moderate fluvial floods have stronger positive short-term effect on GDP growth in developing than in industrialised countries. (Extreme floods have negative impact on GDP growth rate in developing and industrialised economies.)	Fomby et al. (2013), Panwar and Sen (2019), Cunado and Ferreira (2014)	*Medium confidence* (**, *high agreement*, hypothesis would need support from other independent studies)	Share of agricultural GDP larger in developing countries than in industrialised countries.
	Fluvial floods increase between-country income inequality in the short term (up to 5 years after disaster); this effect disappears in the long term (within 10 years after disaster).	Panel data 1965–2004 for 83 countries: Yamamura (2015)	*Low confidence* (*, hypothesis would need support from other independent studies)	Poor people are more dependent upon strongly affected agricultural sector and are less mobile.

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
	Meta-analysis of extreme events impact: Climatic (extreme temperatures, droughts, wildfires, etc.) and hydro-meteorological (floods, storms, wet-mass movements) disasters have relatively stronger adverse impact on economic growth of developing countries than of developed countries.	Klomp and Valckx (2014), Kousky (2014)	Low sensitivity of between-country inequality to weather extremes. *High confidence* (***, results are derived from meta-analysis of 25 independent studies, and more than 750 regressions)	As developing countries rely more on agriculture, climatic and hydro-meteorological extreme events have a larger negative impact on their economies.
S28	Other societal impact—Heat-related mortality			
Global	**Observations:** Excess human mortality. **Attribution:** Ample evidence that exposure to high and low ambient temperatures is associated with excess mortality around the world, across climatic zones. Notable geographical heterogeneity in the shape of the relationship, with warmer climates showing higher optimal temperatures where the minimum mortality risk is observed. Most research is based on data from developed countries in temperate climates, but more research on the topic is recently originating from developing countries and (sub) tropical climates (see below).	Gasparrini et al. (2015b), Guo et al. (2014), Son et al. (2019), Ryti et al. (2016), Mora et al. (2017), Green et al. (2019), Carleton et al. (2020), Chapter 7	Strong sensitivity; *high confidence* (***)	A number of (patho-) physiological pathways have been identified that link exposure to heat and cold with increased mortality risk, predominantly involving cardiorespiratory disease patterns.
Africa	**Attribution:** Higher mortality rates on days with raised temperatures have been documented in a number of African countries (Ghana, Burkina Faso, Kenya, South Africa, Tanzania, Tunisia), with largest risks among children and the elderly. Involved causes of deaths are cardiovascular diseases, respiratory diseases, suicide and other non-communicable diseases.	Scovronick et al. (2018) (South Africa), Wichmann (2017) (South Africa), Azongo et al. (2012) (Ghana), Diboulo and Si (2012) (Burkina Faso), for more references see Chapter 9	Where assessments available, strong sensitivity; *low confidence* (*) Many African countries without assessment (not indicated in Figure 16.1 in favour of showing the results of the available studies)	
Asia	**Attribution:** Exposure to heat and cold increases relative risks of mortality in the tropical/subtropical locations in the Middle East and southeast and South Asia studied, similarly to what is known for East Asian regions. In addition to all-cause mortality, increaes in mortality across a wide range of causes (cardiovascular, respiratory, diabetic, infectious diseases) have been associated with high temperatures, especially heatwaves, in Asia.	Gholampour et al. (2019) (Iran), Alahmad et al. (2019) (Kuwait), Seposo et al. (2015) (Philippines), Dang et al. (2016) (Vietnam), Ingole et al. (2017) (rural India), Fu et al. (2018) (India), Mazdiyasni et al. (2017) (India), for more references, covering East-Asian regions see Chapter 10	Strong sensitivity; *high confidence* (***)	
Australasia	**Attribution:** Exposure to non-optimal ambient temperature is associated with excess mortality/life shortening in Australasia. There is also evidence that increased temperature variability at an hourly time scale increases mortality risk. Evidence of temperature–mortality associations in Australasia stems from studies considering all-cause mortality and specific causes (e.g., out-of-hospital cardiac arrest).	Huang et al. (2012) (Brisbane), Cheng et al. (2017) (five Australian capital cities), Doan et al. (2021) (Brisbane), Nitschke et al. (2011) (Adelaide), Hales et al. (2000) (Christchurch, NZ), Chapter 11	Strong sensitivity, *high confidence* (***)	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
Central and South America	**Attribution:** Evidence that mortality is associated with heat and cold, with notable differences in the contribution of cold versus heat to total temperature-related mortality depending on prevailing climate (dry, temperate, tropical). Population characteristics, such as age, gender, education level and housing conditions, have been shown to explain heterogeneity in observed risks in Brazil.	Péres et al. (2020) (Brazil), Son et al. (2016) (Brazil), Rodrigues et al. (2019) (Brazil), Chapter 12	Strong sensitivity, *medium confidence* (**)	
Europe	**Attribution:** Ample evidence points to the sensitivity of human mortality in Europe to high and low ambient temperature. This encompasses a wide range of mortality causes, especially with regard to heat. Specific pathways such as the association of hot nights with increased mortality risk have also been documented. Besides age and gender, individual fitness has also been shown to modify susceptibility to heat. At the level of city characteristics, population density, air pollution levels and green area coverage have been identified as important modifiers of the heat effect.	Recent European-scale analysis: Martínez-Solanas et al. (2021), Urban et al. (2021); Cause-specific mortality: Gasparrini et al. (2012); Hot nights: Royé et al. (2021); Risk factors: Schuster et al. (2017), Sera et al. (2019), see also Chapter 13	Strong sensitivity, *high confidence* (***)	
North America	**Attribution:** High and low temperatures increase mortality, with impacts varying by age, gender, location and socioeconomic factors. Temperature–mortality associations in the USA and Canada have been intensively researched, with earliest publications on the subject stemming from the early 20th century.	Barreca (2012), Martin et al. (2012), Nordio et al. (2015), Weinberger et al. (2019), Lay et al. (2021), Chapter 14	Strong sensitivity, *high confidence* (***)	
Small Islands	**Attribution:** Elevated summer temperatures are associated with increased non-accidental mortality in Puerto Rico. Stroke and cardiovascular diseases are primary underlying causes of death.	Méndez-Lázaro et al. (2018), Chapter 15	Strong sensitivity, *low confidence* (*) Many Small Island countries without assessment (not indicated in Figure 16.1 in favour of showing the results of the available studies)	
S17	Water distribution—Water-borne diseases			
Global	**Observations:** Water-borne diseases encompass a wide range of pathogens and water-associated transmission pathways. The focus here lies on gastrointestinal infections/diarrhoeal diseases, which are typically associated with water-borne transmissions and constitute a large proportion of the global burden of diseases. It is important to note that a clear distinction between water-borne and food-borne transmission is not possible for some of the pathogens causing gastrointestinal infections (e.g., *Campylobacter*), which were included in the assessment.			

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
	Attribution: Positive associations between ambient temperatures and all-cause diarrhoea are reported from low-, middle- and high-income countries. Recent meta-analyses find, as their central estimates, 3% and 7% increase in all-cause diarrhoea per 1°C rise in ambient temperatures, respectively. Underlying this temperature sensitivity of enteric infections are, however, critical differences between involved pathogens. While bacterial diarrhoea generally shows positive associations with temperature, the risk of viral diarrhoea decreases with higher temperatures. There is also evidence that the incidence of diarrhoeal diseases increases after heavy rainfall and flooding events, especially in areas with low hygiene and sanitation standards. No conclusive evidence exists regarding the effect of droughts on diarrhoeal disease outbreaks, with results dependent on location-specific settings.	Chua et al. (2021), Carlton et al. (2016), Levy et al. (2016)	Low to high sensitivity depending on the sanitary conditions, *medium confidence* (**)	High ambient temperatures, high precipitation and flooding events are associated with increased incidences of water-borne diseases. The strength of the association is modulated by socioeconomic determinants (in particular, hygiene and sanitation standards) and environmental factors (such as flowing or standing water as sources of drinking water).
Africa	**Attribution:** Studies in several African countries (Ethiopia, Senegal, South Africa, Mozambique) provide evidence that both high ambient temperatures and high precipitation show positive associations with diarrhoeal cases. Specifically, for cholera outbreaks, the influence of inter-annual variability in temperature and rainfall, as linked to the ENSO cycle, has been shown, albeit socioeconomic determinants also play a role. There is, e.g., evidence on the critical role of human mobility related to a mass gathering that took place during the initial phase of the 2005 cholera outbreak in Senegal, in addition to the role of rainfall in driving disease transmission. Similarly, there is evidence that the spread of intestinal schistosomiasis in Burkina Faso has been linked to human mobility and water development projects (dam construction), besides climatic factors implicated in the disease transmission. There is also evidence from Africa on positive associations between ambient temperature and gastrointestinal diseases linked to protozoan parasites (*Cryptosporidium*, *Giardia*).	Chapter 7, Finger et al. (2016), Perez-Saez et al. (2015)	Strong sensitivity, *medium confidence* (**)	
Asia	**Attribution:** Weather sensitivity of diarrhoeal diseases has been found in several Asian countries (e.g., Bangladesh, Cambodia, China, Philippines, Vietnam, India). Climatic variables associated with increased incidences of diarrhoea are high temperatures, high humidity and high cumulative rainfall. There is also evidence that diarrhoeal disease incidences (including leptospirosis and typhoid fever) rise following heavy rainfall events and flooding, modulated by the presence/absence of functioning sanitation systems. For seasonal cholera and shigellosis outbreaks in Bangladesh, the influence of inter-annual climate variability linked to the ENSO cycle has also been demonstrated.	Cash and Rod (2014) (cholera, shigellosis, Bangladesh), Phung et al. (2015) (all-cause diarrhoea, Vietnam), Mertens et al. (2019) (all-cause diarrhoea in children, India), Zhang et al. (2019) (infectious diarrhoea, China), Chapters 7 and 10	Strong sensitivity, *medium confidence* (**)	

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Australasia	**Attribution:** Partly inconsistent evidence exists for the associations between water-borne enteric diseases and climatic variables in Australia and New Zealand. While positive associations of temperature and rainfall have been found for some diseases (cryptosporidiosis, giardiasis) in specific locations, other studies were not able to confirm the associations or found inconsistent results across different locations studied. For *Campylobacter* cases, associations with temperatures were generally insignificant, yet a recent outbreak in New Zealand could be linked to contamination of a local water supply following heavy rainfall. Clearer evidence exists regarding the increased incidence of viral diarrhoea (rotavirus) during periods of lower temperature.	Hales (2019) (review), MILAZZO et al. (2017) (*Campylobacter*), Bi et al. (2008) (*Campylobacter*), Britton et al. (2010) (*Cryptosporidium*, *Giardia*); D'Souza et al. (2008) (rotavirus); Lal et al. (2013) (*Cryptosporidium*, *Giardia*, *Campylobacter*), Gilpin et al. (2020) (*Campylobacter*) Milazzo et al. (2017) (*Campylobacter*), Bi et al. (2008) (*Campylobacter*), Britton et al. (2010) (*Cryptosporidium*, *Giardia*), (D'Souza et al., 2008) (rotavirus), Lal et al. (2013) (*Cryptosporidium*, *Giardia*, *Campylobacter*), Gilpin et al. (2020) (*Campylobacter*)	Moderate sensitivity, *low* (*) to *medium* (**) *confidence*	
Central and South America	**Attribution:** Research from Ecuador showed that heavy rainfall events were linked to increased diarrhoeal incidences only if they followed a dry period, whereas after a wet period heavy rainfall events had a protective effect. For the cholera outbreaks starting 1991 in Peru and 2010 in Haiti, recent studies point to the role of climatic factors (especially rainfall) in determining seasonal dynamics of the ongoing epidemic. By contrast, most evidence shows that climate factors were not responsible for the initial emergence of the disease. In particular for Peru, there is evidence that ENSO influenced the resurgence of cholera in 1998, but did not impact the emergence in 1991. In Haiti, recent studies demonstrate that the pathogen strain of *Vibrio cholerae* initiating the cholera epidemic was introduced through foreign emergency aid troops sent to Haiti after the earthquake. Non-climatic factors such as failing sanitation systems, and the immunity status and mobility of susceptible populations were also shown to be critical drivers of disease transmission.	Carlton et al. (2014) (diarrhoea incidence), Ramrez (2015) (cholera, Peru), Ramrez and Grady (2016) (cholera, Peru), Rinaldo et al. (2012) (cholera, Haiti), Orata et al. (2014) (cholera, Haiti)	Strong sensitivity; *medium confidence* (**)	

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
Europe	**Attribution:** Ample evidence exists for the association of ambient temperatures with water-borne/gastrointestinal disease occurrence in Europe. Water-borne disease outbreaks have also been linked to heavy rainfall events, albeit not all studies are consistent in this finding. There is evidence from France that heavy rainfall and associated flush events increased acute gastrointestinal outcomes only if preceded by a dry period. Where heavy rainfall was identified as a driver of water-borne disease outbreaks, single household water supplies were identified as particularly vulnerable.	Kuhn et al. (2020) (*Campylobacter*); Suk et al. (2020) (review flooding-related infectious disease outbreaks), Morral-Puigmal et al. (2018) (gastrointestinal infections), Atchison et al. (2010) (rotavirus), (2016) (aetiology-unspecific water-borne outbreaks), Semenza et al. (2012) (review), Setty et al. (2018) (gastrointestinal infections)	Moderate sensitivity; *medium confidence* (**)	
North America	**Attribution:** In the USA and Canada, water-borne disease outbreaks have been found to be often preceded by heavy rainfall events. For Massachusetts, USA, it was shown that emergency room visits for gastrointestinal illness were associated with heavy rainfall events only in areas with combined sewer overflows, where stormwater runoff and sewage is jointly released into drinking water sources. High temperatures, and especially extreme heat, has also been associated with increased hospitalisations due to gastrointestinal infections in New York State, USA.	Levy et al. (2018), Jagai et al. (2015), Jagai et al. (2017)	Moderate sensitivity, *medium confidence* (**)	
Small Islands	**Attribution:** Weather sensitivity of water-borne diseases are well documented for Small Island States. One study finds positive associations between temperature, rainfall and gastrointestinal infections in the Federal States of Micronesia. The exceptional ENSO-associated severe drought of 2011 in Tuvalu was found to be linked with a large diarrhoea outbreak, with underlying risks especially high where the drought severely lowered the water availability of household tanks and decreased hand washing frequency. There is also clear evidence of substantially increased morbidity and mortality in Small Island States hit by recent category 4–5 tropical cyclones (TCs). For example, TC Maria affecting Puerto Rico in 2017 was associated with up to 3000 excess deaths in the 5 months following the event. TC Winston hitting Fiji in 2016 induced a large burden of enteric infections, with 30% of the registered surveillance cases after the event reporting acute watery diarrhoea. In the Cook Islands and French Polynesia, it has been demonstrated that the incidence of ciguatera fish poisoning (CFP) is associated with sea surface temperature anomalies.	McIver et al. (2015), McIver et al. (2016), Emont et al. (2017), Santos-Burgoa et al. (2018), Zheng et al. (2020), Chapters 7 and 15 Zheng et al. (2020)	Strong sensitivity, *medium confidence* (**)	

Background information for Figure 16.2 Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
S27	Other societal impacts—Vector-borne diseases			
Global	**Observations:** **Attribution:** There is no analysis of the contribution of weather fluctuations to the observed fluctuations of vector-borne disease incidence at the global scale. Attribution of variation in incidence has only been done at the regional level (see below). However, based on these individual assessments, the sensitivity of vector-borne disease incidence to weather fluctuations is rated moderate at global scale (*medium confidence*).		Moderate sensitivity, *medium confidence* (**)	
Africa	**Observations:** *Malaria*: Malaria epidemics are highly seasonal in some parts of Africa (e.g., in Sahelian countries such as Nigeria and Burkina Faso); in others (mainly Central Africa), transmission is not restricted to specific seasons but is year round. *Outbreak in Sudan, 2019*: There was a large outbreak of malaria in Sudan in 2019, with malaria accounting for 12.4% of all diseases surveyed, and 30% increase in mortality compared with the previous year. An earlier outbreak in 2013 led to an increase in the number of severe malaria cases from 18.4% in 2012 to 22.5% in 2013. *Outbreak in Ugandan highlands 1998:* An epidemic of malaria in southwestern Uganda occurred in 1998. The epidemic occurred in a highland area with normally moderate to low malaria transmission. *Dengue:* Dengue outbreaks in Africa are predominantly confined to urban areas.	Sinka et al. (2020), Lindblade et al. (1999) (Uganda outbreak 1998), OCHA (2019) (Sudan 2019), Elsanousi et al. (2018) (Sudan 2013)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: *Malaria:* Intensity and duration of malaria outbreaks across Africa are primarily determined by interventions such as vector control, prophylaxis and anti-malarial availability, as well as socio-political stability. More recent outbreaks are partly attributed to drug resistance and resistance to insecticides used for control, and the arrival of urban-adapted mosquito vectors. Outbreaks in Ugandan (1998) highlands and Sudan (2013 and 2019) have been associated with extreme flooding. Higher than average rainfall resulting from the 1997 El Niño event was shown to be associated with a malaria epidemic in southwest highland Uganda. Specifically, increased rainfall before and during the outbreak was positively correlated with *Anopheles* vector density one month later. *South Africa:* Malaria outbreaks in South Africa are positively associated with La Niña induced extreme rainfall events and sea surface temperature anomalies in the Indian Ocean. *Botswana, Kenya, Tanzania:* Temporal patterns of outbreaks in Botswana, particularly in 1996 (1982–2002), Kenya (1982–2000) and Tanzania (1997–1998) are highly related to seasonal patterns of rainfall, and are also associated with the Indian Ocean Dipole and abnormal rainfall following drought conditions, which support populations of breeding mosquito vectors via water storage in and around the home. *Malawi:* A study of variations in malaria burden in Malawi, between 2004 and 2017 indicated that a unit increase in rainfall 3 months prior to case detection was associated with a 3% increase in childhood malaria burden, and every 1°C increase in temperature was associated with a 3% increase.	Boyce et al. (2016); Adeola et al. (2017) Elsanousi et al. (2018) (Sudan, flooding 2013); Hashizume et al. (2009) (malaria outbreaks, Kenya); Mabaso et al. (2007) (South Africa, La Nina); Behera et al. (2018) (SSTs, South Africa); Thomson et al. (2006) (malaria outbreaks, Botswana); Jones et al. (2007) (malaria outbreaks, Tanzania); Chirombo et al. (2020) (malaria, Malawi); Lindblade et al. (1999) (Uganda outbreak 1998)	High sensitivity of malaria incidence to extreme rainfall events in Uganda and Sudan, *medium confidence* (**) Moderate sensitivity of malaria incidence to ENSO fluctuations in South Africa, *high confidence* (***) Low sensitivity of dengue outbreaks to rainfall and temperature; *low confidence* (*) Summary for Figure 16.2: Weather influence is ranging from high regarding the outbreaks in Uganda (1998) and Sudan (2019), *medium confidence* (**), to low for dengue outbreaks, *low confidence* (*)	*Malaria:* The dominant malaria vector across Africa, *Anopheles gambiae*, breeds in stagnant pools of water left by rainfall. The vector is also an indoor-resting mosquito so is responsive to vector control such as indoor residual spraying. Socio-political status and humanitarian crises can affect the accessibility of healthcare such as anti-malarials.
	Dengue: *Kenya:* Although climate conditions were shown to be important predictors of the number, timing and duration of dengue outbreaks in a predictive study in Kenya, empirical evidence found no association between temperature and precipitation directly on dengue incidence. However, extremely wet conditions in Kenya between 2013 and 2019 were associated with elevated vector abundance. Although climate factors can determine the size of dengue outbreaks, other factors such as the introduction of new serotypes influence outbreak occurrence.	Caldwell et al. (2021) (dengue predictions, Kenya), Nosrat et al. (2021) (dengue vector abundance)		*Dengue:* The dengue virus is carried and spread by *Aedes* mosquitoes, primarily *Aedes aegypti*, and to a lesser extent *Aedes albopictus*, which is becoming increasingly important. *Aedes aegypti* rest and breed in and around dwellings, particularly in urban areas with high population density.

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
Asia	**Observations:** *Dengue:* Dengue is the highest burden vector-borne disease in Asia, although malaria is important seasonally. Dengue is endemic, and large outbreaks of dengue typically occur seasonally. Dengue transmission occurs synchronously across Southeast Asia, with particularly high incidence between 1997 and 1998.	van Panhuis et al. (2015); Lai et al. (2018)		
	Malaria: A large proportion of Asia is endemic for *Plasmodium vivax* malaria transmission.	Battle et al. (2019)		
	Attribution: *Dengue:* Across Asia, variation in temperature is an important climatic driver of seasonal and inter-annual variations in dengue incidence. Local weather anomalies, such as above-average temperatures and rainfall, can trigger dengue outbreaks.	Servadio et al. (2018)	Moderate sensitivity of malaria incidence to climate variation, *low confidence* (*) Moderate sensitivity of dengue to climate variation, *medium confidence* (**)	*Dengue:* During rainfall events induced by El Niño and monsoon season, high rainfall increases the availability of *Aedes* mosquito breeding habitats, subsequently increasing *Aedes* mosquito abundance. Warm and humid conditions accelerate the development of *Aedes* mosquitoes and viruses such as dengue virus inside the mosquito. Urbanisation and population mobility can increase dengue risk owing to introduction of new serotypes and increased breeding habitats in and around homes in urban areas.
	South and Southeast Asia: A nonlinear association between maximum average monthly temperature and the risk of an outbreak of mosquito-borne disease has been reported in South and Southeast Asia between 1980 and 2013, with a peak at temperatures of 33.5°C. *Cambodia:* In Siem Reap, Cambodia, an increase of 1°C in maximum temperatures was associated with a 36.9% increase in dengue cases, and there was a minimal effect of rainfall. *Thailand:* A study on Thailand (1982–2013) found that 8% of the inter-annual variation of dengue relative risk can be explained by inter-annual variations in precipitation and temperature in the previous month, once seasonality and spatial variation have been accounted for.	Servadio et al. (2018) (mosquito-borne disease outbreaks, South and Southeast Asia, 1980–2013) Choi et al. (2016) (dengue, Cambodia 1998–2012) Lowe et al. (2016) (dengue inter-annual variation, Thailand)		
	China: Ecological niche models constructed to explain dengue outbreaks across mainland China between 1980 and 2016 showed that mean temperature of the coldest quarter contributed 62.6% to observed dengue outbreaks. In addition, the East Asian summer monsoon, bringing hot and rainy conditions is also important in determining dengue occurrence.	Liu et al. (2020) (China, dengue outbreaks), Sang et al. (2014) (dengue, temperature, China 2006–2012)		
	India: Using correlation analyses over 1994–2015, a study showed that an increase in the intensity of El Niño events during November–February increases the probability of a malaria outbreak in the following year, in northern and eastern states of India. These findings are supported by a more recent study showing a high correlation between ENSO and dengue cases, with more cases during the monsoon season following large El Niño events across most states.	Dhiman and Sarkar (2017) (India, malaria and El Niño), Pramanik et al. (2020) (India, ENSO)		

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Malaria: Republic of Korea: Generalised linear models and distributed lag nonlinear models for the period 2001–2009 showed a positive association between climate variation and *P. vivax* malaria in temperate Republic of Korea, with every 1°C increase in temperature increasing incidence by 17.7%, and a 10 mm increase in rainfall increasing incidence by 19.1%, when accounting for the time taken for mosquito development and parasite incubation.	Kim et al. (2012) (*P. vivax* malaria inter-annual variation, Republic of Korea)		*Malaria:* Warmer temperatures can increase malaria transmission by accelerating development and breeding of *Anopheles* mosquitoes, as well as shortening the *Plasmodium* parasite incubation period inside the mosquito vector, meaning mosquitoes become infectious quicker. Rainfall creates stagnant pools of water, which act as important mosquito breeding habitats for important vectors *Anopheles dirus* and *An. minimus* in the Greater Mekong sub-region. *An. stephensi* is a major vector in urban areas of south Asia.
Australasia	**Observations:** In Australia, Ross River virus (RRV), Barmah Forest virus (BFV) and dengue are three of the most common and clinically important vector-borne diseases with notable seasonal patterns. RRV and BFV contribute the largest annual disease burden and are endemic to Australia. Dengue exhibits periodic epidemic activity currently limited to the northeast corner of Australia.	Bannister-Tyrrell et al. (2013), Stratton et al. (2017)		
	Attribution: *RRV:* Regression models fitted to surveillance data on RRV, BFV and dengue (from 1993, 1995 and 1991, respectively, through 2015) incorporating seasonal, trend and climate (temperature and rainfall) parameters captured an average of 50–65% variability of the data. Climate variables play a dominant role in explaining the inter-annual variability of these vector-borne diseases.	Stratton et al. (2017) (regression models 1991–2015)	Moderate sensitivity of vector-borne disease (Ross River virus, Barmah Forest virus and dengue) to climate variations, *low confidence* (*)	
	Dengue: Between 1993 and 2005, lower values in the Southern Oscillation Index, coinciding with warmer conditions were associated with an increase in areas of Queensland, Australia reporting dengue cases.	Hu et al. (2010b) (Queensland 1993–2005)		In Cairns, Australia, most dengue transmission occurs in the warmer, wetter months (October–March, which is explained by the reduction in the extrinsic incubation period of the dengue virus at higher temperatures and the increased abundance of *Ae. aegypti* during the wet season.
Central and South America	**Observations:** *Dengue:* New arboviruses have emerged, including chikungunya and Zika, and their burden is greater in the Americas than anywhere else in the world. There was a large Zika epidemic in 2016. *Zika:* Zika emerged and spread in Brazil in 2015, causing a large epidemic in 2016 with 205,578 cases reported.	PAHO and WHO (2021), Lowe et al. (2018b), Puntasecca et al. (2021) Lowe et al. (2018a)		
	Malaria: Incidence of malaria in areas that were on track for elimination have increased in recent years between 2015 and 2017, including in Ecuador, Venezuela, Colombia, Dominican Republic and Panama.	WHO (2020)		

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: *Dengue: Brazil:* An analysis of monthly dengue cases reported in Brazil between 2001 and 2016 showed that the spatial and temporal pattern of 'dengue waves' is partly controlled by weather conditions, in particular precipitation. While human mobility patterns are in general the dominant predictors, precipitation was more important than human mobility for the seasonality of dengue at the mesoregion and finer spatial levels. An empirical analysis of monthly dengue cases data for the 558 microregions of Brazil (2001–2019) showed that the relative risk of dengue increased on average by 1.56 one month after extremely wet conditions compared with normal conditions and 1.43 four months after drought conditions.	Churakov et al. (2019) (2001–2016), Lowe et al. (2021) (2001–2019)	Moderate sensitivity of dengue incidence to climate variations, *high confidence* (***) Moderate sensitivity of malaria incidence to climate variations, *medium confidence* (**)	*Dengue:* Droughts can augment transmission as they drive water storage near households, bringing *Aedes* mosquito breeding sites near humans via household water storage, while extremely wet conditions provide additional mosquito breeding sites.
	Venezuela: Periodic cycles of dengue in northern Venezuela (1991–2016) were shown to correspond to local and ENSO-related climatic variation at seasonal and inter-annual time scales. During El Niño events when conditions were warmer and drier, peaks in dengue were more prevalent. However, other factors that contribute to inter-annual patterns of dengue were not explicitly accounted for, such as introduction of dengue virus serotypes and population immunity.	Vincenti-Gonzalez et al. (2018)		
	Ecuador: An empirical analysis of the inter-annual variability in dengue fever in southern coastal Ecuador (1995–2010) showed that morbidity rates were higher during El Niño events, which are associated with warm and wet conditions, with 28% more cases for each degree of warming of Pacific sea surface temperatures. A subsequent modelling study using incidence data from 2002–2014 showed that a 1°C increase in mean temperature would result in a 40% increase in dengue incidence, although results were highly influenced by the choice of climate data product used in the model. Overall, the climatic variables explained 5% of the inter-annual variation in the standardised morbidity ratio for dengue. The modelling approach was also used to show that the particularly early dengue peak in 2016 may be explained by El Niño induced flooding. *Zika*: The rapid spread of Zika in Brazil in 2016 was partly attributed to the major 2015–2016 El Niño event.	Stewart-Ibarra and Lowe (2013) (Ecuador, 1995–2010) Lowe et al. (2017) (Ecuador, El Niño), Fletcher et al. (2021) (Ecuador, 2002–2014) Muñoz et al. (2017)		
	Malaria: Ecuador: In southern coastal Ecuador (1990–2018), for every 1°C increase in minimum temperature, cases of *P. falciparum* malaria were found to increase by 136%, and *P. vivax* malaria to a lesser extent, by 77%. Additionally, local temperature variations were found to account for almost all the seasonal variation in *P. falciparum* malaria but only a minimal proportion of the *P. vivax* variation, which was much less sensitive to local climate variation.	Fletcher et al. (2020) (malaria, Ecuador 1990–2018)		*Malaria:* Warmer temperatures increase transmission of malaria, by speeding up the development of *Anopheles* mosquitoes, and replication of the parasite inside the mosquito. This relationship is stronger for *P. falciparum*, which is more sensitive to climate than *P. vivax* because of the characteristic relapses in *vivax* infections.

Background information for Figure 16.2				
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Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
Europe	**Observations:** *Dengue and other arboviruses:* The Asian tiger mosquito (*Aedes albopictus*) that transmits dengue, chikungunya and Zika viruses, is present in many southern European countries, including Italy, eastern Spain, southern France and western Balkans. During the summer, the majority of continental Europe has suitable climate conditions to sustain seasonal dengue epidemics. A major outbreak of dengue, resulting in more than 2000 cases, occurred in Madeira in 2012. More recently, the south of France experienced an autochthonous outbreak of dengue and in summer 2017, and Italy experienced a number of outbreaks of chikungunya, with more than 200 cases reported.	Semenza and Suk (2018), Liu-Helmersson et al. (2016) (*albopictus* distribution), Wilder-Smith et al. (2014) (Madeira outbreak), Succo et al. (2016) (France, dengue 2015 outbreak), Rezza (2018) (Italy 2017 chikungunya outbreak)		
	West Nile Fever (WNF): West Nile virus generally causes sporadic outbreaks in Europe, but larger outbreaks can occur. Data from 2002 to 2013 show an increase in the number of districts reporting West Nile Fever cases from 2010. In summer 2010, the number of WNF cases in previously uninfected areas in Europe and its neighbouring countries was the highest number ever reported. During the 2018 transmission season, which started unusually early, more infections were reported than the total from the previous 7 years.	Sambri et al. (2013) (Europe outbreaks), European Centre for Disease Prevention and Control (ECDC) (2010 record of cases), Haussig et al. (2018) (WNF outbreak in summer 2018), ECDC (2018) (2018 season)		
	Attribution: *Dengue:* There is *limited evidence* that weather extremes, such as summer heatwaves in Europe are linked to dengue outbreaks; most outbreaks in Europe have been shown to be highly associated with travel patterns, with 70% of variation in imported cases 2010–2015 in Europe explained by connectivity.	Campbell et al. (2015) (dengue, Europe), Caminade et al. (2012), Massad et al. (2018) (dengue, connectivity), Salami et al. (2020) (dengue, connectivity 2010–2015)	Low sensitivity of dengue incidence to climate variations, *low confidence* (*) Moderate sensitivity of West Nile Fever incidences to climate variations, *medium confidence* (**)	*Dengue:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance.

Background information for Figure 16.2

Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')

Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	West Nile Fever (WNF): A logistic regression analysis of WNF outbreaks reported in Europe between 2002 and 2013 showed elevated West Nile risk with higher temperature anomalies and the detection of water bodies. However, other important non-climatic factors include bird migratory routes, wetlands and previous outbreak occurrences. A study investigating the 2010 summer West Nile Fever outbreak in Europe showed significant positive correlations between cases and elevated temperatures. A less formal analysis of the timing and spatial pattern of the outbreak in summer 2018 also indicates a positive association of WNF cases with temperature and precipitation patterns. Temperatures over the summer of 2018 were higher than the 1981–2010 average in West Nile-affected areas, and some countries such as Italy and the Adriatics experienced above-average rainfall. Warmer temperatures allowed for establishment of the *Culex pipiens* mosquito vector, which was found to be positive for West Nile virus at 35% of surveillance stations in Serbia. In northern Italy, 2010–2015, West Nile Fever outbreaks were preceded by hot summer temperatures. The effect of rainfall on West Nile Fever varies geographically, and results are less consistent. In northern Italy, heavy rainfall was linked to increases in West Nile Fever incidence. In contrast, in Romania between 2011 and 2013, drought conditions were associated with increases in the *Culex* vector abundance and subsequent West Nile virus infections.	Tran et al. (2014) (high temperatures and satellite-based detection of free water bodies predictors for the occurrence of WNF on district level, 2002–2013), Paz et al. (2013) (linkage between the 2010 heat and the WNF eruptions), Haussig et al. (2018) (summer 2018 outbreak), Moirano et al. (2018) (Italy, 2010–2015), (Cotar et al., 2016) (Romania, 2011–2013)		*West Nile Fever:* Temperature speeds up the vectorial capacity of *Culex* mosquitoes as well as viral replication of West Nile. Abundance of *Culex* mosquitoes is sensitive to rainfall, with large amounts flushing out habitats and drought conditions bringing hosts and mosquito vectors into close contact via water storage practices.
North America	**Observations:** *West Nile Fever:* Large epidemic transmission of West Nile Fever occurred in the USA, with unprecedented spread along the eastern coast in 2002–2003. A high number of cases (over 2000) of West Nile were reported between 2013 and 2018, with peaks in the summer season. The economic cost of West Nile Fever is substantial (USD 56 million estimated per year), and treatment is limited.	Ronca et al. (2021)		
	Dengue: Dengue is primarily limited to the southern USA, where climate is suitable for seasonal summer transmission, particularly in Texas, Hawaii and Florida. Around 100 imported cases are reported each year.	Bouri et al. (2012)		
	Lyme disease: Lyme disease in the USA exhibits a seasonal pattern, with peaks in the summer months (June–July). Large outbreaks occurred in the summers of 2009 and 2017.	Nelson et al. (2015), Rochlin et al. (2019a), CDC (2021)		

Background information for Figure 16.2

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Region	Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems	Reference	Synthesis statement (strength of influence, level of confidence)	Underlying mechanism
	Attribution: *West Nile Fever (WNF)*: Positive associations between WNF seasonality, infection risk and warmer temperatures have been found in Connecticut (2000–2005) and in California (2003–2009). Specifically, a study across 17 states in the USA 2001–2005 found that an increase in weekly temperature of 5°C was associated with up to 50% higher reported infections of WNF. Although Lyme closely follows variations in temperature, it is also influenced by human behaviour such as outdoor activity. Drought conditions have been shown to enhance WNF outbreaks in southern Florida.	Soverow et al. (2009) (West Nile, USA 2001–2005), Liu et al. (2009) (Connecticut, 2000–2005), Hartley et al. (2012) (California 2003–2009), Shaman et al. (2005) (drought, Florida 2001–2003)	Moderate sensitivity of West Nile Fever to temperature; *medium confidence* (**) Low sensitivity of dengue outbreaks to rainfall and temperature; *low confidence* (*) Moderate sensitivity of Lyme disease to temperature and rainfall; *high confidence* (***) For Figure 16.2, we summarise: sensitivities range from low (dengue), *low confidence* (*), to moderate (Lyme), *high confidence* (***)	*West Nile Fever:* Temperature speeds up the vectorial capacity of *Culex* mosquitoes as well as viral replication of West Nile. Abundance of *Culex* mosquitoes is sensitive to rainfall, with large amounts flushing out habitats and drought conditions, bringing hosts and mosquito vectors into close contact via water storage practices.
	Dengue: Outbreaks typically occur as a result of increased travel to endemic areas and subsequent importation of cases, with an estimated 100 imported cases every year. Local transmission in the southern USA could be sensitive to weather fluctuations, particularly in Texas, Hawaii and Florida, where climate is suitable for seasonal summer transmission. In an urban area of Georgia in 2015, anomalous increases in daily maximum temperatures led to increases in *Aedes albopictus* mosquito emergence.	Murdock et al. (2017) (albopictus, Georgia)		*Dengue:* Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance.
	Lyme: In New York State (1991–2006), Lyme disease cases were higher when minimum temperatures were higher, with one additional spring day increasing summer cases by 6–8% on average. In contrast, high temperatures have been shown to lead to decreased incidence of Lyme disease in the northeast USA (2002–2006). An earlier onset of the Lyme disease season was associated with reduced rainfall across 12 endemic US states 1992–2007. Although Lyme closely follows variations in temperature, it is also influenced by human behaviour such as outdoor activity.	Lin et al. (2019) (Lyme, New York State), Moore et al. (2014) (rainfall, 12 US states), Tran and Waller (2013) (northeast USA, high temperature, 2002–2006)		*Lyme:* Warmer temperatures shorten the life cycle and increase abundance of *Ixodes* ticks that carry Lyme disease. Increased temperatures also expand the distribution and range of rodent and deer hosts, as well as their activity, increasing human exposure to Lyme disease. High temperatures can leave tick larval nymphs susceptible to desiccation, which can lead to subsequent decreases in Lyme disease.
Small Islands	**Observations:** In recent years, the Caribbean region has experienced an unprecedented crisis of co-occurring epidemics of dengue, chikungunya and Zika viruses. Between 2013 and 2019, 186,050 cases of dengue, 911,842 cases of chikungunya and 143,127 cases of Zika were reported. The Pacific often experiences epidemic outbreaks of dengue with an explosive outbreak, e.g., occurring in the Republic of the Marshall Islands in 2011 infecting 3% of the population. The Cook Islands are currently experiencing a dengue outbreak of rising concern, with an estimated 300 cases reported as of mid-2021. In New Caledonia, cases of dengue are detected every year, causing recurrent outbreaks, along with co-circulation of the Zika virus.	PAHO/WHO (2019) (arboviruses in the Caribbean), Sharp et al. (2014) (dengue, Republic of the Marshall Islands, 2011–2012), Uwishema et al. (2021), WHO (2021) (dengue, Cook Island, 2021), Inizan et al. (2019) (dengue, New Caledonia)		

Background information for Figure 16.2				
Sensitivity of natural, human or managed systems to fluctuations in climate or climate-related systems ('Identification of weather sensitivity')				
Region	**Observed variations or disturbance of the natural, human or managed systems + attribution to fluctuations in climate or climate-related systems**	**Reference**	**Synthesis statement (strength of influence, level of confidence)**	**Underlying mechanism**
	Attribution: *Dengue: Barbados:* Nonlinear and lagged functions of minimum temperature and the standardised precipitation index (SPI-6) explained 14% more of the variation in dengue cases than a baseline model including only monthly and yearly random effects. The greatest increase in dengue risk was found 3–5 months following drought conditions and 0–2 months following extremely wet conditions. *Puerto Rico*: Monthly dengue transmission rates between 2000 and 2011 were 3.4 times higher (95% CI 1.9–6.1) for each 1°C increase in SST and 2.2 higher (95% CI 1.3–3.5) for each 1°C increase in minimum air surface temperature. *Fiji*: Following one of the most powerful storms recorded in the South Pacific, Cyclone Winston, 2016, twice the average number of cases were observed. A rapid risk assessment conducted by Fiji's Ministry of Health and Medical Services and WHO identified several factors that increased the risk of disease transmission and outbreaks including large displaced populations, overcrowded emergency shelters, limited access to clean water, disruption of the sanitation infrastructure, and increased exposure to mosquitos and other disease vectors. *New Caledonia:* During epidemic dengue years between 1971 and 2010 in New Caledonia, case distribution was highly seasonal and associated with temperatures in the previous 1–2 months, and coincided with maximum levels of rainfall and humidity. Inter-annual case variation was also associated with temperature and rainfall, but not with large-scale climate forcings such as ENSO.	Lowe et al. (2018b) (Barbados), Méndez-Lázaro et al. (2014) (Puerto Rico), Sheel et al. (2019) (Fiji), Descloux et al. (2012) (New Caledonia)	Moderate sensitivity of dengue to temperature and precipitation variation; *medium confidence* (**)	*Dengue*: Warmer temperatures between 27°C and 29°C speed up *Aedes* mosquito development and viral replication and incubation inside the mosquito. Rainfall is crucial for the water-dependent stages of mosquito development and increases *Aedes* abundance. Compromised sanitation and water access as a result of flooding and extreme weather events can create new mosquito breeding sites and increase human exposure to *Aedes* mosquitoes.

SM16.7.4 Details of Key Risks by System and Region Identified by WGII Chapters

Table SM16.24 | Key risks by system and region. This table lists a selection of key risks identified by authors of chapters from across the WGII report. In addition to the nature of the key risk, the table provides a description of the consequences of the risk that would constitute a severe outcome (thereby meeting the definition of a key risk as potentially severe), and the hazard, exposure and vulnerability conditions that would contribute to the risk being severe. In addition, it provides the adaptation options identified by authors as having the highest potential for reducing the risk, and an assessment of the confidence in the judgement that this risk could become severe. Methodology: Guidance was provided to each chapter consisting of a general description of the table, explanations of the information requested in each column, and examples of the type of information sought in each column. The general description of the table included the definition of a key risk (a 'potentially severe' risk) and the five types of criteria for identifying them, as described in Section 16.5.1. There is no unique means for applying the criteria to the identification of a key risk. Identification is an expert judgement made by chapter authors, based on the scientific literature and the key risk criteria. The tables attempt to make clear the conditions of hazards, exposure and vulnerability associated with the key risks. A fuller assessment of these key risks can be found in the underlying chapters in sections indicated in the last column.

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Chapter 2: Terrestrial and freshwater ecosystems and their services								
Plant and animal species extinctions	Global	Extinction of up to 54% under the highest emissions scenario	Increases in temperature or changes in precipitation that go beyond the tolerance limits of a species, rates of change that exceed dispersal capabilities, new climate combinations that species cannot tolerate, disappearance of suitable habitat, particularly at high elevations	All plant and animal species are exposed, deforestation, habitat fragmentation, air and water pollution, and competition from invasive species exacerbate exposure	Certain species have evolved in very specific climate conditions, certain species are endemic to a small geographic range, many plants and smaller animal species have limited dispersal capabilities	Reducing agricultural expansion, deforestation, and other forms of habitat destruction will reduce exposure; conservation of corridors or other critical areas can help maintain habitat connectivity; increasing global protected area will save more habitat	*High confidence*, (*robust evidence*, *medium agreement*)	2.4.2.2, 2.5.1.3
Wildfire increase	Global	Wildfire that substantially exceeds natural levels can cause extensive tree mortality, degrade ecosystem integrity, increase carbon emissions, which would exacerbate climate change in a self-reinforcing feedback, and increase property damage, illnesses, and death of people	Increased heat, decreased precipitation, and increased severity of drought, caused by anthropogenic climate change, which would increase aridity of vegetation and soil	All vegetated areas on Earth are exposed, deforestation severely exacerbates exposure to wildfire, other forms of habitat destruction, degradation, and fragmentation increase exposure; people who live in fire-prone areas or areas where smoke accumulates are more exposed to damage, illness and death from wildfire	Biomes and ecosystems that are normally wet or cold where wildfire has been rare are most susceptible to degradation of ecosystem integrity, particularly tropical rainforest and Arctic tundra; people in impoverished living conditions or with pre-existing health conditions are more vulnerable	Reducing deforestation, particularly in tropical and boreal forests will reduce human ignitions and help sustain natural vegetation and soil moisture; prescribed burning or allowing naturally ignited fires to burn in areas of unnatural fire suppression can reduce fuel loads and risks of catastrophic wildfire	*High confidence* (*high agreement*, *robust evidence*)	2.4.4.2, 2.5.3.2, FAQ 2.3
Ecosystem carbon loss	Tropical rainforests and Arctic and boreal permafrost	Tipping points of conversion of major fraction of tropical rainforest to grassland or thawing of extensive areas of permafrost, releasing carbon in a short period equivalent to years or decades of current emissions that would substantially exacerbate climate change	In tropical forest, drought caused by heat of anthropogenic climate change and low precipitation in areas of high inter-annual variability, increased wildfire caused by heat of anthropogenic climate change that dries vegetation; in Arctic tundra, increased temperature substantially exceeding historical levels	All tropical forests and Arctic tundra areas are exposed; areas of tropical deforestation and the more southern tundra areas are most exposed	Tropical rainforests have evolved in wet, humid conditions, so they are susceptible to drought and wildfire; Arctic tundra permafrost requires below-freezing temperatures	Reducing deforestation and use of fire will reduce exposure of rainforests to drought and wildfire; reducing roads and other infrastructure in permafrost areas could reduce exposure to warmer conditions and ignitions from human activities	*Medium confidence* (*high agreement*, *medium evidence*)	2.4.4.4, 2.5.3.4

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Chapter 3: Ocean and coastal ecosystems and their services								
Loss and degradation of warm-water coral reef ecosystems	Tropical and subtropical seas, small islands	Severe degradation of 70–90% of the world's warm-water coral reef ecosystems, with >1.5°C of global average surface warming due to mortality from frequent bleaching, and effects of acidification and sea level-rise	The frequency of severe bleaching-level heat stress exceeding required coral reef recovery time (i.e., Degree Heating Weeks ≥ 8°C per week more than once every 5 years); severe risks projected to occur with >1.5°C of global average surface warming. More extensive losses and reduction in reef growth and extent at greater rates of warming and atmospheric CO_2	Warm-water coral reef ecosystems in all ocean regions have been exposed to bleaching-level heat stress, with some ecosystems like the Great Barrier Reef experiencing decline in coral coverage from repeated bleaching-related morality	Vulnerability is currently high globally, with exceptions in locations with variable temperatures and lower non-climate hazards. Inability of corals to adapt via physiological acclimation or evolutionary processes will contribute to risk becoming severe with >1.5°C of global average surface warming	Some local risk may be reduced through marine protection and management (reduction of other non-climate stressors), coral restoration and possibly emerging technologies like assisted gene flow, assisted evolution or synthetic biology	*Very high confidence* (*robust evidence*, *high agreement*)	2.4.2.2, 2.5.1.3
Risk to marine coastal ecosystem services due to loss of habitat-forming species	Coastal ocean, including estuaries	Loss of ecosystem services (income, food, shoreline protection) from rapid transformations in coastal ecosystems dependent on foundational, habitat-forming species (e.g., corals, kelp and seagrasses) due to warming and marine heatwaves	Warming rate and frequency of marine heatwaves sufficient to promote shift to algae- and turf- dominated systems. Values vary regionally and between systems, but broadly associated with >1.5° global mean surface warming for coral reefs and >2°C for kelp systems	Increasing population in coastal regions, particularly in reef islands near sea level	Vulnerability is highest at the warm end of species' ranges, and where societal dependence on aquaculture, fishing and mariculture is highest	Some local risk may be reduced through identification of refugia, marine protection and management (reduction of other non-climate hazards), and ecosystem restoration	*High confidence* (*medium evidence*, *high agreement*)	3.4.2.1, 3.4.2.2, 3.4.2.3
Risk to species habitat and fisheries due to hypoxia	Shallow ocean waters, including shelf seas, semi-enclosed seas, and coastal waters	Expansion, increased duration and emergence of new seasonal 'dead zones' of hypoxic water, causing species die-offs, reducing habitat and affecting fisheries	Warming increases the rates of aerobic metabolism, especially among microbes, and also enhances stratification, limiting the ability of oxygenated waters to mix. Increased frequency of heavy or extreme precipitation might result in greater nutrient loading of coastal waters, which is known to further exacerbate hypoxia		Vulnerability exacerbated by nutrient loading from human activity, worsening hypoxia in regions dependent on fisheries for livelihoods	Managing nutrient inputs to coastal systems from terrestrial sources is a key tool for managing the occurrence and spread of hypoxic waters	*High confidence* (*robust evidence*, *high agreement*)	3.4.2.4, 3.4.2.7, 3.4.2.8, 3.4.2.9

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Reduced growth and survival of calcifying species, including shellfish	Coastal ocean	Reduced growth and abundance of calcifying species, including shellfish, reef-building corals and calcareous red algae. For shellfish and calcifying algae, risk expected to be severe under RCP8.5 by the end of the century	The key hazard is ocean acidification, with potential synergistic interactions between ocean acidification, warming and deoxygenation. Available data indicated the hazard level is species dependent	As atmospheric CO_2 increases, a greater range of taxa will be exposed to the effects of ocean acidification. Exposure is greatest at mid-to-high latitudes and in warm-water coral reefs	Local warming and deoxygenation are known to exacerbate the vulnerability of some taxa to the effects of ocean acidification. Eastern Boundary-Current Upwelling systems are prone to rapid impacts from ocean acidification	Design considerations and small-scale interventions may reduce the effects of ocean acidification on shellfish operations	*High confidence* (*robust evidence*, *medium agreement*)	3.4.2.1, 3.4.2.2, 3.5
Risk to food security, employment and livelihoods due to impacts on fisheries yields	Global ocean, particularly low latitudes, shelf seas and semi-enclosed seas	Lower fisheries productivity and reduced fisheries yield, with consequences for food security, employment and livelihoods, particularly in areas reliant on seafood for protein and income. Absent management reforms, fishery yield could decline >50% by 2100 in some equatorial regions under RCP4.5	Warming shifts species distributions and warming-associated stratification of the water column reduces transfer of nutrients from the deep, and affects primary productivity. More frequent and intense marine heatwaves exacerbate the hazard	Changes are expected globally, with strongest warming-induced decline in fish biomass predicted for the Atlantic, Pacific and Indian Oceans	Vulnerability expected to be highest in coastal communities that depend directly on fisheries for income, livelihoods and food. Industrial fisheries are less vulnerable, but conflict and inequalities may arise from greater adaptive capacity of industrial fisheries. Implications for coastal communities in terms of lost employment (both direct and indirect) could be significant, as could implications for communities dependent on seafood for protein	Proactive (anticipatory) and adaptive fisheries management could reduce risks, as could diversification of employment and food sources. International agreements also can play a role in maintaining adaptive management over shifting stocks	*Medium confidence* (*moderate evidence*, *moderate agreement*)	3.3, 3.4.3, 3.4.4.2, 3.6.3
Risk to regional marine biodiversity, ecosystem function and associated ecosystem services	Global ocean, but mainly poleward of the tropics	Expansion of species ranges and changes in phenology leading to homogenisation of marine biodiversity at regional scales, species invasions and trophic mismatches. Severe risk would include novel communities providing limited ecosystem services to society	Regional warming and increased heat content of the upper ocean, especially during cooler months, increasing habitat suitability for warmer-affinity species at poleward (leading) range edges. Organisms like phytoplankton that respond to surface temperature are changing phenology at faster rates than organisms that respond to bottom-water temperatures (e.g., eggs of commercially important fish), causing a mismatch between trophic levels	Warmer surface waters expand to mid- and high-latitude oceans	Vulnerability is highest in regions with high fish consumption and high dependence on fisheries for income and livelihoods. For trophic mismatches, risk is greatest with benthic ecosystems and species that spend part of their lives at depth	Implementation of ecosystem-based management to reduce fisheries pressure on geographic spawners, maintain diverse size and age structures, and reduce non-climate hazards, particularly in spawning grounds	*High confidence* (*high agreement*, *medium evidence*)	3.3, 3.4.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk to coastal communities from flooding and sea level rise due to loss of coastal habitat	Coastal ocean, including sandy beaches and saltmarshes	Consequences include loss of life from extreme events, loss of land, and loss of key infrastructure. Flooding, erosion and salinisation of groundwater from sea level rise exceeding adaptive capacity of coastal systems, including soft-sediment shores and coral reefs, and adjacent human communities, including cities and high-value infrastructure	Sea level rise increasing the frequency and severity of flooding and wave overtopping events, of erosion in soft-sediment shorelines, and of salinisation of groundwater in soft-sediment and limestone shorelines	Increasing population and high-value infrastructure in coastal regions, particularly low-elevation coastal cities, delta regions and reef islands	Increasing density in cities and communities adjacent to soft-sediment shores, especially beaches; coastal developments and shoreline engineering degrading coastal habitats and reducing resilience to flooding and erosion	Proactive coastal zone management that blends ecosystem-based adaptation, protective measures and managed retreat from soft sediment shorelines, in order to allow the coast to equilibrate as sea levels rise over coming centuries	*High confidence* (*robust evidence*, *high agreement*)	3.4.2.1, 3.4.2.2, 3.4.2.4, 3.4.2.5, 3.4.2.6, 3.5
Degradation of Arctic ecosystems and loss of traditional Arctic livelihoods	Arctic Ocean	Loss of habitat and changes to the food web due to reduction of seasonal sea ice and to sea level rise, with consequences for Indigenous communities including loss of traditional livelihoods, relocation of communities, and injury from changes in ice/snow conditions	Reduction in sea ice extent and thickness, reducing safe travel, hunting and traditional fisheries; integrated effect of sea ice loss and sea level rise on coastal erosion and wave damage		Commercial activities, including, shipping, petroleum, fisheries and tourism, are increasing with warming, increasing the risks of compound impacts on ecosystems	Options for local and Indigenous communities includes improved and real-time ice forecasting, enhanced search and rescue capabilities, investment in local infrastructure, shift in diets and livelihoods, alleviate non-climate stressors, and commercial fisheries adapting to changes in stock productivity	*High confidence* (*robust evidence*, *high agreement*)	3.4.2.10
Risk of water-related diseases affecting human health and ecosystem services	Global oceans, focus on coastal regions	Impacts on food provisioning, tourism, economy and human health due to increase in geographical extent and frequency of harmful algal blooms, spread of marine pathogens, exposure and bioaccumulation of contaminants	Key hazards include ocean warming, acidification, anoxia, sea level rise, extreme weather/climate events, such as heatwaves, storm surges, heavy rainfall, flooding and drought	Global increase in the extent of areas displaying favourable conditions for proliferation of microbial pathogens and harmful algae	Vulnerability is highest in areas of high seafood consumption, and which are exposed to nutrient pollution from land; may be exacerbated by sea level rise increasing suitable habitats for microbial pathogens	Options includes reducing nutrient pollution from land-based activities; developing predictive model and capacity for improved monitoring and early warning systems; developing sensors for location detection of pathogens and harmful algal blooms	*High confidence*	3.4.2.7, 3.4.2.8, CCB-ILLNESS (Chapter 2), 3.6.2.2
Chapter 4: Water								
Freshwater supplies not meeting demand for agriculture or drinking	Global	Over 1 billion people experiencing 'chronic' water scarcity (less than 1000 m^3 of freshwater per person per year)	Annual mean river flows providing water supplies substantially lower than amount required to meet demand	Populations living in areas prone to reduced water availability	Low ability to manage, store and supply freshwater, due to low levels of wealth, inappropriate governance or inadequate planning and implementation of water infrastructure. The latter could arise from uncertainties in future regional climate projections and *low confidence* in decision-making	Improved water management infrastructure and consumer behaviour	*High confidence*	4.1.1

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Loss of life and damage to property from river flooding	Global	More than 100 million people per year affected by river flooding	Peak river flows exceeding capacity of river channels or flood protection measures by substantial magnitude and/or with high frequency	Populations living on flood plains	Lack of access to early warnings to avoid personal exposure to floods. Poor sanitation governance leading to increased likelihood of disease during and following floods. Absence of insurance cover for property	Improved flood management measures, including communications networks for provision of early warnings and evacuation advice. Improved provision of emergency sanitation facilities. Increased access to insurance cover	*High confidence* (for changes due to hazard alone). *Medium confidence* if exposure and vulnerability considered	4.2
Loss of life and damage to property from wildfire	Global	Substantial increase in number of people per year affected by wildfire	High intensity of fire weather and/or long fire season	Populations living in fire-prone areas	Lack of access to early warnings to avoid personal exposure to wildfire. Pre-existing health conditions exacerbated by exposure to smoke. Absence of insurance cover for property	Improved wildfire management measures, including communications networks for provision of early warnings and evacuation advice. Improved access to healthcare for smoke inhalation-related conditions. Increased access to insurance cover	*High confidence* (for changes due to hazard alone). *Medium confidence* if exposure and vulnerability considered	4.2
Loss of valued aspects of culture due to changes in water (including cryosphere)	Global (especially cold regions for cryosphere impacts)	Loss of environmental character deeply associated with cultural identity	Sea ice reduced below levels that support traditional means of travel. Streamflows changed to levels that discourage species for traditional hunting	Populations with strong cultural identity links to water, snow and ice conditions			*High confidence*	4.4.4
Reduced energy supplies due to hydrological impacts	Global	Widespread and/or frequent disruption to energy supplies affecting large numbers of people	Reduced stream flows affecting hydropower. Increased water temperatures reducing cooling of thermal power stations. Increased flooding impacting electricity distribution networks	Energy infrastructure assets in areas prone to flooding. High reliance on single sources of energy production	Lack of alternative energy supplies or battery storage	Increased resilience of energy infrastructure, diversification of energy supply sources	*High confidence*	4.3.2
Reduced biodiversity in freshwater ecosystems	Global	Substantial loss of species in freshwater ecosystems	Substantial increase in drought conditions in ecosystems dependent on freshwater bodies	Large proportion of freshwater ecosystems in regions prone to drought	Fragmented landscape limiting capacity for species dispersal	Active landscape management, or removal of human land use, to enlarge and connect local freshwater ecosystems	*High confidence*	4.3.5
Chapter 5: Food, fibre and other ecosystem products								
I. Risks related to food security and malnutrition								

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Short-term and/ or chronic food and feed shortage with cascading risk of civil unrest and social disruption	Global, but particularly in arid or flood-prone regions of low-income countries and civil unrest urban areas	Widespread food and feed shortages resulting in price spikes for staple crops, with disproportionate effect on the poor, potentially leading to civil unrest and social disruption. Increase in childhood stunting	Widespread summer heat and drought conditions across major breadbasket regions. Climate extreme events such as flooding or drought in low-income countries	The globally connected food system which relies on these staple crops for food and feed	Vulnerability is higher for those whose income is largely spent on food, in particular those living in persistent poverty, with limited social support, limited trade and transport of food; smallholder producers and countries that rely on agricultural production for livelihoods; low-income households living in flood zones; and areas with civil conflict and poor governance, particularly in urban areas	Policies to support research on agricultural productivity and resilience, increase international grain reserves, increase access to diverse food for low-income people.	*Medium confidence* (*medium evidence*, *medium agreement*)	5.2.2, 5.4.3, 5.12.4
Water insecurity and usage conflict for inland fisheries, affecting food and nutritional security	Global, but in particular low-income Asian and African countries, representing 57% and 25% of global inland catches respectively	Decline in inland fisheries leading to potentially large increase in food insecurity and malnutrition of those people in communities and regions reliant on inland fisheries for food		Exposure will increase as precipitation changes and extreme events (floods, cyclones, storms, heatwaves) intensify	Large numbers of people in low-income countries currently reliant on inland fisheries for direct human consumption and nutritional security. Inland fish provide the equivalency of full dietary animal protein to 158 million people. 43% of inland fish capture comes from 50 low-income food-deficit countries	Local and national governance on water usage prioritisation incorporating food security and nutritional risks	*Medium confidence* (*medium evidence*, *medium agreement*)	5.8.2
II. Risks related to food safety and dietary health								
Risk to health and micronutrient availability due to CO_2- and temperature-related changes in crop quality and nutrition	Global	Worsened health and nutritional outcomes particularly in children and pregnant women, leading to stunting wasting and other forms of malnutrition, including obesity	Higher atmospheric CO_2 concentrations, together with other abiotic changes such as higher temperatures, alter nutrient density and composition in many crops including vegetables and fruits, enhancing underlying drivers of malnutrition	Global exposure	All populations, but the most vulnerable include the elderly, the urban poor, Indigenous communities, women, children and other marginalised groups	Provide integrated adaptation programmes that promote healthy eating, diversify farming systems and build livelihood and social support for low-income households. Increase productivity/resilience of current nutrient dense foods such as fruits and vegetables	(*Robust evidence*, *medium agreement*)	5.4.3, 5.12.3, 5.12.4
Risk of malnutrition, including obesity, due to climate-change-related loss of access to dietary diversity	Global	Limited dietary diversity and more cereal based food leading to malnutrition, including obesity or overweight	Heat, drought, floods or any other climatic shocks that would affect food availability and food prices, in particular animal-sourced foods, vegetables and fruits	Large number of low-income people are affected by volatile food prices	Vulnerability is higher for those in persistent poverty, with limited social support	Stress tolerant adaptation measures that would minimise the food production loss. Climate information services that would minimise the volatility of food price. Social support to increase food access for low-income population	*Medium confidence* (*medium evidence*, *high agreement*)	5.12.4

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Loss of food safety due to climate-related food poisoning or pollutant contamination	Global, but particularly in coastal areas of tropical and Asian countries with high dependence on fisheries and low -income countries which have flood-prone regions and/or limited food safety infrastructure	Food poisoning or pollutant contamination of food through increased prevalence of pathogens, harmful algal bloom, and increased contaminant bioaccumulation	Increases in temperature, higher humidity and atmospheric CO_2 concentrations	Increased incidence and toxicity of harmful algal blooms, increased reliance on harvested aquatic foods due to dietary shortages elsewhere. Food production and storage conditions that would increase pathogen activity, toxic compounds such as mycotoxins and gastrointestinal illness from harvested aquatic species	Small-scale harvesters for home consumption and small economic gain. Larger-scale harvesters exporting products (consumer safety) and supporting community economic stability	Reduction in land-associated inputs in aquatic systems, e.g., those leading to eutrophication and gastrointestinal virus outbreaks. Improved food safety regulations, storage and transport conditions. Food storage and transport conditions that reduce moisture content and improve harvest technologies to reduce harvest damage	*High confidence* (*medium evidence*, *high agreement*)	5.11.1, 5.12.4
III. Risks related to livelihood of people in the food and ecosystem service sector								
Health and livelihood risks to agricultural labourers due to increased temperature and humidity	Humid tropics and regions with expected large temperature increases	Loss of agricultural livelihoods in humid tropics for farm labour, pastoralists and small-scale food producers. Increases in agricultural labour days lost in hot, humid regions	More frequent periods that combine high temperature with high humidity	Manual labourers and field workers, particularly in poor tropical countries will be increasingly exposed to moist heat stress as climate hazards intensify and spread	Farming communities in the humid tropics that rely extensively on manual agricultural labour; livestock keepers	Diversify livelihoods to provide alternative sources of income. Development of and access to remote technology and machines for minimising outdoor work	*Medium confidence* (*medium evidence*, *medium agreement*)	5.12.4
Risk to livelihoods of livestock keepers seriously affected by increasing heat stress suffered by their animals	Humid tropics and regions with expected large temperature increases coupled with changing humidity levels	Loss of livelihoods; production, fertility and reproductive capacity of domesticated animals (particularly cattle) greatly reduced	More frequent and longer periods that combine high temperature with high humidity		Farming communities in the humid tropics that rely extensively on livestock, particularly cattle	Provide shade or cooling for animals; increase access to water; change livestock species	*Medium confidence* (*medium evidence*, *medium agreement*)	5.5.2, 5.12.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk to livelihoods in smallholder farming, fishing and aquaculture communities, including Indigenous communities	Low- and medium-income countries in tropics and semi-tropics	Collapse of rural livelihoods and widespread migration of small-scale food producers and low-income households in rural communities	More frequent extreme events, such as droughts, floods and hurricanes, and rising temperatures and precipitation changes due to climate change	Continued population dynamics and relatively high poverty levels, primarily in low- and middle-income countries, leading to greater numbers of vulnerable people exposed to these climate hazards	Vulnerability is higher for small-scale food producers especially in low- and middle-income countries, the elderly, Indigenous communities, producers with marginal assets, women, children and other marginalised groups	Provide integrated adaptation programmes that diversify farming systems and build livelihood and social support for low-income households; improve educational opportunities for children of affected producers to offer alternative livelihoods	*Medium confidence* (*medium evidence*, *medium agreement*)	5.8.2, 5.9.3, 5.12.3
Risk of food shortages and income loss to island and coastal communities and those that rely on coastal food production, particularly rice and coastal aquaculture	Coastal regions, and low-lying island states	Food shortages, income impacts and loss of infrastructure in mainly rural coastal communities, as a result of reduction in fisheries or aquaculture production. Both smallholding and large rice plantations may become economically unviable	Rapid sea level rise, higher temperatures, altered precipitation, impacts distribution, abundance and suitable habitat of aquatic species on global and regional scales	Exposure will increase with sea level rise and storms becoming intensified	Coastal vulnerability is highest in rural areas and for Indigenous Peoples relying largely on aquatic products and tourism for their livelihoods, and in areas with insufficient institutional support for adaptation and recovery, particularly for severe infrequent events	Convert affected low-lying regions to aquaculture of resilient species, increase biogenic coastal protection facilitate relocation of affected populations. Farm insurance, resilient cropping systems (e.g., agroforestry) and adaption of the build environment to reduce impacts from flooding/landslides	*High confidence* (*robust evidence*, *high agreement*)	5.8.2, 5.8.4, 5.9.3
Risk of hunger, loss of livelihood for fisheries-dependent populations, and transboundary conflict arising from the movement of aquatic resources	Global, but most severe in low-income, tropical coastal regions and small islands	National catch potential of living marine resources projected to decrease up to 25% by 2100, with tropical regions losing 40% of species (under RCP8.5 by 2100). Loss of livelihoods due to projected movements (projected value decrease of USD 6 billion by 2100), increased food insecurity due to reduced global food provision from the sea	Further water warming, and synergistic effects of ocean acidification and deoxygenation affecting abundance and distribution of aquatic resources	Exposure levels will increase as global warming, acidification and deoxygenation will worsen.	Vulnerability is highest for people from coastal regions of low-income countries, including small islands, who are largely dependent on fisheries for income and nutrition, and have no productive alternatives (about 200 million people today)	Fisheries management can substantially expand capacity to respond to a changing climate through interventions in the form of policies, programmes, and actions at multiple scales, but a great deal of political will, capacity building and collective action will be necessary	*Medium confidence* (*medium evidence*, *medium agreement*)	5.8.2, 5.9, Cross-Chapter Box MOVING PLATE in Chapter 5
IV. Risks to ecosystem services								

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk of severe decline in ecosystem provisioning services such as soil health and pollinators in terrestrial systems	Global, especially dryland areas and high-latitude areas	Negative impacts on pollinators, soil organic matter and microorganisms that support soil health, potentially reducing production of crops, fibre and other ecosystem products, and greenhouse gas mitigation capacity	Substantial warming can cause hotter droughts, more wildfires, greater variability in precipitation and shifts in biological events such as flowering		Vulnerability is highest in areas where ecosystem services already low, e.g., few pollinators or soil is already highly degraded	Support ecosystem adaptation approaches which support biodiversity and ecosystem services such as soil carbon sequestration as well as food production and livelihoods, e.g., conservation agriculture, agroecology, agroforestry	*Medium confidence* (*medium evidence*, *medium agreement*)	5.4.3, 5.10.4
Risk of biodiversity declines and reduction in carbon sequestration in aquatic systems	Global especially coastal areas	Species extinctions, reductions in ecosystem engineers, loss of ecosystem services such as food provisioning and greenhouse gas mitigation?	Further water warming, ocean acidification and deoxygenation creating phenology, distribution and primary productivity shifts		Vulnerability will be further increased through coastal habitat modification (e.g., mangrove deforestation) and coastal land use changes (e.g., eutrophication)	Preservation of biogenic habitats, management of terrestrial inputs into aquatic systems	*High confidence* (*medium evidence*, *high agreement*)	3.5.5, 5.9.3
V. Climate-policy-related risks								
Risk to health and well-being due to increased food insecurity and malnutrition from climate-mitigation related policies that solely focus on reducing GHG emissions	Global	Increased food insecurity and malnutrition for vulnerable groups	Policy decisions related to climate change (e.g., biofuels production) that ignore or worsen quality, access and utilisation of food		Vulnerability highest for low-income households, Indigenous groups, ethnic and religious minorities, women, children, refugees and small-scale producers	Support community-based ecosystem adaptation approaches which support viable livelihoods and food systems	*High confidence* (*robust evidence*, *high agreement*)	5.13.2, 5.13.4
Chapter 6: Cities, settlements and key infrastructure; Cross-Chapter Paper: Cities and Settlements by the Sea								
Risk to population from increased heat	Global but higher risk in temperate and tropical cities (Section 6.2.3.1)	Increased heat stress, mortality and morbidity events from urbanisation and climate change. Increased health risks and mortality in elderly population; vulnerability of the young to heat (Section 6.2.3.1)	Substantial increase in frequency and duration of extreme heat events, exacerbated by urban heat island effects. (Section 6.2.3.1) Concentration of a mixture of extreme heat and humidity (Section 6.2.3.1)	Large increases in exposure, particularly in urban areas, (Section 6.2.3) driven by population growth, changing demographics, and projected urbanisation patterns. Urbanisation increases annual mean surface air temperature by more than 1°C. Correlation between rising temperatures and increased heat capacity of urban structures, anthropogenic heat release and reduced urban evaporation (Section 6.2.3.1)	Changing demographics from ageing populations, potential for persistent poverty, slow penetration and increasing cost of air conditioning, and inadequate improvements in public health systems. (Section 6.2.3.1) Inadequate housing and occupations with exposure to heat (Section 6.2.3.1)	Nature-based solutions, e.g., urban greenery at multiple spatial scales; vegetation; shading; lower energy costs; green roofs; community gardens (Section 6.3.3.1) enhanced space conditioning in buildings; broader access to public health systems for most vulnerable populations. Less economic stress on residents through utilities, especially electricity (Section 6.2.3.1). Tree planting in communities that lack urban greening (Section 6.3.3.1)	*High confidence*, (*robust evidence*, *high agreement*)	6.2, 6.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Urban infrastructure at risk of damage from flooding and severe storms	Global, but higher risk in coastal cities	Damage to key urban infrastructure (e.g., buildings, transport networks, and power plants) and services from flood events, particularly high risk within coastal cities, especially those located in low-elevation coastal zones (Section 6.2.3.2)	Substantial increase in frequency and intensity of extreme precipitation (Section 6.2.3.2) from severe weather events and tropical cyclones contributing to pluvial and fluvial floods, which are exacerbated by long-term sea level rise and potential land subsidence (Section 6.2.3.2)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, and projected urbanisation patterns with a geographical focus in coastal regions. Flooding is exacerbated both by encroachment of urban areas into areas that retain water, and lack of infrastructure such as embankments and flood walls (Section 6.2.3.2)	Costly maintenance of protective infrastructure, downstream levee effects, and increased concentrations of coastal urban population. Little investment in drainage solutions (Section 6.2.3.2)	Early warning systems, Adaptive Social Protection (ASP) to reduce vulnerable populations, nature-based solutions, e.g., in sponge cities to enhance flood protection and regulate storm- and floodwaters-this can be improved through reduced risk unto vulnerable urban systems such as stormwater management, sustainable urban drainage system, etc. (Section 6.2.3.2) Green infrastructure can be more flexible and cost effective for providing flood risk reduction (Section 6.3.3)	*High confidence*, (*robust evidence*, *high agreement*)	6.2, 6.3, CCP2
Population at risk from exposure to urban droughts	Cities located in regions with high drought exposure, (e.g., Europe, South Africa, Australia)	Water shortages in urban areas, and restricted access to water resources to vulnerable populations and low-income settlements. People living in urban areas will be exposed to water scarcity from severe droughts (Section 6.2.3.3). Increased environmental health risks when using polluted groundwater (Section 6.2.3.3)	Projections of more frequent and prolonged drought events potentially compounded with heatwave hazards, and land subsidence from coastal cities that extract groundwater. Climate drivers (warmer temperatures and droughts) along with urbanisation processes (land use changes, migration to cities, and changing patterns of water use) contribute to additional risks (Section 6.2.3.3)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics and projected urbanisation patterns. Limitations of engineered water infrastructure is also exposed by flash droughts (Section 6.2.3.3). Settlements are increasingly dependent on imported water resources by locales that may also be exposed to drought risk (Section 6.2.3.3)	Greater water demand from urban populations from in-migration and key economic sectors, and inefficient or ineffective water resource management (Section 6.2.3.3)	Demand and supply side management strategies that include incorporation of IKLK and practices, equitable access to water. Better water resource management will increase quality of water available. More beneficial physical and social teleconnections to bring mutual benefit of water resources between regions (Section 6.2.3.3)	*High confidence*, (*robust evidence*, *high agreement*)	6.2, 6.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Health risks from air pollution exposure in cities	Global, in cities located in Africa, South Asia, the Middle East and East Asia	Increased mortality and morbidity events from respiratory-related illnesses and co-morbidities towards vulnerable urban populations, arising from particulate matter ≤ 2.5 µm in diameter (PM2.5) and tropospheric ozone exposure	Increased emissions of pollutants from anthropogenic (e.g., transportation, electric power generation, large industries, indoor burning of fuel, and commercial and residential sources) and biogenic (e.g., forests, windblown dust, and biomass burning) emissions Potential for severe compound risks arising from droughts and wildfire. Projections for frequency of meteorological conditions indicate expected increase in PM2.5 concentrations (Section 6.2.3.4)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics, projected urbanisation patterns and demand for energy combined with weak regulations for emissions control (Section 6.2.3.4)	High proportion of young or ageing populations vulnerable to respiratory illness, potential for persistent poverty, advection of pollutants from upwind, ex-urban areas and stay-in-shelter policies from COVID-19 (Section 6.2.3.4)	Enhanced monitoring of air quality in rapidly developing cities, investment in air pollution controls, e.g., stricter emissions regulations, and increased GHG emissions controls resulting in co-benefits with air quality improvements. Increase in trees or vegetated barriers with low volatile organic compound (VOC) emissions, low allergen emissions and high pollutant deposition potential to reduce particulate matter and maximise adaptation benefits (Section 6.3.3.2)	*High confidence* (*medium evidence*, *medium agreement*)	6.2, 6.3
Health risks from water pollution exposure and sanitation in cities	Cities located in regions with high drought exposure resulting in polluted water	Increased environmental health risks when using polluted groundwater (Section 6.2.3.3). Vulnerability of users such as women, children, the elderly, ill or disabled (Section 6.3.4.6)	Decreased regional precipitation and changes in runoff and storage from droughts impairs the quality of water available. Less runoff to freshwater rivers can increase salinity, and concentrate pathogens and pollutants (Section 6.2.3.3)	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics and projected urbanisation patterns. Low flows from drought can lead to sedimentation, increase pollutant concentration and blocking of sewer infrastructure networks (Section 6.2.5.8)	Costly maintenance of protective infrastructure. Sanitation systems coupled with flood water management are at risk of damage and capacity exceedance from high rainfall (Section 6.2.5.8)	Investment in well-regulated water sections; wastewater treatment plants; pumping stations. Reducing impacts of floods on sanitation infrastructure through active management such as reducing blockage in sewer infrastructure (Section 6.3.4.6). Adaptive planning; integration of measures of climate resilience; improved accounting and management of water resources (Section 6.3.4.6)	*High confidence* (*medium evidence*, *medium agreement*)	6.2, 6.3
Chapter 7: Health, well-being and the changing structure of communities								
Heat-related mortality and morbidity	Global, but mainly low- to mid-latitude regions	Substantial increase in heat-related mortality and morbidity rates, especially in urban centres and for outside workers. Increased risk of respiratory diseases and cardiovascular disease (CVD) mortality	Substantial increase in frequency and duration of extreme heat events, especially in cities where heat will be exacerbated by urban heat island effects	Large increases in exposure, particularly in urban areas, driven by population growth and urbanisation. Exposure will increase in agricultural areas where there are large numbers of people working outside	Increases in the number of very young and elderly, and of those with other health conditions such as diabetes and associated comorbidities, lack of capacity to implement adaptation measures	Improved building and urban design, passive cooling systems acknowledging that not all will have access to mechanical space conditioning. Broader understanding of heat hazard and better access to public health systems for the most vulnerable	*High confidence* (*robust evidence*, *high agreement*)	7.3, 7.4

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Vector-borne disease incidence	Africa and Asia	Increase in the incidence of some representative vector-borne diseases such as malaria, dengue and other mosquito-borne diseases, in endemic areas and in new risk areas (e.g., cities, mountains, Northern Hemisphere)	Substantial increase in average temperature, precipitation and/or humidity	Large increases in human exposure to mosquito vectors driven by growth in human and mosquito populations, globalisation, population mobility and urbanisation	Lack of effective vaccine, ineffective personal and household protection, poverty, poor hygiene conditions, insecticide resistance, behavioural factors	Improved housing, better sanitation conditions and self-protection awareness. Broader access to public health system for the most vulnerable. The establishment of early-warning system of vector-borne diseases. Cross-border joint control of outbreaks. Sound usage of insecticides	*Medium confidence* (*medium evidence*, *medium agreement*)	7.3, 7.4
Occurrence and intensity of some water-borne diseases	Mostly developing countries (Africa and Asia); global for vibrios	Increase in the occurrence and intensity of water-borne diseases such as vibrios (particularly *V. cholerae*), diarrhoeal diseases, other water-borne gastro-intestinal illnesses	Substantial changes in temperature and precipitation patterns, increased frequency and intensity of extreme weather events (e.g., droughts, storms, floods), ocean warming and acidification, among others	Large increases in exposure, particularly in areas with poor sanitation, flood-prone areas and favourable ecological environment for water-borne disease pathogens	Poor hygiene conditions, lack of clean drinking water and safe food, flood and drought prone areas, vulnerabilities of water and sanitation systems	Improved personal drinking and eating habits, behaviour change, drainage systems, improved water, sanitation and hygiene conditions and better surveillance system	*Medium confidence* (*limited evidence*, *high agreement*)	7.3, 7.4
Occurrence and intensity of some food-borne diseases	Global	Increase in the occurrence and intensity of some food-borne diseases such as *Salmonella* and *Campylobacter*, including in high-income countries	Substantial changes in temperature and precipitation patterns, increased frequency and intensity of extreme weather events (e.g., droughts, storms, floods), ocean warming and acidification, among others	Large increases in exposure, particularly in areas with poor sanitation, flood-prone areas and favourable ecological environment for food-borne disease pathogens	Poor hygiene conditions, lack of clean drinking water and safe food, flood- and drought-prone areas, vulnerabilities of water and sanitation systems	Improved personal drinking and eating habits, drainage systems and improved water, sanitation and hygiene conditions and better surveillance system	*Medium confidence* (*limited evidence*, *high agreement*)	7.3, 7.4
Heat-related psychopathology	Global, but more likely in areas experiencing high temperatures	Substantial increase in psychopathology compared with base rate	Increased number of days with high temperatures		Lack of air conditioning. The elderly may be more susceptible	Emergency shelters for people to escape the heat; enhanced building design to protect inhabitants	*Medium confidence*	7.3
Psychopathology in response to extreme weather events	Global; some areas at greater risk for storms, flooding or wildfires	Substantial increase in psychopathology compared with base rate	Increased frequency of major storms, weather-related flooding or wildfires		Physical infrastructure that is vulnerable to extreme weather, inadequate emergency response and mental health services, social inequality	Improved urban infrastructure, warning systems and post-disaster social support	*High confidence*	7.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Malnutrition due to decline in food availability and increased cost of healthy food	Global, with greater risks in Africa, South Asia, Southeast Asia, Latin America, Caribbean, Oceania	Substantial number of additional people at risk of hunger, stunting and diet-related morbidity and mortality. Severe impacts on low-income populations from low- and middle-income countries (LMICs). Risks especially high to groups that suffer greater inequality and marginalisation (see vulnerability column)	Climate changes leading to reductions in crop, livestock or fisheries yield, including temperature and precipitation changes and extremes, drought, and ocean warming and acidification	Large numbers of people in areas and markets particularly affected by climate impacts on food security and nutrition	High levels of inequality (including gender inequality), substantial numbers of people subject to poverty or violent conflict, in marginalised groups, or with low education levels. Additional contributions to vulnerability from slow economic development; ineffective social protection systems, nutrition services and health services. Low-income smallholder farmers and pastoralists	Multi-sectoral approach to nutrition-sensitive adaptation and disaster risk reduction/management, including food, health and social protection systems. Inclusive governance involving marginalised groups. Improved education for girls and women, maternal and child health, water and sanitation, gender equality, climate services, social protection mechanisms	*High confidence* (*robust evidence*, *high agreement*)	7.3
Chapter 8: Poverty, livelihoods and sustainable development								
Risk of loss of livelihoods and forced migration (social tipping points) due to the degradation of livelihood assets by increasing drought and heat stress, particularly in already vulnerable regions	Sahel and South Asia	Substantial increase of health and livelihood risks due to climate change in countries with poor state support. Forced migration of particularly poor people engaged in climate-sensitive livelihoods and urban dwellers living under chronic poverty	Increasing drought stress in the Sahel region and increasing heat stress in urban areas, particularly affecting the livelihoods of the poor and most vulnerable groups	Increase of population being exposed, e.g., due to forced migration into cities (heat stress in urban areas)	The Sahel region and South Asia rank already today among the most vulnerable world regions also considering the level of poverty and the framework conditions for coping and adaptation (e.g., state fragility). In these regions, the number of people with climate-sensitive livelihoods is high, and thus the direct and indirect effects of increasing temperature will be felt severely; selected adaptation measures might even worsen the situation for the most vulnerable (e.g., relocation)	Adaptation options are limited, since the economic base and enabling conditions for effective adaptation are absent. Forced migration and even more severe challenges are expected	*High confidence*	8.2; 8.3
Risk of increasing chronic poverty due to climate change hazards on climate-sensitive livelihoods	Various regions	The direct and indirect impacts (e.g., due to the modification of access to resources) can increase the likelihood of chronic poverty. In an inequality scenario (SSP4), the number of people that are living in extreme poverty could increase by 100 million	Severe intensification of droughts and sea level rise in coastal zones	Millions of people are exposed to more intensive droughts and heat stress and sea level rise. There is a high probability that the present spatial hotspots will persist into the future even under a 1.5°C warming scenario by 2030	Very limited coping and adaptive capacities, dependency on specific climate-sensitive livelihoods, which increases the risk of chronic poverty, particularly if social safety nets are missing and state support is limited	Very limited adaptation options. Often, livelihood shifts are needed that would require external support or support from the national level, which is often not provided. Negative adaptation cascades	*High/medium confidence* (depending on the world region)	8.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Cascading risks to vulnerability and inequality	Global hotspots of vulnerability (see vulnerability map in Chapter 8)	Exacerbation of vulnerability also increasing inequality and marginalisation	Changing sequences between different climatic hazard events and shorter intervals (higher frequency of events) as well as shifts in the spatial distribution of extreme events	In general, more people will be exposed to such conditions due to intensification of warm spells, droughts and heat stress in various world regions	Time to recover gets shorter—new sequences of hazard cascades leads to a further erosion of coping and adaptive capacities. New cascading vulnerabilities emerge (selling of livestock, forced migration)	Economic diversification, new warning systems, improved international and national support regimes (social safety nets)	*Medium confidence*	8.2, 8.3
Increased risk of food and water insecurity among poor members of society	The highest risk in South Asia, East Asia and the Pacific, and Sub-Saharan Africa	Permanent and perennial loss of livelihoods among the poor due to extreme events. This includes urban households, rural poor, Indigenous People, rainfed-agriculture-dependent livelihoods and cattle ranching as well as fisheries-dependent communities in the Global South and especially in least developed countries	Global temperature warming exceeding 1.5°C, sea level rise and extreme events (droughts, floods, cyclones, etc.)		High level of poverty, precarious settlements and living conditions, informality, and high dependence on climate-sensitive livelihoods. High inequality (socioeconomic, gender, Indigenous People, caste, among others), absence of state programmes such as health, education and proper sanitation social support	Social protection, strengthening capacity building for climate-resilient agriculture, support local fisheries management. Addressing cross-scales and multiple forms of inequalities that amplify or create vulnerabilities)	*Medium confidence* (*medium evidence*, *high agreement*)	Table 8.1, 8.2.1.4, 8.4, 8.5, 8.6
Risk of increasing levels of extreme poverty	Global South Countries	Up to 122 million additional people in extreme poverty due to climate change. Risk highest for poor urban and rural households, including differential impacts by gender, age and ethnicity	Increasing global warming beyond 1.5°C, increased incidence of heatwaves, droughts, floods		Persistence of high socioeconomic inequalities within and across nations; increased numbers of low-income people, and precarious settlements (especially in risk prone areas), poor sanitation and health assistance		*High confidence* (*medium evidence*, *high agreement*)	8.2, 8.4, 8.5
Risk of loss of life, infrastructure and income due to floods, with cascading risks to food security and health	Southeast Asia and Africa, parts of Latin and South America	Material and non-material impacts associated with losses of life, infrastructure, agriculture, income, cascading to food insecurity, incidence of vector- and water-borne disease, in most urban poor, as well as agriculture- and fisheries-based communities	Increasing global warming temperature beyond 1.5°C, incidence of floods and cyclones; extreme precipitation and inland flooding; monsoon-affected countries, cyclones, typhoons and hurricanes	Increased numbers of low-income people, poor and precarious settlements (especially in risk prone areas); increasing population in risk-prone areas	High-level poverty, precarious settlements, informality, subsistence and inequality (by socioeconomic status, gender, ethnicity, caste, religious beliefs, among others). People living in high mountain regions, remoteness and poor infrastructure challenge access to other livelihood options	Social protection, capacity building for climate-resilient agriculture, support for local fisheries management and disaster prevention	*High confidence* (*medium to robust evidence*, *high agreement*)	Table 8.1, 8.4.

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk of food and water security due to drought	Asia and southern and western Africa, and tropical countries in Latin America	Losses in agriculture, fisheries, forestry, cascading to food and water insecurity and forced migration	A warming scenario greater than 1.5°C will be increasing the frequency and intensity of droughts- detrimental for poor countries in the Global South		Inequalities in access and use of water resources		*Medium evidence, high agreement*	8.2, 8.4, 8.5
Risk of mortality, morbidity, and loss of income in poor households due to extreme heat	Global South, mostly in India, Southeast Asia and Sub-Saharan Africa	Large increase in mortality due to extreme heat, mainly outdoor workers, the elderly, ethnic minorities, urban poor	Increasing global warming temperature beyond 1.5°C will exacerbate extreme heat, including urban heat island		High poverty level, informal and precarious settlements, lack of income and air conditioning, health systems. Continued or exacerbated income inequality combined with slow economic growth and ineffective or non-existent social protection, urban planning and cooling systems	Addressing inequalities, increasing investments in social protection, heath and sanitation	*Medium evidence, high agreement*	8.4 [Table 8.7], 8.5, 8.6
Chapter 9: Africa								
Local or global extinction of species and reduction or irreversible loss of ecosystems and their services in freshwater and land ecosystems	Africa	Extinction of around 10% of African species (5–33% depending on organism group)	Increase in annual average temperature and changes in precipitation (both increases and decreases). Quantitative extinction estimate provided for a global warming level of 4.3°C above pre-industrial (RCP8.5 in 2080–2100)		Vulnerability highest among poorly dispersing organisms (plants), ectotherms (e.g., insects), species with narrow and disappearing niches (e.g., mountain endemics) and exacerbated by non-climate hazards (e.g., habitat loss for expanded agriculture, bioenergy and mitigation afforestation projects); vulnerability is high for Protected Areas (PAs) surrounded by transformed land preventing species dispersal and PAs with limited elevational gradients that reduce their potential to act as climate refugia	Improved management and increased coverage and connectivity of protected areas, targeted conservation (e.g., assisted migration); management of land outside PAs to enhance dispersal (e.g., restoration); ecosystem restoration; diversified livelihoods for people dependent on PAs	*Medium confidence*	9.6.2

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risks to marine ecosystem health and livelihoods in coastal communities due to ocean heatwaves, increased acidification and sedimentation/turbidity	Africa, particularly nearshore habitats (coral reefs, seagrass beds and mangroves)	Destruction of 90% of coral reefs and severe degradation of seagrass beds and mangroves, and associated loss of livelihoods in coastal communities	Coral reef impacts provided for RCP4.5; mangroves and seagrass beds will be severely impacted from 2°C		Vulnerability highest for low-income coastal communities (e.g., artisanal fisherfolk, fishmongers) whose livelihood depends on healthy coral reefs, seagrass beds and mangroves	Adaptation options include: (i) ensuring that people have the assets to draw upon in times of need; (ii) providing the flexibility to change; (iii) learning about climate change and adaptation options; (iv) investing in social relationships; and (v) empowering people to have a say in what happens to them, ensuring the ability to determine what is right for them	*High confidence* (*high agreement*, *robust evidence*)	9.6.2, 9.8.5
Risk of food insecurity, malnutrition (micronutrient deficiency) and loss of livelihood due to reduced food production from crops, livestock and fisheries	Africa: risk is more pronounced in dry lowlands and the Sudano-Sahelian savanna zones of Africa. For fisheries, tropical ocean regions are at higher risk due to ocean warming	Severe reduction in food security and increase in malnutrition due to declines up to 5–15% in yield of staple crops, and 30–45% in net primary productivity of rangelands, varying by crop and region. Declines in fish catch potential in tropical west Africa of >50%	Yield impact estimates provided for 1.5–2°C global warming relative to 1980–2010; primary productivity impact on rangelands estimates provided for RCP8.5 at 2050. Fisheries impacts for RCP8.5 in 2080–2100		Vulnerability is highest for food producers dependent on rainfall and temperature conditions, including subsistence farmers, the rural poor, pastoralists and populations reliant on fish for protein and micronutrients	The combination of (i) Climate Information Services (CIS), (ii) institutional capacity building and (iii) strategic financial investment can be effective adaptation responses to projected climate risks	*High confidence*	9.8.2
Risk to water and energy security due to drought-induced shortage of irrigation and hydropower	Africa (especially southern Africa)	Hydropower and irrigation revenues in Zambezi Basin decline up to USD 45 billion relative to baseline scenario. Consumer electricity expenditure could increase 47% across the Southern African Power Pool	Severe risks driven by long-term warming and drying and reduced river runoff, which occurs in some climate models (high uncertainty in hydrologic outcomes)	Increased urbanisation, population and economic growth, increasing electricity and food demand. Dramatic planned expansion in hydropower (+581%) and irrigation capacity (+63%) under the Program of Infrastructure Development in Africa	High reliance on hydropower for national electricity generation in East and Southern African countries (>90% in some countries). Planned for high reliance on irrigated food production. Limited electricity trade between major river basins. Concentrations of hydropower plants within river basins that will experience similar rainfall and runoff patterns. Limited electricity trade between river basins	Increased electricity trade between river basins, which have little correlation in yearly rainfall and runoff. More diverse electricity generation mixes. Catchment restoration and integrated water management schemes. Urban gardening and agriculture	*Medium confidence* (*medium evidence*, *high agreement*)	9.7.2, 9.9.4, Box 9.5

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk of decreased economic output and increased poverty rates due to increased heat and frequency and severity of drought	Africa	Up to 10–20% reduction in aggregate GDP per capita for 1.5–2°C by 2100 and 80% reduction in GDP per capita by 2100 (RCP8.5, SSP5). Up to 43 million Africans pushed into extreme poverty by 2030 (SSP4) by climate change (GWL 1.2°C). Likely widespread across Africa, but with particular severity in Sub-Saharan countries. Most severe for the poor, agriculturally dependent and populations already inhabiting hot climates today	Severe impacts of 5–20% reduction in GDP per capita projected with global warming of 1.5–2°C above pre-industrial due to increases in temperature; increase in the frequency, duration and severity of drought	Effects are nonlinear, so that severe conditions occur when warming is substantial in places already experiencing high temperatures	Conditions underlying severe risk are lower income growth (caused by other factors besides climate change impacts), higher population levels, lower technology transfer from developed countries, low rates of structural economic change implying more of the labour force engaged in agriculture, construction, resource extraction and other highly climate-exposed industries due in part to physical labour outdoors (e.g., 2–16% loss of work hours due to heat, depending on region in Africa)	Structural transformation (e.g., lowering the share of the labour force in agriculture), income growth enhanced by non-climate factors, education of workers and employers on severity of risk and options for reducing risk (fans, cool water, regular breaks, shade, etc.), social transfer payments to alleviate short-run effects of drought and temperature on the poor	*Medium confidence* (*medium agreement*, *medium evidence*)	9.11.2
Risk of increased mortality and morbidity due to increased heat	Africa	Hundreds to thousands of additional deaths per year per region due to heat	Substantial increase in frequency and duration of extreme heat events in an RCP4.5 or RCP8.5 scenario by 2100, including days over deadly heat threshold, exacerbated by urban heat island effects. 50–350 d yr^{-1} above deadly heat threshold, being most severe in West and Central Africa	Large increases in exposure to heat, particularly in urban areas, driven by population growth and increased urbanisation. Total population exposure to extreme heat in African cities will likely increase by a factor of as much as 52 times that of present exposure (i.e., 217 billion person-days per year) by the end of the 21st century. Large and growing urban population residing in informal settlements	Vulnerability is highest for elderly, pregnant women, individuals with underlying conditions, immune-compromised individuals (e.g., from human immunodeficiency virus [HIV]) and young children. Inadequate insulation in housing in informal settlements in urban heat islands. Inadequate improvements in public health systems	Options for reducing heat risk (building codes, use of insulating materials, fans, cool water, regular breaks, shade)	*High confidence*	9.10.2
Risk of increased mortality and morbidity due to increased vector-borne diseases	Africa	Millions of additional deaths over time due to vector-borne diseases	Expansion of geographic areas with suitable temperatures and precipitation for vector-borne diseases at 1.5–2°C global warming	Population at risk of dengue fever projected to double by 2050, and almost triple by 2080, in scenarios with over 2°C warming. New exposure to malaria will be rapid, with an additional 22–36 million projected to face new risk by 2030 (RCP4.5)	Elderly, pregnant women, individuals with underlying conditions, immune-compromised individuals (e.g., from HIV) and young children are most vulnerable to complications from exposure to the risk. Regions without vector control programmes in place or without detection and treatment regimens	Vector control, vaccination and integrated disease control programmes, and outbreak surveillance	*High confidence*	9.10.2

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk of increased mortality and morbidity due to increased diarrhoeal diseases	Africa	Hundreds of thousands of additional deaths due to water-borne diarrhoeal diseases	Increasing temperatures (RCP4.5; early in the century) and surface-water runoff contaminating drinking water supplies, and changing sea salinity and temperatures influencing cholera prevalence		Elderly, pregnant women, individuals with underlying conditions, immune-compromised individuals (e.g., from HIV) and young children are most vulnerable to complications from exposure to the risk. Inadequate water and sanitation infrastructure, especially in rapidly expanding urban areas and informal settlements. Disruption of vaccination programmes and primary healthcare due to climate impacts on the healthcare system or conflict will exacerbate outbreaks	Improved water sanitation and hygiene as well as waste disposal management, vaccination and outbreak surveillance	*High confidence*	9.10.2
Cascading and compounding risks to economies and governance due to severe, concurrent or successive climate-intensified natural disasters (floods, droughts, fires, wind, heat) affecting human settlements and infrastructure	Africa, particularly in coastal cities	Loss of life and disruption of livelihoods together with damage to key urban infrastructure and services from flood events, particularly high risk within coastal cities. Impacts overwhelm capability to recover, respond or adapt. Restricted access to water resources, and water shortages in urban areas disrupting sanitation and food processing and distribution systems	Increase in frequency and intensity of extreme precipitation, exacerbated by long-term sea level rise. More frequent and prolonged drought events, and land subsidence in coastal cities that extract groundwater	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics and projected urbanisation patterns	Unaffordable maintenance of protective infrastructure, downstream levee effects and increased concentrations of coastal urban populations. Greater water resource demand from urban and non-urban populations and key economic sectors	Early-warning systems. Water restrictions. Financial tools for risk management. Monitoring and forecasting systems. Economic incentives for behaviour change. Disaster risk preparedness, response and recovery plan. Enforced, robust environmental regulations and assessments for developments. Leadership locally accountable	*Medium confidence*	9.9, Box 9.4
Chapter 10: Asia								
Heat stress, mortality and morbidity from exposure to extreme heat, heatwaves	Across Asia	Increased heat mortality by up to a factor of 5–7 in some countries, along with increases in heat stress and incidence of morbidity	Mortality impact estimates are based on RCP4.5 and RCP8.5 and associated increase in frequency and duration of extreme heat events, hotter nights and days, all exacerbated by urban heat island	Increased exposure, particularly in dense urban areas, informal settlements driven by increase in built-up area, building type	Vulnerability is exacerbated by built form (e.g., informal settlers living in tin roof houses which heat up fast and take longer to cool down), changing demographics from ageing populations, unequal access to air cooling facilities, inadequate coverage of public health services	Nature-based solutions, e.g., investing in green infrastructure such as green roofs, urban green spaces; improved built form (e.g., passive cooling); increased public awareness about heat impacts and protection measures; more inclusive public health systems, especially for most vulnerable populations	*Medium evidence*, *high agreement*	10.3.7.3, Box 10.3, 10.4.8

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk to life and property due to sea level rise and coastal flooding	South and Southeast Asia	Loss of life and substantial damage to property especially in East Asia, ranging up to hundreds of millions of dollars per year in damages in some cities	Property damage estimates based on 0.2 m SLR and associated coastal flooding; 1.9 m SLR projected for some regions with 5°C warming	Land subsidence in coastal cities will exacerbate % of population exposed to SLR and coastal flooding. In coastal cities such as Bangkok and Ho Chi Minh City, projected land subsidence rates are comparable to, or exceed, expected rates of sea level rises, resulting in an additional 0.2 m sea level rise by 2025 (Moore et al. 2016)	Poor drainage, inadequate flood management interventions, population density of high-risk groups in exposed areas	Sustainable water management through improved storm water management. Infrastructure-based interventions such as polders, dykes, storm sewer upgradation, improving drainage, and increasing height of road embankments and minor bridges. Developing green infrastructure for improving permeability, managing runoff. Instituting flood early-warning systems, emergency plans to deal with flood risk and mitigate waterlogging.	*Medium evidence*, *high agreement*	10.3.7.3, 10.3.7.3.1, Box 10.3
Risk to water security due to urban droughts	Across Asia	Restricted water access, regular tapping into beyond-city resources	Projections of more frequent and prolonged drought events	Large increases in exposure, particularly in urban areas, driven by population growth, changing demographics and projected urbanisation patterns	Greater water resource demand from urban populations and key economic sectors	Demand and supply side management strategies	*Limited evidence*	10.3.7.3, Box 10.3
Urban infrastructure damage due to flooding	Across Asia	Damage to key urban infrastructure and services from flood events	Substantial increase in frequency and intensity of extreme precipitation leading to up to 50% increase in area flooded in some cities	Increased exposure driven by population growth, increased built-up area	Vulnerability exacerbated by poor drainage, inadequate flood management interventions, inadequate or costly protective infrastructure, poor levee management systems, population density of high-risk groups in exposed areas	Adequate building codes to avoid infrastructure development in high-exposure locations. Designing an early-warning system to initiate flood mitigation procedures, such as isolating critical electrical and mechanical operating systems from water	*High confidence* (*robust evidence*, *high agreement*)	10.3.7.3, Box 10.3
Urban infrastructure damage due to permafrost thawing	Northern Russia	Large changes in bearing capacity affecting as much as 50% of residential buildings, 20% of critical infrastructure, tens of billions of dollars of potential damage; trade disruptions	Persistent thawing of ice-rich permafrost, ground subsidence		Presence of ageing infrastructure, high buildings in unstable areas	Land use practices, permafrost monitoring, maintenance of infrastructure and engineering solutions (such as use of thermosiphons) may temporarily offset negative effects of permafrost degradation in small, economically vital areas, but are unlikely to have an effect beyond the immediate areas	*Medium confidence* (*medium evidence*, *high agreement*)	10.3.7.3, Table 10.2

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Migration, displacement from intersection of climatic and non-climatic drivers	South, Southeast Asia	Migration, displacement, implications on cohesion/conflict	Increasing temperatures, climate variability, extreme events	Populations in climate hotspots facing multiple climatic and non-climatic risks simultaneously	Lack of livelihood opportunities in source areas, especially for poor/marginal social groups	Migration itself can be a successful adaptation strategy. Strong social safety nets in destination areas can support migration and enable positive outcomes for migrants	*Medium confidence* (*medium agreement*, *medium evidence*)	Box 10.2
Biodiversity and habitat loss	Asia	Species extinction, biological invasion which would cause damages to ecosystem function and services	Rapid climate warming plus accelerated human disturbances	Polar and high elevated regions, fragmented habitats such as nature reserves	Polar or mountain hills, fragmented habitats facing climate warming which prevent migration of organism	Setup of large national park, connection of isolated nature reserves and protection of polar species in gardens or zoos	*High confidence*	10.4.2.1.6 Biodiversity and habitat loss, 10.4.2.1.7 Invasive species
More frequent and extensive coral bleaching and mortality	Across Asia	Decline in coral recruitment, variation in coral community structure, changes in functional traits, coral—algal symbiosis, reduction in associated faunal biodiversity, reduction in ecosystem services including coastal protection, increase in disease prevalence and slow growth	Climate and non-climate hazards, including ocean warming, ocean acidification, sea level rise, marine heatwaves, resource extraction	Shallowness of reef coral location; increasingly frequent temperature-induced mortality events	Proximity to urban and industrial development area, land-based pollution and destructive shoreline practices; progressive reduction in coral size, cover and population fecundity leading to low recruitment	A coupled socio-ecological-political, restoration and management framework for restoration; ecosystem-based approach; use of coral nurseries as repositories for coral and reef species	*High confidence*	10.4.3, 10.4.6
Degradation and deforestation of mangrove forests and its functional services	Across Asia	Reduction in ecosystem services impacting fisheries, aquaculture and tourism; loss of protection from extreme events impact especially for coastal poor living below poverty line in Southeast Asia	Sea level rise, increasing frequency of tropical cyclones and floods, heavy rainfall, anthropogenic activities	Proximity to human settlement; increasing demand for conflicting coastal management priorities	Increase in coastal population, land use change and increasing extreme events	Interdisciplinary approach to mangrove management and conservation;	*Medium confidence*	10.4.3, 10.4.6
Degradation and loss of seagrass meadows	Across Asia	Destruction of seagrass beds and their community structure; reduction in ecosystem services affecting habitat-dependent species, nursery grounds of fishes and leading to decline in fishery resources	Climatic factors such as ocean warming, extreme events, heatwaves	Extreme events and coastal eutrophication and non-climatic anthropogenic stressors leading to excessive sedimentation	Frequent warming episodes and increasing coastal population and activities such as boating and anchoring, and ecological factors such as grazing herbivores, diseases, increased turbidity/sedimentation from agriculture/aquaculture activities	Restriction of destructive activities, restoration programmes	*Medium confidence*	10.4.3, 10.4.6

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Economic risk to aquafarmers due to disease outbreak in aquaculture farms	Across Asia	Loss of crop, economic loss to aquafarmers, seafood traders	Increasing temperature, heavy precipitation leading to lowering of salinity		Vulnerability exacerbated by poor water quality, high stocking density, simple non-sophisticated small-scale farming systems	Better management systems, early diagnostic facilities	*Medium confidence*	10.4.6
Decline in coastal fishery resources	Across Asia	Shifts or reduction in marine resource abundance; changes in trophic structure, prey–predator relationships, and their cascading effects in different trophic levels; fisheries and allied sectors; coastal communities	Increased surface warming, low/varied primary and secondary productivity, ocean acidification, hypoxic conditions, increasing stratification, changes in coastal upwelling timing and intensity, eutrophication, harmful algal blooms and more frequent extreme events (floods, tropical cyclones and marine heatwaves), loss of critical habitats to sea level rise	Extreme ocean heat will continue to become more frequent, more intense and longer in duration owing to climate change, affecting fisheries and food webs, and leading to mass mortality, disease outbreaks and reduced biodiversity across coastal systems	Unhealthy and reducing habitats (mangroves, macro-algal communities, coral reefs, estuaries and beaches); can affect the metabolism, growth, feeding behaviour, spawning and recruitment	Location/species specific fishery management protocols, restoration of coastal critical habitats for increased recruitment success	*High confidence*	10.4.6 (cross ref. to 10.4.3)
Deaths, injuries, infectious diseases and mental disorders due to floods	Across Asia	Increased flood-related deaths and lower well-being due to drowning, injuries, infectious diseases and mental disorders	Increase in frequency of heavy rainfall and subsequent flooding	A large number of people living in the flood-prone areas	Low preparedness and coping strategies in the communities to flooding such as river water management and early-warning system	Disaster preparedness including river water management, early-warning system and local coping strategies	*Medium confidence*	10.4.8
Risk to food and water security due to drought	Across Asia	Increased deaths due to starvation and other causes related with malnutrition	Increase in frequency of low rainfall and subsequent drought	A large number of people living in the drought-prone areas	Low preparedness and coping strategies in the communities to drought such as water management and early-warning system	Disaster preparedness including water management system, early-warning system and local coping strategies	*High confidence*	10.4.8
Risk of water and vector-borne diseases	Across Asia	Increased deaths due to water and vector-borne diseases	Population living in low hygiene and sanitation conditions and areas where the vectors exist	Rising ambient temperature and rainfall, and increased frequency of extreme events, including flooding and drought	Low hygiene and sanitation conditions, and inactive vector control programmes	Early-warning system, vector control programmes, water management and sanitation programmes	*Medium confidence*	10.4.8

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Chapter 11: Australasia								
Loss and degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values in Australia due to ocean warming and marine heatwaves	Australia	Widespread destruction of coral reef ecosystems and dependent socio-ecological systems. Three mass bleaching events from 2016 to 2020 have already caused significant loss of corals in shallow-water habitats across the Great Barrier Reef. Globally, bleaching is projected to occur twice each decade from 2035 and annually after 2044 under RCP8.5 and annually after 2051 under RCP4.5. A 3ºC global warming could cause over six times the 2016 level of thermal stress.	Increase in background warming and heatwave events degrade reef-building corals by triggering coral bleaching events at a frequency greater than the recovery time. Fish populations also decline during and following heatwave events	Increasing geographic area affected by rate and severity of ocean warming	Vulnerability to increases in sea temperature is already very high because of other stressors on the ecosystem, including sediment, pollutants, and overfishing	Minimising other stressors on the ecosystem. Efforts on the Great Barrier Reef may slow the impacts of climate change in small regions, or reduce short-term socioeconomic ramifications, but will not prevent widespread bleaching	*Very high confidence*	11.3.2, Box 11.2, Table 11.14
Loss of alpine biodiversity in Australia due to less snow	Southeast Australian Alps Bioregion	Loss of endemic and obligate alpine wildlife species and plant communities (feldmark and short alpine herb-fields) as well as increased stress on snow-dependent plant and animal species	Projected decline in annual maximum snow depth by 2050 is 30–70% (low emissions) and 45–90% (high emissions); projected increases in temperature and decreases in precipitation	Alpine species face elevation squeeze due to lack of nival zone and alpine environments have restricted geographic extent	Narrow ecological niche of species including snow-related habitat requirements; encroachment from sub-alpine woody shrubs; vulnerability generated by non-climatic stressors including weeds and feral animals, especially horses	Reducing pressure on alpine biodiversity from land uses that degrade vegetation and ecological condition, along with weed and pest management	*High confidence*	11.3.1, Tables 11.2, 11.3, 11.4, 11.5, Table 11.14
Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires	Southern Australia	If regenerative capacities of the dominant (framework) canopy tree species are exceeded, a long lasting or irreversible transition to a new ecosystem state is projected with loss of characteristic and framework species, including loss of some narrow-range endemics	Hotter and drier conditions have increased extreme fire weather risk since 1950, especially in southern and eastern Australia. The number of severe fire weather days is projected to increase 5–35% (RCP2.6) and 10–70% (RCP8.5) by 2050	Shift in landscape fire regimes to larger, more intense and frequent wildfires over extensive areas (~10 million hectares) of forests and woodlands from longer fire seasons and more hazardous fire conditions and increasing human-sourced ignitions from urbanisation and projected increase in frequency of lightning strikes	The resilience and adaptive capacity of forests is being reduced by ongoing land clearing and degrading land management practices	Increased capacity to extinguish wildfires during extreme fire weather conditions; avoiding and reducing forest degradation from inappropriate forest management practices and land use	*High confidence*	11.2, 11.3.1, Box 11.1, Table 11.14

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins	Southern Australia and southeast New Zealand	Observed decline in giant kelp in Tasmania since 1990, with less than 10% remaining by 2011 due to ocean warming. Extensive loss of kelp -140,187 hectares across Australia. Loss of bull kelp in southern New Zealand, replaced by the introduced kelp following the 2017/18 marine heatwave. Further loss of native kelp is projected with warming oceans.	Ocean warming and marine heatwave events	Coastal waters around Australia and New Zealand	Giant kelp are already Federally listed in Australia as an endangered marine community type. In Australia, kelp forests are vulnerable to nutrient poor East Australian Current waters pushing further south, warming waters and increased herbivory from range-extending species.	Minimizing other stressors, local restoration, and transplantation of heat-tolerant phenotypes.	*High confidence*	[11.3.2, Table 11.14]
Loss of human and natural systems in low-lying coastal areas from ongoing sea level rise	Australasia	Nuisance and extreme coastal flooding are already occurring due to sea-level rise (SLR). For 0.2–0.3 m SLR, coastal flooding is projected to become more frequent, e.g. current 1-in-100 year flood would occur every year in Wellington and Christchurch. For 0.5 m SLR, the value of buildings in New Zealand exposed to coastal inundation could increase by NZ$12.75 billion and the current 1-in-100 year flood in Australia could occur several times a year. For 1.0 m SLR, the value of exposed assets in New Zealand would be NZ$25.5 billion. For 1.1 m SLR, the value of exposed assets in Australia would be A$164–226 billion. This would be associated with displacement of people, disruption and reduced social cohesion, degraded ecosystems, loss of cultural heritage and livelihoods, and loss of traditional lands and sites sacred	Rising sea level (0.2–0.3 m by 2050, 0.4–0.7 m by 2090), storm surges, rising ground water tables	Population growth, new and infill urbanisation, tourism development in low-lying coastal areas. Buildings, roads, railways, electricity and water infrastructure. The Torres Strait Islands and remote Māori communities are particularly exposed and sensitive	Ineffective planning regulations, reduced availability and increased cost of insurance, and costs to governments as insurers of last resort. Inadequate investment in avoidance and preparedness, exacerbating underlying social vulnerabilities. Financial and physical capacities to cope and adapt are uneven across populations, creating equity issues	Risk reduction coordinated across all levels of government with communities. Statutory planning frameworks, decision tools and funding mechanisms that can address the changing risk. Planning and land use decisions, including managed retreat where inevitable., Improved capacity of emergency services, early-warning systems improved planning and regulatory practice, and building and infrastructure design standards. Options that anticipate risk and adjust as conditions change	*High confidence*	11.2, Table 11.3, 11.3.2; 11.3.5; 11.3.10; 11.4; Box 11.6, , Table 11.14

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Disruption and decline in agricultural production and increased stress in rural communities across south western, southern and eastern mainland Australia due to hotter and drier conditions	South western, southern and eastern mainland Australia	Projected decline in crop, horticulture and dairy production, e.g. decline in median wheat yields by 2050 of up to 30% in south-west Australia and up to 15% in South Australia. Increased heat stress in livestock by 31–42 days per year by 2050 Reduced winter chilling for horticulture. Increased smoke impacts for viticulture. Flow-on effects for agricultural supply chains, farming families and rural communities across south-western, southern and south-eastern Australia, including the Murray-Darling Basin (MDB).	Hotter and drier conditions with constraints on water resources and more frequent and severe droughts in south-western, southern and eastern Australia	Across south western, southern and eastern Australia, many production regions are exposed including the MDB which supports agriculture worth A$24 billion/year, 2.6 million people in diverse rural communities, and important environmental assets containing 16 Ramsar listed wetlands.	Existing financial, social, health and environmental pressures on rural, regional and remote communities. Existing competition for water resources among communities, industries and environment, and uncertainty about sharing of water under a drying climate.	Better planning to reduce and accommodate competing water demands. Improved governance and collaboration to build rural resilience, including regional and basin-scale initiatives. Improved water policies and initiatives (e.g. MDB Plan) and changes in management and technologies. Resilience-focused planning for rural settlements, land-use, industry, infrastructure and value chains. Adoption of information, tools and methods to better manage uncertainty, variability and change. Incremental changes in farm management practices (e.g. stubble retention, weed control, water-use efficiency, sowing dates, cultivars). In some regions, major changes may be necessary, e.g. diversification in agricultural enterprises, transition to different land-uses (e.g. carbon sequestration, renewable energy production, biodiversity conservation) or migration to another area. Flows in waterways based on Indigenous knowledge to protect cultural assets.	*High confidence*	11.2, 11.3.4, 11.3.6.3, 11.4.1, Table 11.11, Boxes 11.1 and 11.3, Table 11.14

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Increase in heat-related mortality and morbidity for people and wildlife in Australia	Australia	During 1987–2016, natural disasters caused 971 deaths and 4370 injuries, with more than 50% due to heatwaves. Annual increases are projected for excess deaths, additional hospitalisations and ambulance callouts. Heatwave-related excess deaths in Melbourne, Sydney and Brisbane are projected to increase by about 300/year (RCP2.6) to 600/year (RCP8.5) during 2031–2080 relative to 1971–2020, assuming no adaptation. Significant heat-related mortality of wildlife species (flying foxes, freshwater fish) has been observed and is projected to increase.	Increased frequency, intensity and duration of extreme heat events	Pervasive, but differentially affecting some wildlife species depending on their thermal tolerances and occupational groups (e.g., outdoor workers) and those living in high-exposure areas (e.g., urban heat islands). Health risks multiply with other harmful exposures, e.g., to wildfire smoke	Lower adaptive capacity for young/old/sick people, those in low-quality housing and with lower socioeconomic status, areas served by fragile utilities (power, water). Remote locations with extreme heat and inadequate cooling in housing infrastructure (such as remote Indigenous communities). For wildlife, impacts of extreme heat events are being amplified by habitat loss and degradation.	Urban cooling interventions including irrigated green infrastructure and increased albedo, education to reduce heat stress, heatwave/fire early-warning systems, battery/generator systems for energy system security, building standards that improve insulation/cooling, accessible well-resourced primary health care For wildlife, removing human stressors, reducing pressures from ferals and weeds, and ensuring there is suitable habitat.	*High confidence*	11.2, 11.3.1, 11.3.5, 11.3.6, 11.4, Table 11.14
Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply-chains and services due to extreme events	Australasia	Widespread and pervasive damage to human activities generated by interdependencies and interconnectedness of physical, social and natural systems. Examples include: Failure of transport, energy and communication infrastructure and services, heat-stress, injuries and deaths, air pollution, stress on hospital services, damage to agriculture and tourism, insurance loss from heatwaves and fires; failure of transport, stormwater and flood-control infrastructure and services from floods and storms; water restrictions,	Heatwaves, droughts, fires, floods, storms and sea level rise. This includes cascading and compound events such as heatwaves with fires, storms with floods, or droughts followed by heavy rainfall and extreme sea levels. .	Highly populated areas, rural and remote settlements, traditional lands and sacred sites. Greater urban density and population growth increases exposure in high-risk areas. Different exposure for different hazards, e.g. heatwaves: urban and peri-urban areas; fire: peri-urban areas and settlements near forests; floods: people, property and infrastructure from pluvial floods in cities and settlements and fluvial floods on floodplains; storms: buildings and infrastructure in cities and settlements.	Existing social and economic challenges (e.g. those caused by COVID-19) and socio-economic and cultural inequalities; competing resource and land use demands across sectors; inadequate planning, policy, governance, decision making and disaster resilience capacity; and non-climatic stresses on ecosystems. Vulnerabilities generated by interdependencies and interconnectedness of physical, social and natural systems.	Flexible and timely adaptation strategies that prepare socio-economic and natural systems for surprises and unexpected threats. Multi-sector coordinated actions that address widespread impacts, redress existing vulnerabilities and building adaptive capacity and systemic resilience. Improved coordination between and within levels of governments, communities and private sector. Greater use of dynamic decision frameworks and suitable economic and social assessment tools. Improved emergency services and early warning systems; use of climate resilient standards for buildings and infrastructure. Transformational adaptations e.g. managed retreat, that can be planned in stages.	*High confidence*	11.2, 11.3.4, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.9, 11.3.10, 11.4, – 11.5.1, Boxes 11.1, 11.4 and –11.6

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		reduced agricultural production, stress for rural communities, mental health issues, lack of potable water from droughts; damage to buildings, roads, railways, electricity and water infrastructure, loss of assets and lives, displacement of people, reduced social cohesion, and degraded ecosystems from extreme sea-level rise. Large aggregate costs due to lost productivity and major disaster relief expenditure, creating unfunded liabilities and supply chain disruption, e.g., the 2019–2020 Australian fires cost A$8 billion. The impact of a 1, 2 or 3°C global warming (relative to 1986–2005) on Australian GDP growth is estimated at -0.3%/year, -0.6%/year and -1.1%/year, respectively, while for New Zealand estimates are -0.1%/year, -0.4%/year and -0.8%/year, respectively. Impacts on Māori tribal investments in forestry, agriculture, horticulture, fisheries and aquaculture.						

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Inability of institutions and governance systems to manage climate risks	Australasia	Climate hazards overwhelm the capacity of institutions, organisations, systems and leaders to provide necessary policies, services, resources, coordination and leadership. Failed adaptation at the institutional and governance level has widespread, pervasive impacts for all areas of society. This includes a reliance on reactive, short-term decision making that locks in existing exposures, leaves perverse incentives and interconnected and systemic impacts unaddressed, and generates high costs, fiscal impacts. This worsens vulnerability and leads to maladaptation, inequities and injustices within and across generations, as well as actions that do not uphold the rights, interests, values and practices of Indigenous Peoples. Resultant failure to take adaptation action generates litigation risk.	The increasing frequency, duration, severity and complexity of extreme weather events, droughts and sea-level rise	All sectors, communities, organisations and governments	Fragmented institutional and legal arrangements, under-resourcing of services, lack of dedicated funding instruments and resources to support communities and local government, uneven capability to deal with uncertainty, and conflicting values and competing policy and political interests	Pre-emptive options that avoid and reduce risks. Redesign of policy, statutory frameworks and funding arrangements for addressing changing risks and uncertainties that enable just and collaborative governance across scales and domains. Addressing existing vulnerabilities, and capacity, capability and leadership deficits within and across all levels of government, all sectors, Indigenous peoples and communities. Risk and vulnerability assessment methodologies and decision-making tools that build resilience and address changing risks and vulnerabilities. Co-designed adaptation approaches implemented with communities including Māori tribal organisations and Australian Aboriginal and Torres Strait Island peoples.	*High confidence*	11.2, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.10, 11.4, 11.5.1, Boxes 11.1–11.6

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Chapter 12: Central and South America								
Risk of food insecurity due to frequent/extreme droughts	Central and South America	Disruption of food provision chains/inability to acquire food for large parts of the population, reduced capacity for production of goods (food, fibre, fuel), reduced food security and increased malnutrition	More frequent and/or longer drought and extreme hot periods. Desertification of semiarid regions. High variability in the yearly rainfall patterns, particularly a severe decrease in rainfall at the onset of the rainy season. Decrease in amount of rainfall overall	More people exposed to food insecurity due to spatially more extensive drought, high population growth rate (including rural areas) and more population dependent on goods	Reduced capacity of farmers, especially small-scale farmers, to adapt to changing climatic conditions. Soil degradation. Limited institutional and governance-related capacities, inefficient water management including water storage and irrigation systems. Insufficient governmental support via extension service, infrastructure, technology, insurance, early-warning systems, research and innovation	Improved water governance (storage, irrigation) with inclusion of climate change considerations, improved water eco-efficiency (recycling and reusing). Reducing grazing pressure on vulnerable lands, prevention of deforestation and recovery of degraded lands. Support for development and adoption of improved or less susceptible key food security and more lucrative crops. Institutional support to small-scale farmers (funding, information), reduced inequalities and power relations in food production systems, and more efficient food provision chains. Implementation of state and national Adaptation Plans. Improved seasonal climate forecasts	*Medium confidence* (*medium evidence*, *high agreement*)	12.3.1–12.3.8, 12.4, 12.5.9
Risk to life and infrastructure due to floods and landslides	Central America; South American Monsoon; and Northwest, North, Southeast and Southwest South America	Death and severe health effects, disruption of critical infrastructure and basic service provision systems	More frequent and stronger storms and heavy precipitation events. For some regions, possibly higher rainfall variabilities combined with higher extreme rainfall. Changing snow conditions and thawing of permafrost. Retreating glaciers resulting in glacier lakes forming and increased glacier lake outburst flood hazard	More people exposed to floods and landslides, due to changing hazards, land use and increased population, together with occupation of more risk-prone areas. More people in poverty living in high-risk areas on steep slopes in urban areas or flood plains in urban and rural areas	Vulnerable populations are usually low income and marginal. Low resilience in infrastructure and critical service systems. Limited government support through insurance, monitoring and early-warning systems, as well as poor disaster management after extreme events	Generally high potential for adaptation, with future risks strongly depending on adaptation and development pathways. Integrated disaster risk management, increasing resilience of infrastructure and service systems. Relocation of people in high-risk areas. Better land use planning and urban development planning	*Medium confidence* (*medium evidence*, *medium agreement*)	12.3.1–12.3.4, 12.3.6, 12.3.7, 12.4, 12.5.9

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk of water insecurity	Central America; South American Monsoon; and Northwest, North, Southeast and Southwest South America	Tens to more than hundred million people exposed to water stress and scarcity. For a 2.7°C global warming scenario in 2050, up to 112 million people will be exposed to increasing water resources stress in Meso-America, up to 28 million in Brazil, and up to 31 million in the rest of South America	Seasonal water availability change and decline due to glacier shrinkage and snow cover change, more pronounced dry periods, and precipitation and circulation changes. Following 2°C projections, regions between 10 and 30° S may experience a reduction of 20% in precipitation during dry season (50% in central Brazil)	Increased demand from intensification of agriculture, mining, hydropower and urbanisation. Increase in population and water use/demand dependent on high contribution of glacier/snow melt, especially during drought conditions	Unjust and unequal water consumption and distribution, decreasing water management and storage. Low governance capacities, dependence on melt water contribution, low water infrastructure efficiency, vulnerable and growing urban areas	Improved and integrated water governance (management strategies that consider dams, water use and hydropower plans). Reduction of hydroelectric power and investment in other renewable energy sources. Ecosystem-based adaptation projects. Efficient water storage for dry periods. Diversification of water sources (wastewater reuse, rainwater harvesting). Strong public participation and knowledge integration, including IKLK	*High confidence*	12.3.1, 12.3.2, 12.3.4–12.3.7, 12.4, 12.5.9
Risk of severe health effects due to increasing epidemics (in particular, vector-borne diseases)	Central America; South American Monsoon; and Northwest, North, Southeast and Southwest South America	Severe health effects and damage to health systems. Higher epidemics of vector-borne diseases malaria, dengue fever, Zika and leishmaniasis, together with diarrhoeal diseases. Following the RCP8.5 scenario, the geographic distribution of the malaria pathogen Plasmodium falciparum could cover 35–46% of South America by 2070	Higher max and min temperatures increase the geographical range of vectors, leading to predicted area of climate suitability and elevation ranges expansion	Density of population increased by urbanisation, resulting in higher transmission rates. Increased population exposed to arboviruses due to expansion of *Aedes* spp., including places of higher altitude and latitude—Argentina, Guatemala, Ecuador, Brazil, Bolivia	Low sanitation conditions, particularly in low-income neighbourhoods and for Indigenous Peoples. Insufficient coverage of appropriate water provision and sewage systems. Underfunding of health system services. Poor malaria control status and low structural and economical capacity to cope. Water accumulation in puddles and containers increases breeding sites for mosquitoes. Increase in infections can increase the incidence of more severe forms of dengue	Improved housing protection. More distributed and better public health services, together with improved infrastructure. Changes in water storage technologies, as well as water supply practices and systems. Integration of Indigenous knowledge and vulnerabilities into current debates on adaptation, especially funding, within the UNFCCC. Social and educational measures	*High confidence (robust evidence, high agreement)*	12.3.1–12.3.7, 12.4, 12.5.9
Systemic risks of surpassing infrastructure and public service systems	Central and South America	Break-down of public service systems, including infrastructure and health services due to cascading impacts of natural hazards and epidemics, affecting large part of the population	Higher frequency and magnitude of climate hazards (storms, floods, landslides) together with an increase in spatial and temporal distribution of pathogens/vectors for malaria, dengue, Zika and leishmaniasis	More people and infrastructure exposed to climate/weather events. Increase in the population exposed to arboviruses due to expansion of the area of occurrence of competent vectors	Increasing vulnerability of public service and infrastructure systems. Insufficient disaster management. Little improvement, maintenance and expansion of public health care systems. Low/decreasing system resilience	Increase of systems' resilience, based on identification of thresholds in the system and where impacts cascades can be broken	*Medium confidence (medium evidence, medium agreement)*	12.3.1–12.3.8, 12.4, 12.5.9

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risk of large-scale changes and biome shifts in the Amazon	South American Monsoon; and North and Northeast South America	Transitioning from tropical forest into other biomes such as seasonal forest or savannah through forest degradation and deforestation. Risk of shift from carbon sink to source. Projected tropical forest area reduction due to only climate forcing is 15% larger by 2050 for RCP8.5 than for RCP2.6. Combined effect of climate change and deforestation and forest fires predict over 60% reduction by 2050 (RCP8.5). Socioeconomic damage (primarily from changes in ecosystem services) over a 30-year period after Amazon Forest dieback is estimated to USD 957–3589 billion	More frequent, stronger and persistent dry conditions. Temperature increase and reduction in annual rainfall. Mean decrease in precipitation of up to 20% during July–November in the Amazon Basin is projected for 2070–2099	Reduced availability of natural sources (food, fibre), for local people. Land use and land cover change (e.g., mining, deforestation). Loss of biodiversity and ecosystem services. Health impacts from increased forest fires, particularly for Indigenous Peoples	Strong dependence on non-climatic drivers, in particular land use change, deforestation, forest fire practises. Low or decreased capacity to monitor and control deforestation	Policies for reduced rates of deforestation and slash-and-burn, increased reforestation. Landscape planning and increase of conservation areas protected from any economic and human activity outside of Indigenous Peoples. Community-led fire management based on Indigenous knowledge. Use of biological assets and biomimetic designs to create high-value products and services for current and new markets learning from Amazonian natural processes and ecosystems, improving local economies	*Medium confidence*	12.3.3–12.3.5, 12.4, 12.5.9
Risk to coral reef ecosystems due to coral bleaching	Central America; and North and Northeast South America	Degradation and possible death of the Mesoamerican coral reef, the second-largest reef in the world. Severe damage to habitat for nearly a thousand marine species, as well as degrading coastal protection and other ecosystem services, decreased food security from fisheries, lack of income from tourism. For RCP4.5 scenario, by year 2050, virtually entire coral reef will experience annual severe bleaching events	Ocean sea surface temperature increase, surface seawater aragonite saturation stress due to higher atmospheric CO_2 concentration, leading to ocean acidification and coral bleaching	Continued exposure to increased atmospheric CO_2 levels and increased sea surface temperatures together with destruction from coastal development, fishing practises and tourism	Ecosystem highly sensitive to water temperature and pH fluctuations. High levels of negative human interference with reefs	Limit global warming and CO_2 emissions. Reducing bleaching events to every 5 years could be enough for reefs to recover. Rapidly approaching hard adaptation limits	*High confidence (robust evidence, high agreement)*	12.3.1, 12.3.3, 12.3.5, 12.4, 12.5.9

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Risks to coastal socio-ecological systems due to sea level rise, storm surges and coastal erosion.	Central America; and Northwest, North, Northeast, Southeast, South, and Southwest South America	Coastal flooding and erosion causing severe damage to coastal population and infrastructure. Loss of fisheries and aquaculture, reef degradation and other declines in coastal protection due to increased storm surges and waves. Destruction of coastal marshes and mangroves. Salt-water intrusion and land subsidence. More than 4 million people could be exposed to flooding from relative sea level by 2100, assuming RCP8.5 without adaptation. When projecting sea level rise and increased population, >9 million people could be exposed	Continuing and high trajectories of sea level rise, with 0.29–0.59 cm under RCP2.6 and 0.61–1.10 cm under RCP8.5 by 2010 (relative to 1985–2005) projected. More intense and persistent coastal flooding, salt-water intrusion, coastal erosion	Increased number of people, infrastructure and services exposed, need of relocation of millions of people	Poor planning in coastal development and infrastructure, disproportionate vulnerability and limited adaptation options for rural communities and Indigenous Peoples, increasing urbanisation in coastal cities. Vulnerable touristic facilities in coastal regions generating large economic losses and unemployment	Coastal integrated management strategies, ecological restoration and nature-based solutions, specifically coastal protection including protection and rehabilitation of reefs, planting of seagrasses and mangroves. Artificial hard structures such as concrete breakwaters, seawalls, groins and revetments. Planned relocation of settlements based on need of relocation of up to millions of people.	*Medium confidence*	12.3.1–12.3.3, 12.3.5–12.3.8, 12.4, 12.5.9
Chapter 13: Europe								
Risk of stress and mortality to people due to increasing temperatures and heat extremes	Europe (whole continent), but risk increases from Northern to Southern Europe	On average, three times more heat-related deaths at 3°C GWL (compared with 1.5°C GWL). With 2°C warming), up to 200 million people could be at high risk of heat stress (compared with 2 million for the period 1986–2005) with more than 50% of the population at risk of thermal discomfort	Increased frequency and duration of heatwaves and hot temperature extremes coupled with high humidity across the whole continent irrespective of scenarios by mid-century, with an increasing gradient towards southern regions (WGI, Chapter 11 (Seneviratne et al, 2021), Chapter 12 (Ranasinghe et al., 2021)	Substantial population growth (especially in Southern Europe) largely contributes to the risk severity (as from SSP3, SSP5)	Increasing proportion of elderly population (in most SSP scenarios except SSP5), inequalities (SSP3) and prevalence of underlying health conditions	Bundle all measures to achieve full acclimatisation: (1) building retrofitting, (2) urban planning (including green/blue infrastructures), (3) behavioural changes; (4) public health intervention programmes and plans, and (5) active cooling	*High confidence* (*medium confidence* in adaptation potential)	13.6, 13.7, 13.10.2.1, SM13.10
Risk of marine and terrestrial ecosystems disruptions	Europe	Large-scale reorganisation of marine, terrestrial and freshwater ecosystems. Considerable reduction of recovery capacity and biome shift. Habitat loss, amplified in coastal areas by sea level rise, amplified risk of wildfires	Increased frequency and duration of heatwaves (including marine heatwaves) and hot temperatures, especially during critical organismal developmental changes	Stresses to ecosystems due to synergistic drivers such as pollution, habitat fragmentation, negative impacts of adaptation and mitigation options	Lower migration potential of species due to life cycle and habitat, habitat fragmentation not allowing movement of species, lack of statutory policies to provide protection and facilitate rewilding	Reduction of additional stressors to increase adaptation potential. Increasing network of effective protected areas to allow fast recovery after shocks	*High confidence* in the direction, *medium confidence* in the relative change	13.4, 13.5, 13.10.2.1, SM13.10

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Risk of losses in crop production, due to compound heat and dry conditions, and extreme weather	Southern Europe (*high confidence*), Central Europe (*medium confidence*)	Reduced crop production; up to 50% loss in yields with highest losses in southern region. Decreasing water availability constrains the use of irrigation as an adaptation option. Combined with limited effectiveness of other adaptation options, this leads to lower production and abandonment of cropland	Projected increase in co-occurring droughts and heatwaves with dominant signal in heatwaves occurrence, which will lead to more frequent hot and dry events and projected increase in wildfire hazards (WGI Chapters 11, 12, Seneviratne et al., 2021, Ranasinghe et al., 2021)	High population growth (e.g., in SSP5); increase in the extent of natural systems exposed to heat and drought hazards	Lack of water to increase irrigation; increase in soil loss and erosion and dry soils with little potential for evapotranspiration; lack of governance for some mixed farming practices	(1) Changes in sowing and harvest dates, and crop varieties, (2) drought-risk management, including protective vegetative cover and irrigation, (3) mixed farming practices, including agroforestry, (4) diversification and change of crop and animal species to those better adapted to warmer temperatures and less water requirement, (5) soil management	*Medium* to *high confidence*, but *high confidence* in Southern Europe, *medium confidence* in Central Europe	13.2, 13.5, 13.10.2.2, SM13.10
Risk of water scarcity to multiple interconnected sectors	Southern Europe, Central and Eastern Europe	One-third to over one-half million people exposed to moderate water scarcity in southern regions by mid-century owing to competing demands from agriculture, energy generation, domestic and municipal water consumption	Drought increase (especially in the Mediterranean) up to 10%; more severe and persistent reductions in runoff, changes in groundwater recharge; changes in seasonal precipitation patterns, with condition worsening for higher levels of warming (3°C) WGI, Chapters 11, 12)	Land use change (SSP3); population growth and rate of urbanisation (SSP5)	Most water currently needed by agriculture. Current development and economic trends point at an increase in vulnerability for those sectors highly relying on water resources mostly under conditions of SSP3 and SSP5	(1) reduce water demand (e.g., increasing irrigation efficiency); (2) enhance water availability; (3) changed priorities of water uses (who gets water first); (4) integrated land and water management and water–food–energy nexus solutions	*High confidence* (Southern Europe) and *medium confidence* (Central and Eastern Europe)	13.2, 13.5, 13.6, 13.10.2.3, SM13.10
Risks of mortality and damage to coastal infrastructure and economic assets due to coastal and inland flooding	Low-lying European coastal zones (lower concern in Scandinavia), and some river floodplains; small catchments and mountain area (pluvial flooding)	Expected annual damage (number of people) costs increase by a factor of at least 10 (at least 16), with large adaptation and mitigation. Local loss of marine and terrestrial ecosystems reduces or eliminate their ability to lessen the impacts	Increase in events with peak discharge >100-year return period; sea level rise exceeding locally relevant thresholds (e.g., small dunes and walls) beyond 2050; extreme rainfall events exacerbated by climate change	Exposure to flood risk is projected to stabilise or increase in the future depending on SSPs	Current trends show a decrease in flood vulnerability in high-income countries which will continue into the future. In the longer term, inability to adapt infrastructure such as drainage systems would contribute to vulnerability; inappropriate building practices	(1) protect: flood mitigation (dikes, barriers, drainage, pumps, nourishment, wetlands), (2) accommodate: damage mitigation (floodproofing, floating, temporary use of land, storage basins), (3) relocate: retreat landwards (managed realignment, no building zone, planned retreat) (4) relate: move seawards/advance (islands, new extend coastline)	*High confidence*	13.2, 13.6, 13.10.2.4, SM13.10

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Chapter 14: North America; Cross-Chapter Paper 6: Polar								
Risk to ecosystems and human health and well-being within and beyond polar regions due to sea ice loss and attendant ecosystem alterations	Polar seas	Loss of sea ice results in loss of habitat and altered trophic pathways. Reductions in sea ice extent and altered timing of sea ice melt cascade through the food web, with consequences for polar ecosystems including changes in the source and strength of primary productivity and borealisation of arctic marine ecosystems. Loss of migration, feeding and breeding areas for sea-ice-dependent species lead to severe declines. Cumulative changes impair large commercial fisheries, especially those that provide critical macronutrients globally (e.g., krill, walleye pollock)	Sea ice loss (reductions in extent and thickness) in the Arctic scales with, and lags, atmospheric carbon (decades or more). September sea ice loss is anticipated under all future scenarios but is greatest under SSP5 8.5, where near ice-free conditions may occur between 2040 and 2060. Warmer conditions lead to delayed sea ice formation and earlier sea ice melt, and phenological mismatch with phytoplankton, nutrients, mixing and spring daylight, impacting blooms, stratification and other critical ecological processes with impacts on key subsistence and fishery species. Changes in sea ice and warming will alter species distributions and location of fishery resources	All sea ice habitats are exposed, especially under high-emission scenarios. Exposure is highest at edges of polar boundaries and in the Arctic near-shore regions	These seasonal systems, which depend on ice-derived nutrients and productivity during the 'light' season are highly sensitive to change. Sea-ice-dependent species (e.g., seals; polar bears) that rely on sea ice for habitat will be directly impacted; changes in the timing of sea ice melt and extent will impact ice-driven trophic pathways and polar systems that rely on ice algae and sea-ice-driven phytoplankton blooms. Large catcher–processer vessels may be able to follow shifting resources more easily than small-scale shore-based vessels. Increased pressure for fisheries to follow poleward shifting species will challenge international agreements and regional management plans. Limited resources for monitoring of polar regions hinders assessment of current and future resources	Few adaptation options exist under end of century SSP58.5 owing to significant loss of sea ice. Under moderate and high mitigation scenarios, ecosystem management and indigenous co-management can help sustain productive ecosystems. Combined with mitigation monitoring, forecasts and climate-informed ecosystem-based management of fisheries, species and habitats can increase productivity and offset climate impacts to some extent through reducing non-climate pressures. Effectiveness declines with increasing atmospheric CO_2	*High confidence* (*robust evidence*, *high agreement* for risk, *medium confidence* for adaptation)	3.4.2.10, Cross-Chapter Box MOVING PLATE; CCP6.2, 14.5.2, 14.5.6, 14.6, 14.7, SM14.6, WGI SPM (IPCC, 2021)

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Multiple risks to arctic socio-ecological system function, structure and productivity	Arctic	Changes to sea ice increase human safety issues, wave energy and shoreline erosion. Loss of sea ice and ecosystem alterations impair access to, and availability of, subsistence resources, impacting the well-being and health of Indigenous Peoples and local communities. Compounding impacts alter Arctic Indigenous communities through loss of traditional livelihoods, relocation of communities, and injury from changes in ice/snow (e.g., falling through the ice). Loss of mental, emotional and spiritual health benefits, including stress relief; impacts on cultural well-being, including connections to identity, history, traditions and ancestors	Substantial loss of multi-year ice, reduction in seasonal sea ice extent, thickness and predictability and sea level rise. Compound impacts on the productivity of local and subsistence resources	Marine social-ecological systems along Arctic coasts and in regions of seasonal sea ice formation and melt. Subsistence hunters and fishers that traverse sea ice to access subsistence resources areas will be impacted. Local communities that provision with local resources and depend on ice and snow for travel	Sea-ice-dependent marine species are sensitive to compounding impacts of loss of sea ice and ecosystem change. Redundancy and diversity in subsistence use attenuates impacts, but systematic loss of species and resources can erode resilience and increase risk for Indigenous Peoples that depend on the cultural and provisioning services of Arctic ecosystems	Measures that protect or enhance diversity and flexibility in subsistence resources and measures that stabilise access to critical provisioning resources will increase resilience in the near term. Co-management, co-production of knowledge, increased communication via technology, improved access to real-time ice forecasting, enhanced search and rescue capabilities, investment in local infrastructure, access to a diversity of subsistence resources, stabilisation of income and food resources help promote adaptation. Efficacy of such measures scale positively with carbon mitigation	*High confidence* (*robust evidence, high agreement*)	CCP6.2.2–4, CCP6.2.7, 14.5.4, 14.5.6, 14.5.2, 14.6, Chapter 14 ES
Ecological and cultural risks due to increased shipping (due to sea ice reduction)	Arctic	Increased potential for fuel spill with high consequences for biodiversity and ecology as well as linked to food security and cultural impacts for Indigenous Peoples. Underwater noise impacts sensitive marine mammals. Potential for invasive species introduction	Reduction in sea ice extent; potential increase in navigability	Increased shipping associated with near ice-free areas in the Arctic (projected for 2040–2060 under SSP5 8.5), sensitive nearshore areas, especially those near navigational hazards	Fragile ecosystems increasingly stressed by heat (warming and extreme heat), wave action and ecosystem-wide changes. Areas with low regional biodiversity (high impact of spills), distance from ports and emergency response, lack of rapid response, difficulty of remediating oil spills on ice, limited search and rescue and other infrastructure, etc.	International agreements and treaties (e.g., Polar Code) and other regulations, investment in infrastructure, research and science, identification of particularly sensitive areas (especially culturally significant areas)	*High confidence* (*robust evidence, high agreement*)	CCP 6.2, 6.3, Box 6.1, 14.5.4, 14.5.9

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Permafrost loss impacting human communities and cities in the Arctic	Arctic	Increased human safety concerns related to loss of and damage to homes, roads, travel and access; road infrastructure failure from permafrost loss, landslides and subsidence, impacts on oil and gas extraction facilities and access. Trade disruptions related to transportation infrastructure, especially around critical food and medical resources, impact safe navigation, travel ability; decreased access to wild foods, loss of freedom and autonomy	Rising air temperatures contributing to persistent permafrost loss; heat and precipitation extremes contributing to sudden thawing and erosion events	Towns and communities in areas with permafrost. Areas of rapid thaw and combined impacts of land and coastal erosion	Cities and towns built on permafrost, terrestrial Arctic ecosystems, infrastructure and extractive platforms built on permafrost, coastal areas. Areas with intensifying warming and rapid thaw. Limited or ageing infrastructure, especially lack of resources to increase road, drinking water and building infrastructure. Limited disaster relief funds or support for relocation	Multiple adaptation options (e.g., design changes, changes to operating and maintenance protocols) depending on type of infrastructure, site conditions and location, project climate change impacts and other factors; investment in local infrastructure, relocation, disaster relief	*High confidence* (*robust evidence*, *low agreement* on adaptation)	CCP6.2.5, CCP6.2.6, CCP6.2.7, 14.4.6, 14.4.9, 14.5
Sea level rise, storms and flooding pose a risk to coastal cities, commerce and trade	North America	Damage and losses to property, loss of life, cost of evacuation, local transportation interruption, port-facility damage and delays, supply-chain delay	Sea level rise exceeding current design and accelerating deterioration of buildings and transportation infrastructure; storm surge and flooding from hurricanes and other large storm events. Seawater intrusion of drinking water. King tide flooding events that erode infrastructure. Loss of natural barriers to environmental degradation and changes in river output and sediment deposition	Low-lying cities and townships in regions with high SLR (Box 14.4), coastal population along the south and southeast coast of the USA and the East coast of Mexico where large hurricanes increase storm flooding and damage	Ageing infrastructure, lack of emergency response, lack of planning, especially around climate change. High use ports with few nearby alternatives	Various adaptation plans are in place in North America outlining city- and town-specific measures to reduce risk and inform urban planning. High-resolution projections of sea level rise can inform infrastructure design. Conservation and restoration of natural shoreline protection can attenuate storm surge (e.g., mashes, wetlands), planned relocation	*High confidence* (*medium evidence*, *high agreement*)	14.5.9, 14.5, 14.5.5. Box 14.4 SLR
Major ecosystem change, including species and biome shifts, altered abundances, which may be accelerated by indirect effects of disturbances	North America	Shifts or loss of ecosystems that provide significant ecosystem services	Warming and drying that leads to unfavourable conditions for species both directly as well as indirectly through increased disturbances	Terrestrial ecosystems in the south and southwest USA exposed to drought and warming, Arctic ecosystems exposed to sea ice and permafrost loss, coastal nearshore ecosystems subject to OA, urbanised estuarine ecosystems, mid- to low-elevation forests	Degraded ecosystems with reduced biodiversity and reduced redundancy in linkages and species niches. Systems with a few highly connected species that are sensitive to climate conditions. Ecosystems subject to increasing frequency of disturbances or those experiencing multiple hazards simultaneously	Ecosystem conservation and restoration, climate-informed resource management, monitoring and science-based decision making can help reduce cumulative impacts from non-climate stressors and increase connectivity and biodiversity	*Medium confidence* (*medium evidence*, *medium agreement*)	14.5.1, 14.2, 14.7

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risks to health and ecosystems from increased frequency, duration or extent of harmful algal blooms or other hazardous water quality conditions	North America	Major drinking water contamination episodes resulting in exposure to gastrointestinal diseases; numerous and extensive cyanobacteria (blue-green algae) blooms causing highly hazardous conditions at water recreational sites and destruction of aquatic biota and aesthetic quality of lakes and other water bodies	Joint occurrence of very warm temperatures and high nutrient loading, e.g., from extreme precipitation and high runoff from agricultural lands, especially causing breaching of manure lagoons	Ageing drinking water treatment systems drawing on surface water sources subject to contamination. Algal bloom events in heavily used recreational waters near major population centres	Especially vulnerable are populations with weak immune systems (elderly and young); individuals and pets making frequent use of susceptible water recreational sites. Inadequate monitoring and warning systems; lack of planning for distribution of safe alternative drinking water during quality emergencies	Upgrade water supply, sewer and stormwater infrastructure; implement nitrogen-loading reduction programmes in agricultural areas	*High confidence* (*robust evidence*, *high agreement*)	14.4.3, 14.4.4, 14.5
Heat-related human morbidity and mortality	Canada, USA, Mexico (North America)	Substantial increase in heat-related mortality rates, especially in urban areas, elderly, and outdoor workers	Substantial increase in frequency and duration of extreme heat events	Large increases in exposure, particularly in urban areas (e.g., urban heat effect)	Ageing populations, poverty, continued lack of access to air conditioning, and inadequate improvements in public health systems	Improved access to cool environments (e.g., cooling stations, green spaces, air conditioning in buildings [especially residential]); increased public health response during heatwaves (e.g., increased access to cooling stations). Broader access to public health systems for the most vulnerable	*Very high confidence* (*very high agreement*, *robust evidence*)	14.5.6, 14.5
Loss of life and property, increased morbidity, mental and physical health impacts, and ecosystem disturbance and transformation from large wildfires	North America	Substantial increases in costs of firefighting and suppression, loss of life and damages to property and structures; impaired air and water quality; physical and mental health impacts, significantly altered ecosystems, forest structure and function, tree stress, moose physiology and disease, changes in vegetation type, tree regeneration, changes in species composition, and watershed sedimentation from post-wildfire erosion	Warming and increased frequency and duration of drought, extreme heat combined with reduced humidity, changes to fire weather	Population centres with and without proximity to densely forested areas, temperate and low- to mid-elevation forests, grasslands, above ground power lines, populations in regions with drought and aridification (e.g., California, Colorado, Oregon, eastern Washington, southwest British Columbia)	Distance from fire response resources, places without shelter in place infrastructure, limited early-warning systems, limited evacuation potential. Smoke and air quality impacts are highest for those with pre-existing medical or mental health conditions. Regional proximity to forest ecosystems exposed to heat and aridification and changes in freshwater resources	Rapid response, risk communication and fire monitoring, emergency planning, shelter in place facilities. Forest management to reduce density of dry fuel, freshwater preservation (e.g., through conversion of irrigated grasslands to temperate forests), preservation of riparian zones around rivers and streams	*Medium confidence* (*robust evidence*, *medium agreement*)	14.4.1, 14.4.4, Box 14.2 wildfires, CCP6.2.2

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Climate-sensitive mental health outcomes from compound climate hazards	Northern Canada, USA, Mexico	Increased occurrence of mental health problems exacerbated by climate change direct and indirect impacts	Temperature rise, leading to extreme heat events, severity and prevalence of intense storms, increased wildfires, changes in wildlife and vegetation, and disruptions to ecosystems	Negative mental health impacts from climate change are widespread across North America and differ by region and community depending on the hazard	Those experiencing poverty; elders/seniors; youth; those with already-present mental health challenges; those living at the frontlines of a changing climate; those most closely reliant on the land and environment for livelihoods, culture, identity and sustenance	No effective adaptation options identified with confidence	*Very high confidence* (*very high agreement*, *medium evidence*)	CCP6.2.7, 14.5.6, 14.5
Compounding and cascading climate change impacts on fisheries and aquaculture and food and nutritional security	Documented in all large marine ecosystems of North America	Disruption of fisheries through redistribution and declines in biomass. Loss of fisheries reduces access to marine sources of protein and nutrition and threatens regional and global food and nutrition security	Marine heatwaves, harmful algal blooms (HABs), low-oxygen zone, OA, substantial increase in ocean temperatures concomitant changes to marine food webs and ocean productivity (e.g., food resources), changes in ocean chemistry (OA, salinity, dissolved oxygen), shifts in ocean circulation	Exposure of fished species to changing ocean conditions, fisheries at southern (trailing) edges of species distributions, fisheries near geopolitical boundaries, fisheries near boundaries of protected areas. Fisheries in regions with protected species	Fisheries for species with narrow physiological tolerances at various life stages (e.g., larval phase), lack of diversity in income or target species portfolios. Fisheries already utilised at or near maximum sustainable yield (MSY), small-scale or shore-based fisheries with less ability to follow shifting resources, historically large fisheries with high investment, concentration of wealth and power and lack of representation in management; strong self-reinforcing density dependence in target fisheries, marine food webs sensitive to bottom-up productivity, and ectothermic nature of fish; transboundary populations	Ecosystem-based fisheries management, co-management, policy flexibility, portfolio approach to rationalised fisheries (diversification), disaster relief, adjustments in fisheries harvest rates (may release prey species from predation) or fishery locations (to follow poleward fish redistribution), maintenance of redundant subpopulations (portfolio of stocks); coordinated planning between aquaculture and fisheries management	*High confidence* (*high agreement* and *robust evidence* for shifting stocks, *medium evidence* on productivity changes and adaptation)	14.5.4, 14.5.6, 14.4.2, 14.6; CCP6.2.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risks to agricultural income and livelihoods, food security, due to drought, changes in temperature, and reduced surface water availability	Terrestrial agriculture and livestock systems across North America	Reduced crop yields and profits, lost livelihoods, higher food prices, pressures to transfer water out of agriculture, increased conflicts (especially where water rights are poorly defined and enforced), accelerated aquifer depletion, increased stream desiccation due to reduced return flows	Temperature rise; extended drought, together with loss of groundwater and/or snowpack water storage	Aridification especially in Southwest USA, and northern Mexico; extensive irrigated agriculture in areas dependent on snow-fed streams, especially where reservoir capacity is limited and water distribution systems are tuned to current seasonal flow patterns	Numerous water users located in small catchments lacking access to alternative sources of supply. Prior severe depletion of groundwater preventing its use as a late-season or drought-year substitute for surface sources. Insufficient reservoir capacity to provide both winter flood protection and reliable summer water deliveries. Inflexible, poorly documented water rights impeding development of efficient water markets	Utilising traditional and sustainable agriculture methods that promote soil quality and reduce erosion, agroforestry and ecosystem-based approaches can improve microclimates. Implement groundwater sustainability regulations and investment in recharge. Create incentives for water conservation and phased retirement of relatively unproductive irrigated land. Enhance flexibility of water allocation by improving water rights; documentation and enforcement to facilitate water banking and voluntary transfers; cultivate crops with drought tolerance, shift agricultural regions to favourable areas, diversify agriculture crops at the farm level, utilise sustainable intensification practices, repair and restore soil condition to retain water, prevent erosion	*High confidence* (*high agreement*, *medium evidence*)	14.4.3, 14.4.2,14.5
Risk to the well-being, health, property and safety of communities and cities in North America from cascading and compounding climate change hazards, non-climate stressors and social structural predisposing factors	North America	Large losses in livelihoods and welfare (through impoverishment, malnutrition, migration, displacement) decrease ability of households and governments to manage adverse effects of climate change. This may also further increase inequity and impair effective adaptation and response	Heatwaves and warming contribute to increased heat stress, altered conditions impact food production, compounding and cascading impacts of multiple hazards erode infrastructure and increase costs especially in the near term from extreme weather events (e.g., hurricanes, flooding, heatwaves) and in the longer term from persistent change (e.g., OA, SLR)	Large population centres with ageing infrastructure, urban forests and those along shorelines and coastal areas. Livelihoods around resource utilisation and provision services	Small rural communities, large coastal cities with limited or outdated urban planning; systemic racial and economic inequalities that result in structural legacies that reinforce inequity and increase disproportionate impacts; lack of early-warning systems, weak international agreements on borders and rapidly increasing access to valuable resources in the Arctic, impoverished populations, uninsured populations; populations highly dependent on natural resources, food buyers, remote communities with limited access to public infrastructure and services	Multiple adaptation activities depending on sector that are often less expensive than costs from exposure. This is facilitated by inclusive governance and dynamic decision-making tools. Implementation of early-warning systems, social equality programmes, inclusive decision making and governance, livelihood diversification, coastal protection through nature-based solutions, increasing urban vegetation and tree cover, access to cooling infrastructure, livelihood and property insurance, shelter-in-place and other emergency response planning and investments	*High confidence* (*robust evidence*, *high agreement*)	14.5.5, 14.5.2., 14.5.4, 14.6, 14.5.9, Box 14.7 nature-based solutions

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Chapter 15: Small Islands								
Loss of marine and coastal biodiversity and ecosystem services (KR1)	Small islands	Further and accelerating degradation of ecosystems leading to ecosystem loss or impaired provision of services (e.g., coastal protection, carbon sequestration, tourism, fisheries)	Accelerated sea level rise with increased wave height and energy, shoreline retreat, increase in frequency and/or intensity of extreme wave events; increase in the frequency and intensity of bleaching events, increase in acidity of the oceans	Increasing human populations: larger numbers of people living along the coast and depending on marine and coastal ecosystem services, e.g., for provision of food security or income	Limited financial resources to promote alternative options to ecosystem services, limited human capacity, small land area, pollution and other stresses, increase in development and populations, increase in anthropogenic pressures exerted on marine and coastal ecosystems (e.g., through overfishing, tourism development and other activities causing habitat degradation)	Conservation strategies, such as Marine Protected Areas (MPAs) and protection of terrestrial ecosystems, that would protect ecosystems and reduce other stresses; protection of resilient sites from local anthropogenic disturbances; habitat restoration (coral, seagrass and mangrove replanting); building on higher grounds to reduce direct human pressure exerted on marine and coastal ecosystems	*High confidence* (*robust evidence*, *medium agreement*)	15.3.3.1
Submergence of reef islands (KR2)	Small Islands	Increase above natural rate of island disappearance, especially over the second half of this century and for the smallest reef islands	Under RCP8.5, rapid increase in the rate of sea level rise associated with increased wave height and energy; and intensification of tropical cyclones in some regions	Risk will be exacerbated by projected population growth in some countries and territories (e.g., Maldives, Kiribati), although still high at current population	Limited land and relocation alternatives, increasing human disturbances caused to the reef-island system, population growth increasing both the pressure exerted on land and land needs	Over the next decades: on natural and rural islands, nature-based solutions; on urban islands, engineering-based protection. High-end scenario: internal and potentially international migration and limits to adaptation	*Low confidence* (*limited evidence*, *low agreement*)	15.3.3.1.2
Loss of terrestrial biodiversity and ecosystem services (KR3)	Small Islands	Increased habitat and climatic niche loss and/or degradation, resulting in further and accelerating loss/impairment of ecosystem services, structure and/or functioning, and decreased biodiversity (particularly decreased functional redundancy)	Continued global warming, increasing/accelerated SLR, increasing intensity of intense tropical cyclones; increased frequency of drought, floods and wildfires	Increasing human population on islands exposes more natural landscape area to risk of conversion/impairment and associated impacts	(i) High levels of biodiversity limited to one or a few neighbouring islands with a large proportion of endemics (but low functional redundancy) and food/habitat specialists with limited range dispersal capacities; (ii) significant and increasing proportions of natural habitat lost/degraded/fragmented (e.g., agriculture or settlement; (iii) encroachment of protected areas due to limited resources available for adequate protection, poor governance, poor management	Development of ridge to reef conservation strategies which maintain, protect and include conservation of critical habitat outside of protected areas. These should allow for species shifts not just across individual islands but across regional and archipelagic extents (including neighbouring continents). Greater inclusion of community/private stakeholders in conservation strategies	*High confidence* (*medium evidence*, *high agreement*)	15.3.3.3

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Water insecurity (KR4)	Small Islands	Freshwater demand increasingly exceeding supply, resulting in increasing populations unable to meet consumption, food production and economic needs, especially but not only on atoll islands (half of the SIDS already experiencing freshwater resource stress)	Increasing aridity, negative trends in annual and seasonal total and extreme precipitation, increasing duration and/or frequency of drought, decrease in groundwater recharge, decreased streamflow, salinisation and size reduction of freshwater lens due to sea level rise and extreme sea level events; groundwater recharge is projected to decrease by 58% for 31 Small Island States	Population growth, population density increases, especially in urban and coastal areas, increasing urbanisation in coastal areas, expansion of economic activities with high water demands (e.g., tourism); more remote island communities may become progressively less viable, resulting in their involuntary relocation to places where water insecurity may already exist	Increased domestic water consumption; limited technological transition; increased poverty and inequality; persistent limited water management and governance capacities; accelerated urbanisation; limited water quality monitoring and assessment; limited environmental awareness	Improve community awareness about the need for water conservation and maintaining the cleanliness of drinking water. Identification/use of traditional (pre-modern) water supply systems, especially at times of water shortage	*Medium* to *high confidence* (*robust evidence*, *medium agreement*). '*Medium agreement*' reflects the presence of considerable diversity across islands; '*robust evidence*' reflects the existence of water insecurity as an issue for almost every small island	15.3.4.3
Risk of loss of lives and assets, food insecurity and economic disruption due to destruction of settlements and infrastructure (KR5)	Small Islands	Widespread loss of human lives, assets, food insecurity and economic disruption as settlements are rendered unliveable and infrastructure is destroyed	Substantial increase in frequency and intensity of precipitation impacting on severity of flooding and aggravated by the intensification of tropical cyclones and sea level rise. Substantial decrease in precipitation and more frequent and prolonged drought	Large increases in exposure, particularly in urban settlements, driven by population growth and projected urbanisation patterns	Persistent poverty, slow economic recovery and growth. Inadequate infrastructure maintenance	Nature-based solutions; ecosystem-based adaptation; traditional and indigenous architecture; revised building codes and planning standards; drainage infrastructure upgrade; water demand management. Relocation as a last resort	*High confidence* (*medium evidence*, *high agreement*)	15.3.4.1, 15.3.4.4, 15.3.4.5
Degradation of human health and well-being (KR6)	Small islands	Increase in vector-borne disease, food- and water-borne disease, heat-related illness, malnutrition, disruption to health and sanitation systems, mortality and psychological trauma resulting from extreme events	Altered frequency and/or severity of extreme weather events (floods, inundation, extreme rainfall, extreme heat, etc.). Altered rainfall patterns and rising air temperatures. Rising seawater temperatures. Changes to ecological systems	Increases in exposure due to population growth and urbanisation and persistently large numbers of low-income people, especially in urban areas and in coastal locations (where they may be more exposed to disease vectors or physical risks). Compromised safety or supply of food and clean water	Vulnerability exacerbated by limited economic growth, high income inequalities, limited financial capacities, limited land alternatives, limited access to clean and safe freshwater, persistent food insecurity, overstretched health infrastructure, unfamiliar pests and pathogens, malnutrition, human migration/population displacement leading to poorer health outcomes and disease transmission	Greater investment in health and sanitation infrastructure (hospitals, clinics, etc.). Surveillance of disease vectors (e.g., mosquitos, water- and food-borne pathogens). Widespread uptake and use of mosquito nets. Reduction of poverty and inequalities	*Low confidence* (*limited evidence*, *medium agreement*)	15.3.4.2

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Economic decline and livelihood failure (KR7)	Small Islands	Substantial decrease in revenues from fishing licences and substantial increase in the destruction of production systems are likely to affect the whole population of some countries	Increase in atmospheric and sea surface temperatures, increased wave height and energy, sea level rise, increased intensity of tropical cyclones in some island regions	Large increases in exposure due to increasing population growth with low-income households	Prevalence of climate-sensitive economic activities (especially fisheries and aquaculture, agriculture, tourism); loss of fisheries and tourism revenue; limited diversification of economic activities and economic opportunities	Diversification of economic activities; limits to adaptation	*High confidence* (*medium evidence*, *high agreement*)	15.3.4.4, 15.3.4.5
Loss of cultural resources and heritage (KR8)	Small Islands	Loss or significant change in cultural resources that contribute to adaptive capacity and resilience, including IKLK, identity, social cohesion, social and kinship reciprocity networks, practices	Increased climate impacts including inundation of significant cultural areas on land, species range shifts and biodiversity loss associated with increasing sea surface temperatures	Population and settlement concentration in coastal areas increases exposure of cultural heritage to climate-driven coastal hazards and risk of uninhabitability and associated loss of intangible cultural systems	Incapability of maintaining cultural heritage due to lack of resources for protection and continuation. Loss of cultural asset reduces resilience building opportunities by undermining IKLK-based climate adaptation options	Integrating cultural heritage into climate adaptation plans and strategies; promote nature-based solutions that are congruent with cultural heritage; utilise appropriate technologies to protect culturally sensitive natural capital	*Low confidence* (*limited evidence*, *medium agreement*)	15.3.4.7
Risk of reduced habitability of reef and non-reef islands leading to increased migration (KR9)	Small islands	Substantial increase in island land areas deemed permanently uninhabitable by people, resulting in the displacement, resettlement or permanent out-migration of entire island communities	Under RCP4.5, increase in the frequency, magnitude and spatial extent of extreme sea level events and associated coastal flooding, with associated salinisation of freshwater resources, terrestrial ecosystem degradation, and land loss due to increased coastal erosion or permanent submergence. Increase in aridity and/or frequency and duration of drought events and/or negative precipitation trends associated with decline in quantity and quality of ground and surface water resources	Large increases in population exposure due to population growth and urbanisation; degradation of coral reefs reducing coastal protection (as a result of repeated bleaching events and human activity); degradation of mangrove ecosystems	Limited economic growth, high income inequalities, limited financial capacities, limited land alternatives, and persistently large numbers of low-income people, especially in urban areas in coastal locations; persistent limited freshwater and terrestrial resource management technology, infrastructure and policy	Over the next decades: promote alternatives to natural threatened resources (e.g., freshwater), promote accommodation (e.g., building standard). High-end scenario: planned and participatory internal and international migration (permanent and circular) and limits to adaptation	*High confidence* (*medium evidence*, *high agreement*)	15.3.4.6
Cross-Chapter Paper 1: Biodiversity hotspots								
Loss of species in biodiversity hotspots	Global (land and ocean)	Increasing risk of extinction of 20% of animal and plant species in biodiversity hotspots	Risk increases rapidly beyond 2°C global warming	Warming and/or climate change velocities above the global average	Present human impacts already exceed predicted impacts of climate change in many areas. If species are endemic (unique to an area), they will be unable to disperse into more suitable climatic conditions	Expanded network of protected areas connected by dispersal corridors; restoration of lost and degraded habitats, and biodiversity-friendly use of land and sea	*High confidence* (*medium evidence*)	CCP1 {101.2.1}

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Loss of freshwater biodiversity	Global	Increasing risk of local species extinctions and population declines, especially of endemic species in biodiversity hotspots	Increase in drought, heatwaves, warming beyond 2°C	Warming and/or climate change velocities above the global average	Present human impacts already exceed projected impacts of climate change. Vulnerability exacerbated by water withdrawals for human use, dams, pollution and invasive species	Reduce present human impacts. Facilitate species dispersal by removing barriers. Prevent pollution and excessive water removal from rivers and lakes	*High confidence* (*strong evidence*)	CCP1 101.2.3
Loss of terrestrial biodiversity	Global	Increasing risk of local species extinctions and population declines, especially of endemic species in biodiversity hotspots	Increase in drought, wildfires, floods, storms and warming greater than 2°C	Warming and/or climate change velocities above the global average	Present human impacts already exceed predicted impacts of climate change. Vulnerability exacerbated by habitat loss due to deforestation, farming and urbanisation, pollution, invasive introduced species	Improve management of and expand network of protected areas and dispersal corridors. Restore lost and degraded habitats, including native forests. Nature-friendly farming, forestry and land use	*High confidence* (*medium evidence*)	CCP1 101.2.2
Decline of marine biodiversity	Global	Further loss of thousands of species in low latitudes with decline of tropical fisheries and associated food security. Increased risk of species extinctions and population declines, especially of endemic species in enclosed seas	Increase in marine heatwave frequency to intervals of less than 6 years, warming of greater than 1.5°C	Warming and/or climate change velocities above the global average	Direct human impacts from overexploitation and pollution. Failure to allow recovery of natural food webs, especially top predators, impacted by fisheries. Vulnerability exacerbated by fishing of all kinds through direct (removal of top predators, habitat destruction, bycatch) and indirect (food webs) impacts	Expand network of fully protected Marine Reserves to 30% of ocean where most biodiversity occurs. Cessation of habitat destruction by seabed trawling and dredging. Allow recovery of natural food webs through sustainable ecosystem-based fishing practices	*High confidence* (*medium evidence*)	CCP1 101.2.4
Cross-Chapter Paper 5: Mountains								
People and infrastructure at risk from landslide and flood hazards	Mountain Areas in Central-South America, Asia and Africa	About 13% of people at risk of increased landslide activity in certain regions (e.g. High mountain Asia) and twofold average increase in the number of people exposed to inland flooding with highest increases in South Asia, Southeast Asia and North-western South America; flood magnitude exceeding current safety thresholds (by mid-century in many regions); moderate to high increase of land, people and infrastructure at risk of glacier outburst floods by the end of the century	Increase in extreme precipitation (all mountain regions), change in freeze/thaw transitions or changes in snowpack conditions (WGI, Chapter 12, Ranasinghe et al., 2021); likelihood of severe consequences higher at 1.5°C and very high at 4°C	People and infrastructure settling in new hazard prone locations, increase in agricultural activities and urban areas. Present levels of exposure are already critical in mountain areas. SSP3 conditions lead to highest risks	Current levels of vulnerability continuing into the future in certain regions mostly related to conditions such as limited financial resources and low adaptive capacity (Northwestern South America and South Asia) which are realised mostly under SSP3 and SSP4 conditions.	Low-regret measures (e.g., raising awareness, consider long planning horizons), mix of hard and soft measures, flood defence with capacity for return period >80–100 years, resettlements	*Medium evidence*, *medium agreement*	CCP5.2.7.2, CCP5.3.1, CCP5.2.1, CCP5.4, SMCCP5.4

Key risk	Geographic region	Consequence that would be considered severe, and to whom	Hazard conditions that would contribute to this risk being severe	Exposure conditions that would contribute to this risk being severe	Vulnerability conditions that would contribute to this risk being severe	Adaptation options with highest potential for reducing risk	Confidence in key risk identification	Chapter and section
Risks to local livelihoods and the economy from changing water resources	All mountain regions with hot spots in Northwestern South America and South Asia.	By mid-century up to 50–100% of the lowland population being water stressed in area already water stressed today (e.g. dependent on essential but largely insufficient share of freshwater).. Water tower function critically impaired in some regions (e.g. Upper Indus Basin)	Temperature increase and decrease in solid precipitation (snow), which leads to decrease in snow and to accelerated melting of glaciers (WGI Chapter 12, 11, Ranasinghe et al, (2021), Seneviratne et al. (2021), SROCC Chapter 2, Hock et al., (2019))	SSP3 conditions will lead to highest exposure especially in regions predicting high demographic trends (e.g., Asia)	Current level of unsustainable agriculture (extensive irrigation, inadequate seed varieties), current level of high dependency of water supplies from snow melt and glaciers. Higher competition for water, little diversification of economic sectors (from today's conditions). Highest risk under SSP3 conditions	Implementation of integrated water resource management, improved community-level water governance, consideration of water–food–energy nexus	*High agreement*, *medium evidence*	CP5.2.7.2, CCP5.2.2.1, CCP5.3.2.2, CCP5.4, SMCCP5.4
Risks of ecosystem change and species extinctions due to temperature shifts	All mountain regions	Extinction of 15% of species (4–48%) at 5°C global surface air temperature increase	Increasing mean annual and seasonal temperature and increased frequency of droughts (WGI Chapter 12, Ranasinghe et al., 2021,) and crossing of thresholds, e.g., melting of ice	Presence of endemic species on isolated mountain tops with no scope to disperse to higher altitudes or latitudes	Species unable to survive higher temperatures or competition with species better adapted to the new conditions. Those with low capacity to disperse and colonise new areas	Translocation of species, management of competition from colonising species, better fire management	*Medium evidence*, *high agreement* (with respect to risk, not the adaptation options)	CCP5.3.1, CCP5.3.2.3, SMCCP5.4
Risk to intangible losses and cultural values	All mountain regions	Intrinsic value and place attachment losses due to change in landscape character, which can also translate to economic losses for regions where aesthetic mountain landscape is valuable for tourism	Temperature increases leading to glacier retreat and variable- or low-snow seasons	Not assessed	Low adaptability to societal value change, deep attachment to irreplaceable physical, social and cultural dimensions of place and lack of diversification options (e.g., for tourism, agriculture)	Addressing 'ecological grief' and addressing changes in societal values by exploring opportunities due to changes in landscape character, redefine 'aesthetics'	*Limited evidence*, *medium agreement*	CCP5.3.2.4

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