

## Technical Summary

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## TS.0 Introduction

This Technical Summary of the *IPCC Special Report on Ocean and Cryosphere in a Changing Climate (SROCC)* consists of the Executive Summaries of all chapters (1-6) of the Special Report, the Executive Summary from the integrative cross-chapter box on low-lying islands and coasts, and supporting figures drawn from the chapters and the Summary for Policymakers. The Technical Summary follows the structure of the Report (Table TS.1).

Section TS.1 (Chapter 1) introduces important key concepts, summarizes the characteristics and interconnection of ocean and cryosphere and highlights their importance in the earth system and for human societies in the light of climate change. TS.2 (Chapter 2) assesses changes in high mountain cryosphere and their impacts on local mountain communities and far beyond. TS.3 (Chapter 3) evaluates the state of knowledge concerning changes and impacts in the Arctic and Antarctic ocean and cryosphere systems, including challenges and opportunities for societies. TS.4 (Chapter 4) focusses on regional and global changes in sea level, the associated risk to low-lying islands, coasts and human settlements, and response options. TS.5 (Chapter 5) assesses changes in the ocean and marine ecosystems, including risks to ecosystem services and vulnerability of the dependent communities. TS.6 (Chapter 6) examines extremes and abrupt or irreversible changes in the ocean and cryosphere in a changing climate, and identifies sustainable and resilient risk management strategies. All Chapters and their Executive Summaries build on findings since the *IPCC Fifth Assessment Report (AR5)* and, whenever applicable, outcomes of the *IPCC Special Report on Global Warming of 1.5°C (SR15)*.

**Table TS.1:** Structure of the Technical Summary (TS) and Chapters included in the IPCC Special Report on Ocean and Cryosphere in a Changing Climate (SROCC).

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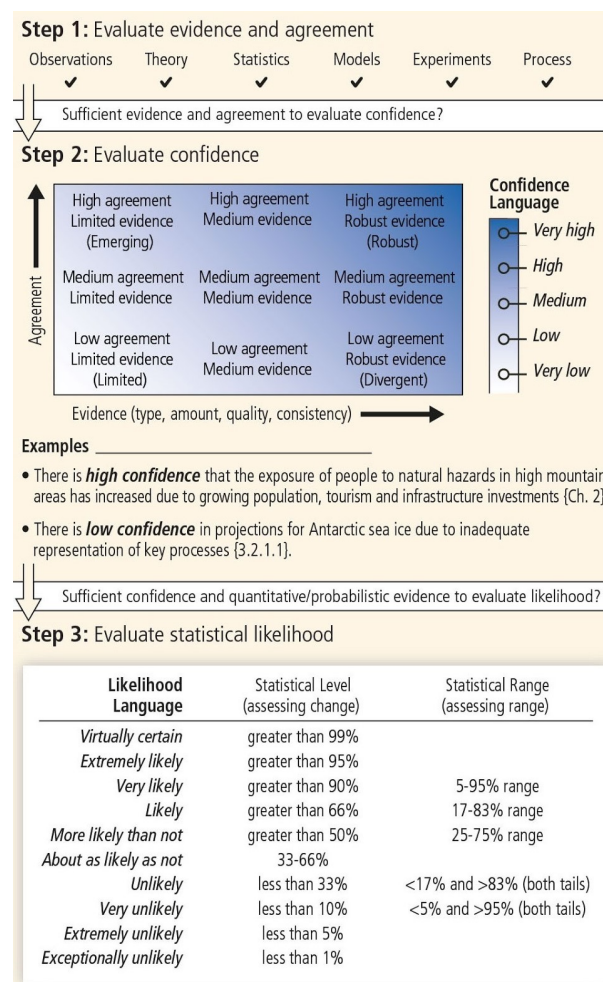
TS.1	Chapter 1: Framing and Context of the Report
TS.2	Chapter 2: High Mountain Areas
TS.3	Chapter 3: Polar Regions
TS.4	Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities
TS.5	Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities
TS.6	Chapter 6: Extremes, Abrupt Changes and Managing Risks
TS.7	Integrative Cross-Chapter Box: Low Lying Islands and Coasts

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SROCC uses IPCC calibrated language<sup>1</sup> for the communication of confidence in the assessment process (see Chapter 1 and references therein). This calibrated language is designed to consistently evaluate and communicate uncertainties that arise from incomplete knowledge due to a lack of information, or from disagreement about what is known or even knowable. The IPCC calibrated language uses qualitative expressions of confidence based on the robustness of evidence for a finding, and (where possible) uses quantitative expressions to describe the likelihood of a finding (Figure TS.1).

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<sup>1</sup> Each finding is grounded in an evaluation of underlying evidence and agreement. The summary terms for evidence are: limited, medium or robust. For agreement, they are low, medium or high. In many cases, a synthesis of evidence and agreement supports an assignment of confidence. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. This Report also uses the term ‘*likely range*’ to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range. For more details see Chapter 1, Section 1.9.2 and Figure 1.4, and: Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe and F.W. Zwiers, 2010: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 4 pp.



**Figure TS.1:** Schematic of the IPCC usage of calibrated language, with examples of confidence and likelihood statements from this report (for more details see Section 1.9.2, Figure 1.4 and Cross-Chapter Box 5 in Chapter 1).

References to chapter sections, boxes, cross-chapter boxes as well as to figures and tables are provided in curly brackets {} at the end of each statement below.

## TS.1 Framing and Context of the Report

This special report assesses new knowledge since the IPCC 5th Assessment Report (AR5) and the Special Report on Global Warming of 1.5°C (SR1.5) on how the ocean and cryosphere have and are expected to change with ongoing global warming, the risks and opportunities these changes bring to ecosystems and people, and mitigation, adaptation and governance options for reducing future risks. Chapter 1 provides context on the importance of the ocean and cryosphere, and the framework for the assessments in subsequent chapters of the report.

**All people on Earth depend directly or indirectly on the ocean and cryosphere.** The fundamental roles of the ocean and cryosphere in the Earth system include the uptake and redistribution of anthropogenic carbon dioxide and heat by the ocean, as well as their crucial involvement of in the hydrological cycle. The cryosphere also amplifies climate changes through snow, ice and permafrost feedbacks. Services provided to people by the ocean and/or cryosphere include food and freshwater, renewable energy, health and wellbeing, cultural values, trade, and transport. {1.1, 1.2, 1.5; Figure TS.2}

**Sustainable development is at risk from emerging and intensifying ocean and cryosphere changes.** Ocean and cryosphere changes interact with each of the United Nations Sustainable Development Goals (SDGs). Progress on climate action (SDG13) would reduce risks to aspects of sustainable development that

are fundamentally linked to the ocean and cryosphere and the services they provide (*high confidence*<sup>2</sup>). Progress on achieving the SDGs can contribute to reducing the exposure or vulnerabilities of people and communities to the risks of ocean and cryosphere change (*medium confidence*). {1.1}

**Communities living in close connection with polar, mountain, and coastal environments are particularly exposed to the current and future hazards of ocean and cryosphere change.** Coasts are home to approximately 28% of the global population, including around 11% living on land less than 10 m above sea level. Almost 10% of the global population lives in the Arctic or high mountain regions. People in these regions face the greatest exposure to ocean and cryosphere change, and poor and marginalised people here are particularly vulnerable to climate-related hazards and risks (*very high confidence*). The adaptive capacity of people, communities and nations is shaped by social, political, cultural, economic, technological, institutional, geographical, and demographic factors. {1.1, 1.5, 1.6, Cross-Chapter Box 2 in Chapter 1}

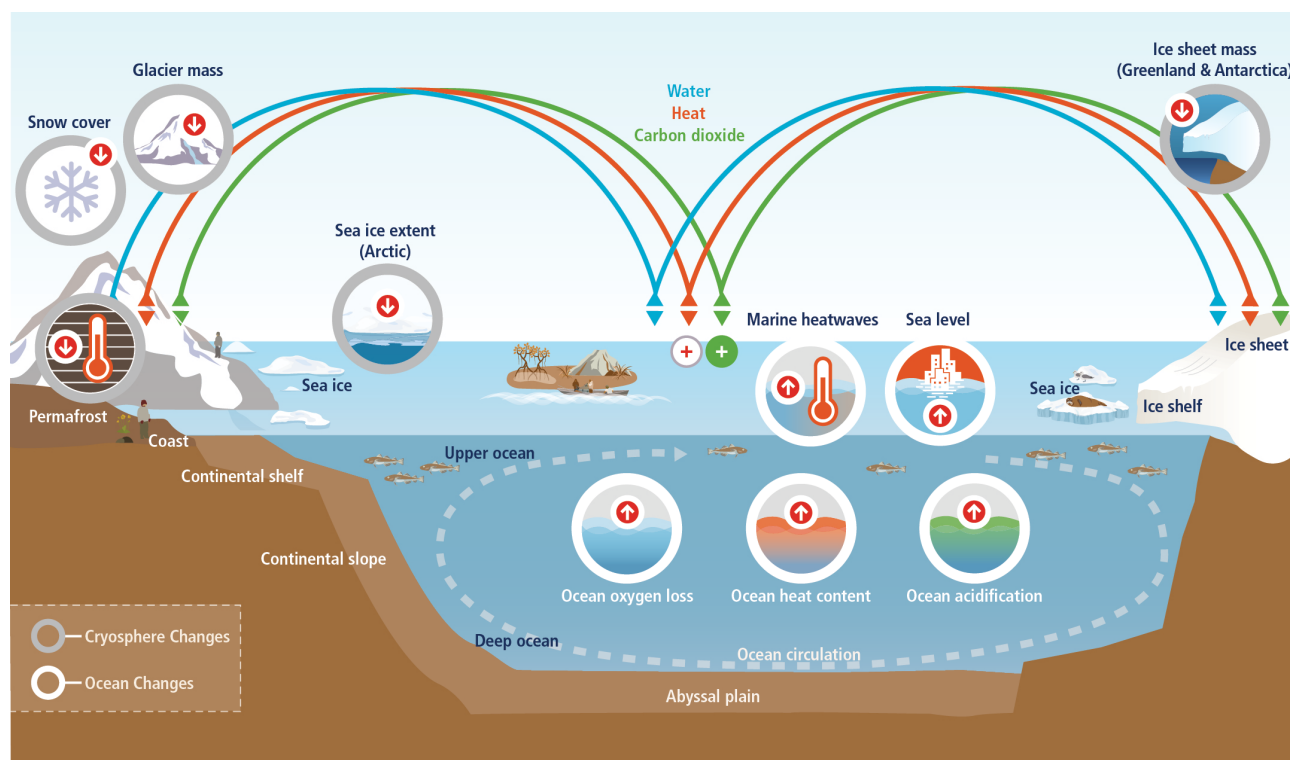
**Ocean and cryosphere changes are pervasive and observed from high mountains, to the polar regions, to coasts, and into the deep ocean.** AR5 assessed that the ocean is warming (*0-700 m: virtually certain*<sup>3</sup>; *700-2000 m: likely*), sea level is rising (*high confidence*), and ocean acidity is increasing (*high confidence*). Most glaciers are shrinking (*high confidence*), the Greenland and Antarctic ice sheets are losing mass (*high confidence*), sea-ice extent in the Arctic is decreasing (*very high confidence*), Northern Hemisphere snow cover is decreasing (*very high confidence*), and permafrost temperatures are increasing (*high confidence*). Improvements since AR5 in observation systems, techniques, reconstructions and model developments, have advanced scientific characterisation and understanding of ocean and cryosphere change, including in previously identified areas of concern such as ice sheets and Atlantic Meridional Overturning Circulation. {1.1, 1.4, 1.8.1, Figure TS.3}

**Evidence and understanding of the human causes of climate warming, and of associated ocean and cryosphere changes, has increased over the past 30 years of IPCC assessments (*very high confidence*).** Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels (SR1.5). Areas of concern in earlier IPCC reports, such as the expected acceleration of sea level rise, are now observed (*high confidence*). Evidence for expected slow-down of Atlantic Meridional Overturning Circulation is emerging in sustained observations and from long-term palaeoclimate reconstructions (*medium confidence*), and may be related with anthropogenic forcing according to model simulations, although this remains to be properly attributed. Significant sea level rise contributions from Antarctic ice sheet mass loss (*very high confidence*), which earlier reports did not expect to manifest this century, are already being observed. {1.1, 1.4}

**Ocean and cryosphere changes and risks by the end-of-century (2081-2100) will be larger under high greenhouse gas emission scenarios, compared with low emission scenarios (*very high confidence*).** Projections and assessments of future climate, ocean and cryosphere changes in SROCC are commonly based on coordinated climate model experiments from the Coupled Model Intercomparison Project Phase 5 (CMIP5) forced with Representative Concentration Pathways (RCPs) of future radiative forcing. Current emissions continue to grow at a rate consistent with a high emission future without effective climate change mitigation policies (referred to as RCP8.5). The SROCC assessment contrasts this high greenhouse gas emission future with a low greenhouse gas emission, high mitigation future (referred to as RCP2.6) that gives a two in three chance of limiting warming by the end of the century to less than 2°C above pre-industrial. {Cross-Chapter Box 1 in Chapter 1; Table TS.2}

<sup>2</sup> In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Section 1.9.2 and Figure 1.4 for more details).

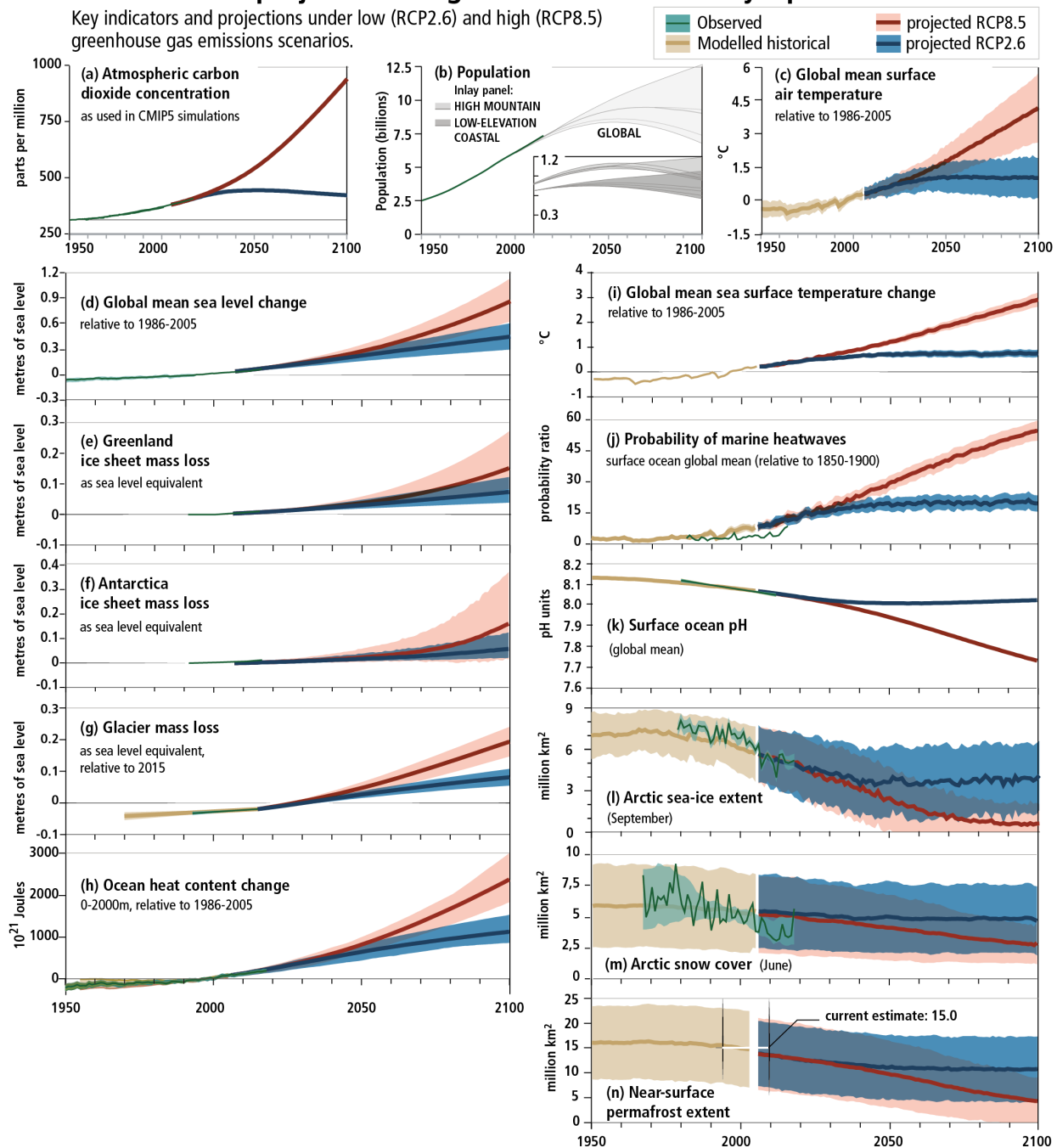
<sup>3</sup> In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Section 1.9.2 and Figure 1.4 for more details). This Report also uses the term ‘*likely range*’ to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.



**Figure TS.2:** Schematic illustration of key components and changes of the ocean and cryosphere, and their linkages in the Earth system through the global exchange of heat, water, and carbon (Section 1.2). Climate change-related effects (increase/decrease indicated by arrows in pictograms) in the ocean include sea level rise, increasing ocean heat content and marine heat waves, increasing ocean oxygen loss and ocean acidification (Section 1.4.1). Changes in the cryosphere include the decline of Arctic sea ice extent, Antarctic and Greenland ice sheet mass loss, glacier mass loss, permafrost thaw, and decreasing snow cover extent (Section 1.4.2). For illustration purposes, a few examples of where humans directly interact with ocean and cryosphere are shown (Figure modified from Box 1.1, Figure 1 in Chapter 1; for more details see Box 1.1).

## Observed and projected changes in the ocean and cryosphere

Key indicators and projections under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios.



**Figure TS.3:** Changes in the ocean and cryosphere that have already occurred, and projected future changes this century under low (RCP2.6) and high (RCP8.5) greenhouse gas emission scenarios. Context is shown by changes in: (a) atmospheric carbon dioxide concentration {Cross-Chapter Box 1 in Chapter 1, Figure 1.3}; and (b) global population including the range of future population scenarios for global, high mountain and low-elevation coastal populations across the Shared Socioeconomic Pathways. Additionally, around 4 million people live in the Arctic (2010), with an increase of 4% projected for 2030 {1.1, 2.1, 4.3, Cross-Chapter Box 1 in Chapter 1}. Pervasive and intensifying ocean and cryosphere changes are shown in lower panels for observed (green) and/or modelled historical (brown) changes, and contrasting differences in future changes under high (red; RCP8.5) and low (blue; RCP2.6) greenhouse gas emission scenarios. Changes are shown for: (c) global mean surface air temperature change relative to 1986-2005 with *likely* range. AR5 assessed that observed surface temperature increase from preindustrial (1850-1900) to 1986-2005 was  $0.61 (\pm 0.6) ^\circ\text{C}$  {Cross-Chapter Box 1 in Chapter 1}; (d) Global mean sea level change (metres) relative to 1986-2005 with *likely* range {4.2.3}; (e, f) Greenland and Antarctic ice sheet mass loss, as contribution to global sea level (metres), relative to 1992 with  $\pm 1$  standard deviation range {3.3.1}; (g) Glacier mass loss, as contribution to global sea level (metres), relative to 2015 with *likely* range {Cross-Chapter Box 6 in Chapter 2, Table 4.1}; (h) Global ocean heat content change (0-2000 m depth; in  $10^{21}$  joules) relative to 1986-2005 with 5-95% range {Figure 5.1}; (i) Global mean sea surface temperature change ( $^\circ\text{C}$ ) relative to 1986-2005 with 5-95% range. {Box 5.1, 5.2.2}; (j)



Probability ratio of surface ocean marine heatwaves, global mean relative to 1850-1900 with 5-95% range. A probability ratio of 10 equals a 10-times increase in the probability of experiencing a marine heatwave relative to 1850-1900 {6.4.1}; (k) Global mean surface pH (on the total scale) with 5-95% range. Assessed observational trends between 1980-2012 are centred on 1996 and compiled from open ocean time series site longer than 15 years {Box 5.1, Figure 5.6, 5.2.2}; (l) Arctic sea ice extent in September (millions of km<sup>2</sup>) with *likely* range. Observed shading denotes 5-95% range across three satellite-derived products {3.2.1, 3.2.2 Figure 3.3} (*Note*: Antarctic sea ice is not shown here due to *low confidence* in future projections {3.2.1}); (m) Arctic snow cover in June (land areas north of 60°N in millions of km<sup>2</sup>) plotted as 5-year moving averages with *likely* range. Observed shading denotes 5-95% range across 5 snow products {3.4.1, 3.4.2, Figure 3.11}; (n) Near-surface permafrost extent (millions of km<sup>2</sup>) with *likely* range {3.4.1, 3.4.2, Figure 3.10}. Differing baseline intervals and temporal coverage of observations reflect data limitations for quantifying the full extent of ocean and cryosphere change since the preindustrial {1.8.1, Figure 1.3}.

**Table TS.2:** Projected change in global mean surface air temperature and key ocean variables for the *near-term* (2031-2050) and *end-of-century* (2081-2100) relative to the *recent past* (1986-2005) reference period from CMIP5. Small differences in the projections given here compared with AR5 reflect differences in the number of models available now compared to at the time of the AR5 assessment (for more details see Cross-Chapter Box 1 in Chapter 1).

	Scenario	Near term: 2031-2050		End-of-century: 2081-2100	
		Mean	5-95% range	Mean	5-95% range
Global mean surface air temperature (°C) <sup>4</sup>	RCP2.6	0.9	0.5 to 1.4	1.0	0.3 to 1.7
	RCP4.5	1.1	0.6 to 1.6	1.8	1.0 to 2.6
	RCP6.0	1.0	0.5 to 1.5	2.3	1.3 to 3.2
	RCP8.5	1.3	0.7 to 2.0	3.7	2.5 to 4.9
Global mean sea surface temperature (°C) <sup>5</sup> (section 5.2.5)	RCP2.6	0.64	0.56 to 0.72	0.73	0.60 to 0.87
	RCP8.5	0.95	0.86 to 1.03	2.58	2.34 to 2.82
Surface pH (units) <sup>5</sup> (section 5.2.2.3)	RCP2.6	-0.072	-0.072 to -0.072	-0.065	-0.064 to -0.066
	RCP8.5	-0.108	-0.107 to -0.109	-0.315	-0.314 to -0.317
Dissolved oxygen (100-600 m) (% change) (section 5.2.2.4) <sup>5</sup>	RCP2.6	-0.9	-0.6 to -1.2	-0.6	-0.3 to 0.9
	RCP8.5	-1.4	-1.2 to -1.6	-3.9	-3.5 to -4.5

**Characteristics of ocean and cryosphere change include thresholds of abrupt change, long-term changes that cannot be avoided, and irreversibility (*high confidence*).** Ocean warming, acidification and deoxygenation, ice sheet and glacier mass loss, and permafrost degradation are expected to be irreversible on timescales relevant to human societies and ecosystems. Long response times of decades to millennia mean that the ocean and cryosphere are committed to long-term change even after atmospheric greenhouse gas concentrations and radiative forcing stabilise (*high confidence*). Ice melt or the thawing of permafrost

<sup>4</sup> Calculated following the same procedure as AR5. The 5-95% model range of global mean surface air temperature across CMIP5 projections was assessed in AR5 as the *likely* range, after accounting for additional uncertainties or different levels of confidence in models.

<sup>5</sup> The 5-95% model range for global mean sea surface temperature, surface pH and dissolved oxygen (100-600 m) as referred to in the SROCC assessment as the *very likely* range (see also Chapter 1, Section 1.9.2, Figure 1.4).



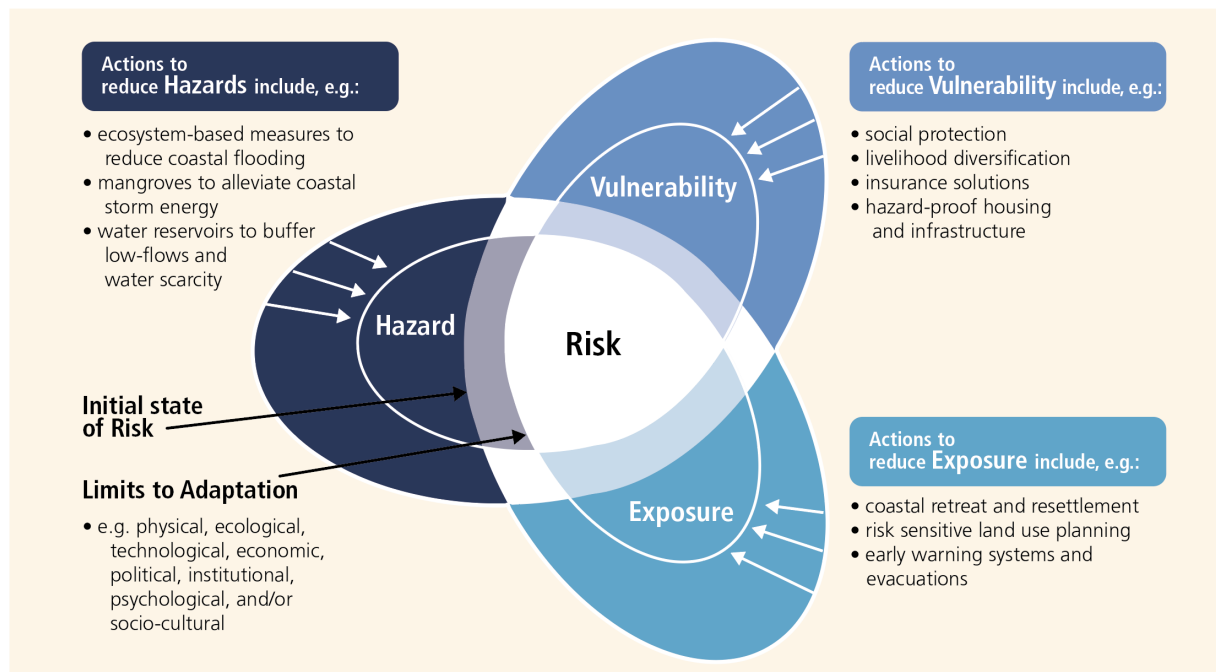
involve thresholds (state changes) that allow for abrupt, nonlinear responses to ongoing climate warming (*high confidence*). These characteristics of ocean and cryosphere change pose risks and challenges to adaptation {1.1, Box 1.1, 1.3}.

**Societies will be exposed, and challenged to adapt, to changes in the ocean and cryosphere even if current and future efforts to reduce greenhouse gas emissions keep global warming well below 2°C (*very high confidence*).** Ocean and cryosphere-related mitigation and adaptation measures include options that address the causes of climate change, support biological and ecological adaptation, or enhance societal adaptation. Most ocean-based local mitigation and adaptation measures have limited effectiveness to mitigate climate change and reduce its consequences at the global scale, but are useful to implement because they address local risks, often have co-benefits such as biodiversity conservation, and have few adverse side effects. Effective mitigation at a global scale will reduce the need and cost of adaptation, and reduce the risks of surpassing limits to adaptation. Ocean-based carbon dioxide removal at the global scale has potentially large negative ecosystem consequences. {Cross-Chapter Box 2 in Chapter 1, 1.6.1, 1.6.2; Figure TS.4}

**The scale and cross-boundary dimensions of changes in the ocean and cryosphere challenge the ability of communities, cultures and nations to respond effectively within existing governance frameworks (*high confidence*). Profound economic and institutional transformations are needed if climate-resilient development is to be achieved (*high confidence*).** Changes in the ocean and cryosphere, the ecosystem services that they provide, the drivers of those changes, and the risks to marine, coastal, polar and mountain ecosystems, occur on spatial and temporal scales that may not align within existing governance structures and practices (*medium confidence*). This report highlights the requirements for transformative governance, international and transboundary cooperation, and greater empowerment of local communities in the governance of the ocean, coasts, and cryosphere in a changing climate. {1.5, 1.7, Cross-Chapter Box 2 in Chapter 1, Cross-Chapter Box 3 in Chapter 1}

**Robust assessments of ocean and cryosphere change, and the development of context-specific governance and response options, depend on utilising and strengthening all available knowledge systems (*high confidence*).** Scientific knowledge from observations, models and syntheses provides global to local scale understandings of climate change (*very high confidence*). Indigenous knowledge and local knowledge provide context-specific and socio-culturally relevant understandings for effective responses and policies (*medium confidence*). Education and climate literacy enable climate action and adaptation (*high confidence*). {1.8, Cross-Chapter Box 4 in Chapter 1}

**Long-term sustained observations and continued modeling are critical for detecting, understanding and predicting ocean and cryosphere change, providing the knowledge to inform risk assessments and adaptation planning (*high confidence*).** Knowledge gaps exist in scientific knowledge for important regions, parameters and processes of ocean and cryosphere change, including for physically plausible, high impact changes like high-end sea level rise scenarios that would be costly if realised without effective adaptation planning and even then may exceed limits to adaptation. Means such as expert judgement, scenario-building, and invoking multiple lines of evidence enable comprehensive risk assessments even in cases of uncertain future ocean and cryosphere changes. {1.8.1, 1.9.2; Cross-Chapter Box 5 in Chapter 1}



**Figure TS.4:** There are options for risk reduction through adaptation. Adaptation can reduce risk by addressing one or more of the three risk factors: vulnerability, exposure, and/or hazard. The reduction of vulnerability, exposure, and/or hazard potential can be achieved through different policy and action choices over time until limits to adaptation might be reached. The figure builds on the conceptual framework of risk used in AR5 (for more details see Cross-Chapter Box 2 in Chapter 1).

## TS.2 High Mountain Areas

The cryosphere (including, snow, glaciers, permafrost, lake and river ice) is an integral element of high-mountain regions, which are home to roughly 10% of the global population. Widespread cryosphere changes affect physical, biological and human systems in the mountains and surrounding lowlands, with impacts evident even in the ocean. Building on the IPCC's Fifth Assessment Report (AR5), this chapter assesses new evidence on observed recent and projected changes in the mountain cryosphere as well as associated impacts, risks and adaptation measures related to natural and human systems. Impacts in response to climate changes independently of changes in the cryosphere are not assessed in this chapter. Polar mountains are included in Chapter 3, except those in Alaska and adjacent Yukon, Iceland, and Scandinavia, which are included in this chapter.

### Observations of cryospheric changes, impacts, and adaptation in high mountain areas

**Observations show general decline in low-elevation snow cover (*high confidence*), glaciers (*very high confidence*) and permafrost (*high confidence*) due to climate change in recent decades.** Snow-cover duration has declined in nearly all regions, especially at lower elevations, on average by 5 days per decade, with a *likely* range from 0 to 10 days per decade. Low elevation snow depth and extent have declined, although year-to-year variation is high. Mass change of glaciers in all mountain regions (excluding the Canadian and Russian Arctic, Svalbard, Greenland and Antarctica) was *very likely*  $-490 \pm 100 \text{ kg m}^{-2} \text{ yr}^{-1}$  ( $123 \pm 24 \text{ Gt yr}^{-1}$ ) in 2006–2015. Regionally averaged mass budgets were *likely* most negative (less than  $-850 \text{ kg m}^{-2} \text{ yr}^{-1}$ ) in the southern Andes, Caucasus and central Europe, and least negative in High Mountain Asia ( $-150 \pm 110 \text{ kg m}^{-2} \text{ yr}^{-1}$ ) but variations within regions are strong. Between 3.6 and 5.2 million  $\text{km}^2$  are underlain by permafrost in the eleven high-mountain regions covered in this chapter corresponding to 27–29% of the global permafrost area (*medium confidence*). Sparse and unevenly distributed measurements show an increase in permafrost temperature (*high confidence*), for example, by  $0.19 \pm 0.05^\circ\text{C}$  on average for about 28 locations in the European Alps, Scandinavia, Canada, and Asia during the past decade. Other observations reveal decreasing permafrost thickness and loss of ice in the ground. {2.2.2, 2.2.3, 2.2.4, Figure TS.5}

**Glacier, snow and permafrost decline has altered the frequency, magnitude and location of most related natural hazards (*high confidence*). Exposure of people and infrastructure to natural hazards has increased due to growing population, tourism and development (*high confidence*).** Glacier retreat and permafrost thaw have decreased the stability of mountain slopes and the integrity of infrastructure (*high confidence*). The number and area of glacier lakes has increased in most regions in recent decades (*high confidence*), but there is only *limited evidence* that the frequency of glacier lake outburst floods has changed. In some regions, snow avalanches involving wet snow have increased (*medium confidence*), and rain-on-snow floods have decreased at low elevations in spring and increased at high elevations in winter (*medium confidence*). The number and extent of wildfires have increased in the Western USA partly due to early snow melt (*medium confidence*). {2.3.2, 2.3.3}

**Changes in snow and glaciers have changed the amount and seasonality of runoff in snow-dominated and glacier-fed river basins (*very high confidence*) with impacts on agriculture (*medium confidence*).** Winter runoff has increased in recent decades due to more precipitation falling as rain (*high confidence*). In some glacier-fed rivers, summer and annual runoff have increased due to intensified glacier melt, but decreased where glacier melt water has lessened as glacier area shrinks. Decreases were observed especially in regions dominated by small glaciers, such as the European Alps (*medium confidence*). In some areas, where glacier and snow meltwater has decreased, especially where other climatic drivers or socio-economic stressors are also present, agricultural productivity has declined, e.g., in the Western USA, High Mountain Asia and the tropical Andes (*medium confidence*). There is *limited evidence* of impacts on operation and productivity of hydropower facilities resulting from changes in seasonality and both increases and decreases in water input, for example, in Central Europe, Iceland, Western Canada and USA, and low latitude Andes. {2.3.1}

**Species composition and abundance have markedly changed in high-mountain ecosystems in recent decades (*very high confidence*), partly due to changes in the cryosphere (*high confidence*).** Habitats for establishment by formerly absent species have opened up or been altered by reduced snow cover (*high confidence*), retreating glaciers (*very high confidence*), and thawing of permafrost (*medium confidence*). Reductions in glacier and snow cover have directly altered the structure of many freshwater communities (*high confidence*). Reduced snow cover has negatively impacted the reproductive fitness of some snow-dependent plant and animal species, including foraging and predator-prey relationships of mammals (*high confidence*). Upslope migration of individual species, mostly due to warming and to a lesser extent due to cryosphere-related changes, has often increased local species richness (*very high confidence*). Some cold-adapted species, including endemics, in terrestrial and freshwater communities have declined in abundance (*high confidence*). While the plant productivity has generally increased, the actual impact on provisioning, regulating, and cultural ecosystem services varies greatly (*high confidence*). {2.3.3}

**Tourism and recreation activities such as skiing, glacier tourism and mountaineering have been negatively impacted by declining snow cover, glaciers and permafrost (*medium confidence*).** In several regions, worsening route safety has reduced mountaineering opportunities (*medium confidence*). Variability and decline in natural snow cover have compromised the operation of low-elevation ski resorts (*high confidence*). Glacier and snow decline have impacted aesthetic, spiritual and other cultural aspects of mountain landscapes (*medium confidence*), reducing the well-being of people. {2.3.5, 2.3.6}

**Adaptation in agriculture, tourism and drinking water supply has aimed to reduce the impacts of cryosphere change (*medium confidence*), though there is *limited evidence* on their effectiveness owing to a lack of formal evaluations, or technical, financial and institutional barriers to implementation.** Artificial snowmaking has generally been effective to sustain ski tourism in some regions (*medium confidence*). Release and storage of water from reservoirs according to sectoral needs (agriculture, drinking water, ecosystems) has reduced the impact of seasonal variability on runoff (*medium confidence*). {2.3.1, 2.3.5}

**Future projections of cryospheric changes, their impacts and risks, and adaptation in high mountain areas**

**Snow cover, glaciers and permafrost are projected to continue to decline in almost all regions throughout the 21st century (*high confidence*).** Compared to 1986–2005, low elevation snow depth will

*likely* decrease by 10–40% for 2031–2050, regardless of Representative Concentration Pathway (RCP) and for 2081–2100, *likely* by 10–40 % for RCP2.6 and by 50–90% for RCP8.5. Projected glacier mass reductions between 2015 and 2100 are *likely* 22–44% for RCP2.6 and 37–57% for RCP8.5. In regions dominated by smaller glaciers and relatively little ice cover (e.g., Central Europe, Caucasus, Low Latitudes), glaciers will lose more than 80% of their current mass by 2100 under RCP8.5 (*medium confidence*). Permafrost thaw and degradation will increase during the 21st century (*very high confidence*) but quantitative projections are scarce. {2.2.2, 2.2.3, 2.4.4}

**Most types of natural hazards are projected to change in frequency, magnitude and areas affected as the cryosphere continues to decline (*medium confidence*).** Glacier retreat and permafrost thaw are projected to decrease the stability of mountain slopes, and increase the number and area of glacier lakes (*medium confidence*). Resulting landslides and floods, and cascading events, will also emerge where there is no record of previous events (*medium confidence*). Snow avalanches are projected to decline in number and runout distance at lower elevation, and avalanches involving wet snow even in winter will occur more frequently (*medium confidence*). Rain-on-snow floods will occur earlier in spring and later in autumn, and be more frequent at higher elevations and less frequent at lower elevations (*high confidence*). {2.3.2, 2.3.3}

**River runoff in snow-dominated and glacier-fed river basins will change further in amount and seasonality in response to projected snow cover and glacier decline (*very high confidence*) with negative impacts on agriculture, hydropower and water quality in some regions (*medium confidence*).** The average winter snow melt runoff is projected to increase (*high confidence*), and spring peaks to occur earlier (*very high confidence*). Projected trends in annual runoff vary substantially among regions, and can even be opposite in direction, but there is *high confidence* that in most regions average annual runoff from glaciers will have reached a peak that will be followed by declining runoff at the latest by the end of the 21st century. Declining runoff is expected to reduce the productivity of irrigated agriculture in some regions (*medium confidence*). Hydropower operations will increasingly be impacted by altered amount and seasonality of water supply from snow and glacier melt (*high confidence*). The release of heavy metals, particularly mercury, and other legacy contaminants currently stored in glaciers and permafrost, is projected to reduce water quality for freshwater biota, household use and irrigation (*medium confidence*). {2.3.1}

**Current trends in cryosphere-related changes in high-mountain ecosystems are expected to continue and impacts to intensify (*very high confidence*).** While high mountains will provide new and greater habitat area, including refugia for lowland species, both range expansion and shrinkage are projected, and at high elevations this will lead to population declines (*high confidence*). The latter increases the risk of local extinctions, in particular for freshwater cold-adapted species (*medium confidence*). Without genetic plasticity and/or behavioral shifts, cryospheric changes will continue to negatively impact endemic and native species, such as some coldwater fish (e.g. trout) and species whose traits directly depend on snow (e.g. snowshoe hares) or many large mammals (*medium confidence*). The survival of such species will depend on appropriate conservation and adaptation measures (*medium confidence*). Many projected ecological changes will alter ecosystem services (*high confidence*), affecting disturbance regimes (e.g. fire, rock fall, slope erosion) with considerable impacts on people (*medium confidence*). {2.3.3}

**Cultural assets, such as snow- and ice-covered peaks in many UNESCO World Heritage sites, and tourism and recreation activities, are expected to be negatively affected by future cryospheric change in many regions (*high confidence*).** Current adaptation strategies, such as snowmaking to support ski tourism, are projected to be less effective in most parts of Europe, North America and Japan already at 1.5°C global warming relative to the pre-industrial period, with effectiveness further reduced beyond 2°C warming (*high confidence*). Diversification through year-round activities supports adaptation of tourism under future climate change (*medium confidence*). {2.3.5, 2.3.6}

### **Enablers and response options to promote adaptation and sustainable development in high mountain areas**

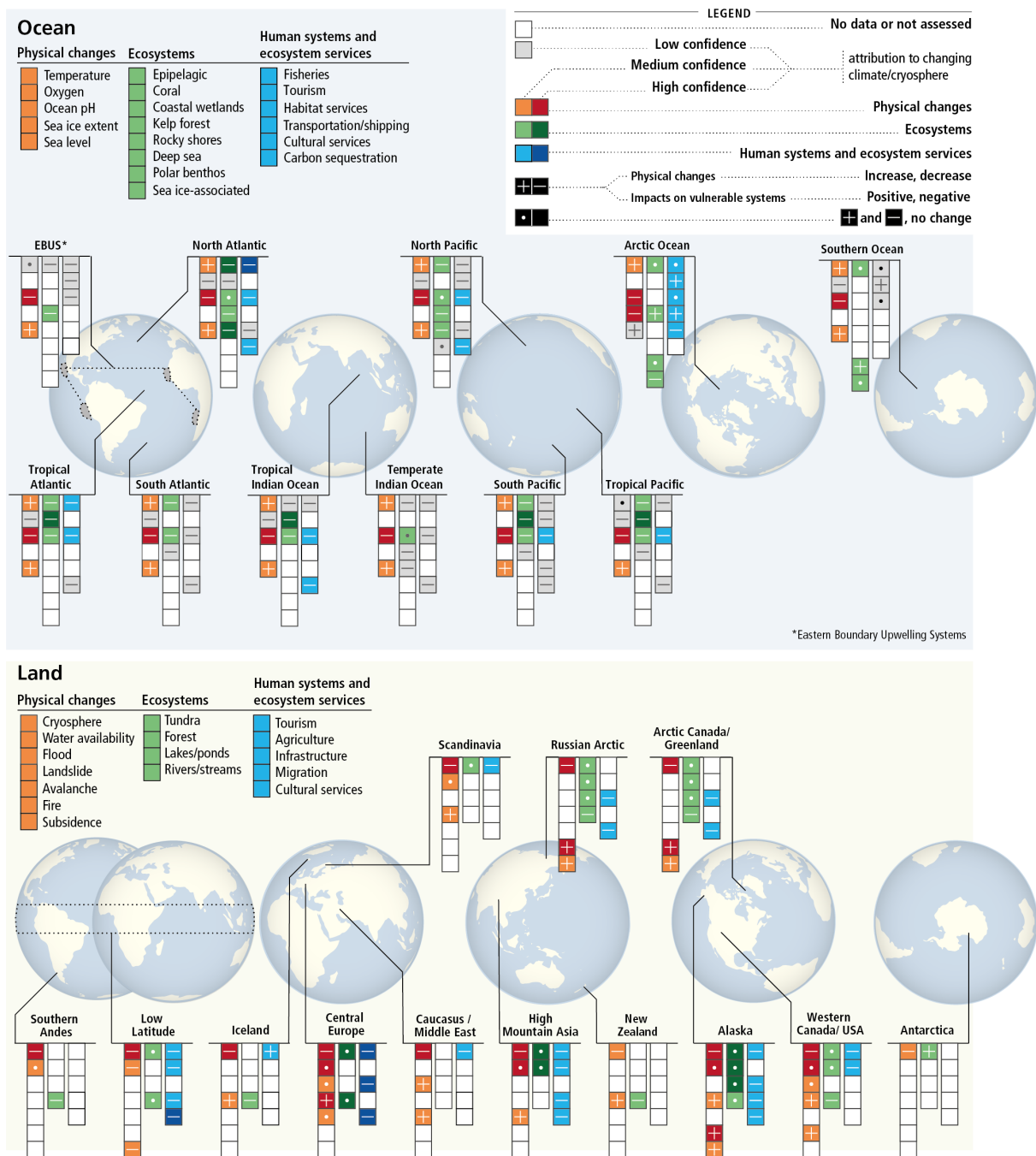
**The already committed and unavoidable climate change affecting all cryosphere elements, irrespective of the emission scenario, point to integrated adaptation planning to support and enhance water availability, access, and management (*medium confidence*).** Integrated management approaches for water, in particular for energy, agriculture, ecosystems and drinking water supply, can be effective at dealing with

impacts from changes in the cryosphere. These approaches also offer opportunities to support social-ecological systems, through the development and optimization of storage and the release of water from reservoirs (*medium confidence*), while being cognisant of potential negative implications for some ecosystems. Success in implementing such management options depends on the participation of relevant stakeholders, including affected communities, diverse knowledge and adequate tools for monitoring and projecting future conditions, and financial and institutional resources to support planning and implementation (*medium confidence*). {2.3.1, 2.3.3, 2.4}

**Effective governance is a key enabler for reducing disaster risk, considering relevant exposure factors such as planning, zoning, and urbanization pressures, as well as vulnerability factors such as poverty, which can challenge efforts towards resilience and sustainable development for communities (*medium confidence*).** Reducing losses to disasters depend on integrated and coordinated approaches to account for the hazards concerned, the degree of exposure, and existing vulnerabilities. Diverse knowledge that includes community and multi-stakeholder experience with past impacts complements scientific knowledge to anticipate future risks. {CCB-1, 2.3.2, Figure 2.8, Box 2.4, 2.4}

**International cooperation, treaties and conventions exist for some mountain regions and transboundary river basins with potential to support adaptation action. However, there is *limited evidence on the extent to which impacts and losses arising from changes in the cryosphere are specifically monitored and addressed in these frameworks*.** A wide range of institutional arrangements and practices have emerged over the past three decades that respond to a shared global mountain agenda and specific regional priorities. There is potential to strengthen them to also respond to climate-related cryosphere risks and open opportunities for development through adaptation (*limited evidence, high agreement*). The Sustainable Development Goals (SDGs), Sendai Framework and Paris Agreement have directed some attention in mountain-specific research and practice towards the monitoring and reporting on targets and indicators specified therein. {2.3.1, 2.4}

## Observed regional changes in the ocean and cryosphere and related impacts



**Figure TS.5:** Synthesis of regional consequences and impacts in ocean-, polar- and high mountain regions assessed in SROCC. For each region, physical changes (red boxes), impacts on key ecosystems (green boxes), and impacts on human systems and ecosystem services (blue boxes) are shown. Physical changes are attributable to rising greenhouse gas concentrations and associated warming at either global or regional scales with the indicated confidence. Physical changes in the oceans refer to averages horizontally and vertically for each of the named regions. For mountain regions, only impacts that are at least partly attributed to a change in the cryosphere are shown, and only if assessed at *medium* or *high confidence* for the respective region. For physical changes, + or – refers to an increase or decrease in amount or frequency in the measured parameter. For impacts on ecosystems, human systems and ecosystems services, + or – depicts a positive (beneficial) or negative (adverse) impact, respectively. A dot represents both positive and negative impacts being observed. The physical changes in the ocean are defined as: Temperature is change in 0-700m layer of the ocean, Oxygen in the 0-1200 m layer or oxygen minimum layer, Ocean pH as surface pH. Ecosystems in the ocean: Coral refers to coral reefs and cold water corals. For polar ecosystems, the pelagic realm which includes open waters deeper than 200m is included in the category epipelagic. Habitat services refer to supporting structures and services (e.g. habitat, biodiversity, primary production). Ecosystems on Land: Tundra refers to tundra and alpine meadows and terrestrial Antarctic ecosystems. The underlying information is given for land regions in SM2.11 (Appendix 2.A) and SM3.4, and for ocean regions in SM 5.11 and SM3.4. {2.3.7, 4.2.2.6, 5.2.2, 5.2.3, 5.3.3, 5.4,5.6}

### TS.3 Polar Regions

This chapter assesses the state of physical, biological and social knowledge concerning the Arctic and Antarctic ocean and cryosphere, how they are affected by climate change, and how they will evolve in future. Concurrently, it assesses the local, regional and global consequences and impacts of individual and interacting polar system changes, and it assesses response options to reduce risk and build resilience in the polar regions. Key findings are:

***The polar regions are losing ice, and their oceans are changing rapidly. The consequences of this polar transition extend to the whole planet, and are affecting people in multiple ways***

**Arctic surface air temperature has *likely* increased by more than double the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming.** For each of the five years since AR5 (2014-2018), Arctic annual surface air temperature exceeded that of any year since 1900. During the winters (January-March) of 2016 and 2018, surface temperatures in the central Arctic were 6°C above the 1981-2010 average, contributing to unprecedented regional sea ice absence. These trends and extremes provide *medium evidence* with *high agreement* of the contemporary coupled atmosphere-cryosphere system moving well outside the 20th century envelope. {Box 3.1; 3.2.1.1}

**The Arctic and Southern Oceans are continuing to remove carbon dioxide from the atmosphere and to acidify (*high confidence*).** There is *medium confidence* that the amount of CO<sub>2</sub> drawn into the Southern Ocean from the atmosphere has experienced significant decadal variations since the 1980s. Rates of calcification (by which marine organisms form hard skeletons and shells) declined in the Southern Ocean by  $3.9 \pm 1.3\%$  between 1998 and 2014. In the Arctic Ocean, the area corrosive to organisms that form shells and skeletons using the mineral aragonite expanded between the 1990s and 2010, with instances of extreme aragonite undersaturation. {3.2.1.2.4}

**Both polar oceans have continued to warm in recent years, with the Southern Ocean being disproportionately and increasingly important in global ocean heat increase (*high confidence*).** Over large sectors of the seasonally ice-free Arctic, summer upper mixed layer temperatures increased at around 0.5°C per decade during 1982-2017, primarily associated with increased absorbed solar radiation accompanying sea ice loss, and the inflow of ocean heat from lower latitude increased since the 2000s (*high confidence*). During 1970-2017, the Southern Ocean south of 30°S accounted for 35-43% of the global ocean heat gain in the upper 2000 m (*high confidence*), despite occupying ~25% of the global ocean area. In recent years (2005-2017), the Southern Ocean was responsible for an increased proportion of the global ocean heat increase (45-62%) (*high confidence*). {3.2.1.2.1, Figure TS.5}

**Climate-induced changes in seasonal sea ice extent and thickness and ocean stratification are altering marine primary production (*high confidence*), with impacts on ecosystems (*medium confidence*).** Changes in the timing, duration and intensity of primary production have occurred in both polar oceans, with marked regional or local variability (*high confidence*). In the Antarctic, such changes have been associated with locally-rapid environmental change, including retreating glaciers and sea ice change (*medium confidence*). In the Arctic, changes in primary production have affected regional species composition, spatial distribution, and abundance of many marine species, impacting ecosystem structure (*medium confidence*). {3.2.1; 3.2.3, 3.2.4}

**In both polar regions, climate-induced changes in ocean and sea ice, together with human introduction of non-native species, have expanded the range of temperate species and contracted the range of polar fish and-ice associated species (*high confidence*).** Commercially- and ecologically-important fish stocks like Atlantic cod, haddock and mackerel have expanded their spatial distributions northwards many 100 km, and increased their abundance. In some Arctic areas, such expansions have affected the whole fish community, leading to higher competition and predation on smaller-sized fish species, while some commercial fisheries have benefited. There has been a southward shift in the distribution of Antarctic krill in the South Atlantic, the main area for the krill fishery (*medium confidence*). These changes are altering biodiversity in polar marine ecosystems (*medium confidence*) {3.2.3; Box 3.4}.



**It is *very likely* that Arctic sea ice extent continues to decline in all months of the year; the strongest reductions in September ( $-12.8 \pm 2.3\%$  per decade; 1979-2018) are *likely* unprecedented in at least 1000 years.** It is *virtually certain* that Arctic sea ice has thinned, concurrent with a shift to younger ice: since 1979, the areal proportion of thick ice at least 5 years old has declined by approximately 90%. It is *very likely* that approximately half the observed sea ice loss is attributable to increased atmospheric greenhouse gas concentrations. Changes in Arctic sea ice have potential to influence midlatitude weather on timescales of weeks to months (*medium confidence*). {3.2.1.1; Box 3.2}

**It is *very likely* that Antarctic sea ice cover exhibits no significant trend over the period of satellite observations (1979 to 2018).** While the drivers of historical decadal variability are known with *medium confidence*, there is currently *limited evidence* and *low agreement* concerning causes of the strong recent decrease (2016-2018), and *low confidence* in the ability of current-generation climate models to reproduce and explain the observations. {3.2.1.1}

**Shipping activity during the Arctic summer increased over the past two decades in regions for which there is information, concurrent with reductions in sea ice extent (*high confidence*).** Transit times across the Northern Sea Route have shortened due to lighter ice conditions, and while long-term, pan-Arctic datasets are incomplete, the distance travelled by ships in Arctic Canada nearly tripled during 1990-2015 (*high confidence*). Greater levels of Arctic ship-based transportation and tourism have socio-economic and political implications for global trade, northern nations, and economies linked to traditional shipping corridors; they will also exacerbate region-specific risks for marine ecosystems and coastal communities if further action to develop and adequately implement regulations does not keep pace with increased shipping (*high confidence*). {3.2.1.1; 3.2.4.2; 3.2.4.3; 3.4.3.3.2; 3.5.2.7}

**Permafrost temperatures have increased to record high levels (*very high confidence*), but there is *medium evidence* and *low agreement* that this warming is currently causing northern permafrost regions to release additional methane and carbon dioxide.** During 2007-2016, continuous-zone permafrost temperatures in the Arctic and Antarctic increased by  $0.39 \pm 0.15^{\circ}\text{C}$  and  $0.37 \pm 0.10^{\circ}\text{C}$  respectively. Arctic and boreal permafrost region soils contain 1440-1600 Gt organic carbon (*medium confidence*). Changes in permafrost influence global climate through emissions of carbon dioxide and methane released from the microbial breakdown of organic carbon, or the release of trapped methane. {3.4.1; 3.4.3}

**Climate-related changes to Arctic hydrology, wildfire and abrupt thaw are occurring (*high confidence*), with impacts on vegetation and water and food security.** Snow and lake ice cover has declined, with June snow extent decreasing  $13.4 \pm 5.4\%$  per decade (1967-2018) (*high confidence*). Runoff into the Arctic Ocean increased for Eurasian and North American rivers by  $3.3 \pm 1.6\%$  and  $2.0 \pm 1.8\%$  respectively (1976-2018; *medium confidence*). Area burned and frequency of fires (including extreme fires) are unprecedented over the last 10,000 years (*high confidence*). There has been an overall greening of the tundra biome, but also browning in some regions of tundra and boreal forest, and also changes in the abundance and distribution of animals including reindeer and salmon (*high confidence*). Together, these impact access to (and food availability within) herding, hunting, fishing, forage and gathering areas, affecting the livelihood, health and cultural identity of residents including Indigenous peoples (*high confidence*). {3.4.1; 3.4.3; 3.5.2}

**Limited knowledge, financial resources, human capital and organisational capacity are constraining adaptation in many human sectors in the Arctic (*high confidence*).** Harvesters of renewable resources are adjusting timing of activities to changes in seasonality and less safe ice travel conditions. Municipalities and industry are addressing infrastructure failures associated with flooding and thawing permafrost, and coastal communities and cooperating agencies are in some cases planning for relocation (*high confidence*). In spite of these adaptations, many groups are making decisions without adequate knowledge to forecast near- and long-term conditions, and without the funding, skills and institutional support to engage fully in planning processes (*high confidence*). {3.5.2, 3.5.4, Cross-Chapter Box 9}

**It is *extremely likely* that the rapid ice loss from the Greenland and Antarctic ice sheets during the early 21st century has increased into the near present-day, adding to the ice sheet contribution to**

**global sea level rise.** From Greenland, the 2012-2016 ice losses ( $-247 \pm 15 \text{ Gt yr}^{-1}$ ) were similar to those from 2002-2011 ( $-263 \pm 21 \text{ Gt yr}^{-1}$ ) and *extremely likely* greater than from 1992-2001 ( $-8 \pm 82 \text{ Gt yr}^{-1}$ ). Summer melting of the Greenland Ice Sheet has increased since the 1990s (*very high confidence*) to a level unprecedented over at least the last 350 years, and two-to-fivefold the pre-industrial level (*medium confidence*). From Antarctica, the 2012-2016 losses ( $-199 \pm 26 \text{ Gt yr}^{-1}$ ) were *extremely likely* greater than those from 2002-2011 ( $-82 \pm 27 \text{ Gt yr}^{-1}$ ) and *likely* greater than from 1992-2001 ( $-51 \pm 73 \text{ Gt yr}^{-1}$ ). Antarctic ice loss is dominated by acceleration, retreat and rapid thinning of major West Antarctic Ice Sheet outlet glaciers (*very high confidence*), driven by melting of ice shelves by warm ocean waters (*high confidence*). The combined sea level rise contribution from both ice sheets for 2012-2016 was  $1.2 \pm 0.1 \text{ mm yr}^{-1}$ , a 29% increase on the 2002-2011 contribution and a  $\sim 700\%$  increase on the 1992-2001 period. {3.3.1}

**Mass loss from Arctic glaciers ( $-212 \pm 29 \text{ Gt yr}^{-1}$ ) during 2006-2015 contributed to sea level rise at a similar rate ( $0.6 \pm 0.1 \text{ mm yr}^{-1}$ ) to the Greenland Ice Sheet (*high confidence*).**

Over the same period in Antarctic and subantarctic regions, glaciers separate from the ice sheets changed mass by  $-11 \pm 108 \text{ Gt yr}^{-1}$  (*low confidence*). {2.2.3, 3.3.2}

**There is *limited evidence* and *high agreement* that recent Antarctic Ice Sheet mass losses could be irreversible over decades to millennia.** Rapid mass loss due to glacier flow acceleration in the Amundsen Sea Embayment of West Antarctica and in Wilkes Land, East Antarctica, may indicate the beginning of Marine Ice Sheet Instability, but observational data are not yet sufficient to determine whether these changes mark the beginning of irreversible retreat. {3.3.1; Cross-Chapter Box 8 in Chapter 3; 4.2.3.1.2}

***The polar regions will be profoundly different in future compared with today, and the degree and nature of that difference will depend strongly on the rate and magnitude of global climatic change<sup>6</sup>. This will challenge adaptation responses regionally and worldwide.***

**It is *very likely* that projected Arctic warming will result in continued loss of sea ice and snow on land, and reductions in the mass of glaciers. Important differences in the trajectories of loss emerge from 2050 onwards, depending on mitigation measures taken (*high confidence*).** For stabilised global warming of  $1.5^\circ\text{C}$ , an approximately 1% chance of a given September being sea ice free at the end of century is projected; for stabilised warming at a  $2^\circ\text{C}$  increase, this rises to 10-35% (*high confidence*). The potential for reduced (further 5-10%) but stabilised Arctic autumn and spring snow extent by mid-century for RCP2.6 contrasts with continued loss under RCP8.5 (a further 15-25% reduction to end of century) (*high confidence*). Projected mass reductions for polar glaciers between 2015 and 2100 range from  $16 \pm 7\%$  for RCP2.6 to  $33 \pm 11\%$  for RCP8.5 (*medium confidence*). {3.2.2; 3.3.2; 3.4.2, Cross-Chapter Box 6 in Chapter 2}

**Both polar oceans will be increasingly affected by  $\text{CO}_2$  uptake, causing conditions corrosive for calcium carbonate shell-producing organisms (*high confidence*), with associated impacts on marine organisms and ecosystems (*medium confidence*).** It is *very likely* that both the Southern Ocean and the Arctic Ocean will experience year-round conditions of surface water undersaturation for mineral forms of calcium carbonate by 2100 under RCP8.5; under RCP2.6 the extent of undersaturated waters are reduced markedly. Imperfect representation of local processes and sea-ice interaction in global climate models limit the ability to project the response of specific polar areas and the precise timing of undersaturation at seasonal scales. Differences in sensitivity and the scope for adaptation to projected levels of ocean acidification exist across a broad range of marine species groups. {3.2.1; 3.2.2.3; 3.2.3}

**Future climate-induced changes in the polar oceans, sea ice, snow and permafrost will drive habitat and biome shifts, with associated changes in the ranges and abundance of ecologically-important species (*medium confidence*).** Projected shifts will include further habitat contraction and changes in abundance for polar species, including marine mammals, birds, fish, and Antarctic krill (*medium confidence*). Projected range expansion of subarctic marine species will increase pressure for high-Arctic species (*medium confidence*), with regionally-variable impacts. Continued loss of Arctic multi-year sea ice will affect ice-related and pelagic primary production (*high confidence*), with impacts for whole ice-associated, seafloor and open ocean ecosystems. On Arctic land, projections indicate a loss of globally-

<sup>6</sup> Projections for ice sheets and glaciers in the polar regions are summarized in chapters 4 and 2, respectively.

unique biodiversity as some high-Arctic species will be outcompeted by more temperate species and very limited refugia exist (*medium confidence*). Woody shrubs and trees are projected to expand, covering 24–52% of the current tundra region by 2050. {3.2.2.1; 3.2.3; 3.2.3.1; Box 3.4; 3.4.2; 3.4.3}

**The projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial and subsistence fisheries with implications for regional economies, cultures and the global supply of fish, shellfish, and Antarctic krill (*high confidence*). Future impacts for linked human systems depend on the level of mitigation and especially the responsiveness of precautionary management approaches (*medium confidence*).** Polar regions support several of the world's largest commercial fisheries. Specific impacts on the stocks and economic value in both regions will depend on future climate change and on the strategies employed to manage the effects on stocks and ecosystems (*medium confidence*). Under high emission scenarios current management strategies of some high-value stocks may not sustain current catch levels in the future (*low confidence*); this exemplifies the limits to the ability of existing natural resource management frameworks to address ecosystem change. Adaptive management that combines annual measures and within-season provisions informed by assessments of future ecosystem trends reduces the risks of negative climate change impacts on polar fisheries (*medium confidence*). {3.2.4; 3.5.2; 3.5.4}

**Widespread disappearance of Arctic near-surface permafrost is projected to occur this century as a result of warming (*high confidence*), with important consequences for global climate.** By 2100, near-surface permafrost area will decrease by 2–66% for RCP2.6 and 30–99% for RCP8.5. This could release 10s to 100s of Gt C as carbon dioxide and methane to the atmosphere for RCP8.5, with the potential to accelerate climate change (*medium confidence*). Methane will contribute a small proportion of these additional carbon emissions, on the order of 0.01–0.06 Gt CH<sub>4</sub> yr<sup>-1</sup>, but could contribute 40–70% of the total permafrost-affected radiative forcing because of its higher warming potential. There is *medium evidence* but with *low agreement* whether the level and timing of increased plant growth and replenishment of soil will compensate these permafrost carbon losses. {3.4.2; 3.4.3}

**Projected permafrost thaw and decrease in snow will affect Arctic hydrology and wildfire, with impacts on vegetation and human infrastructure (*medium confidence*).** About 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is expected to increase small lake area by over 50% by 2100 for RCP8.5 (*medium confidence*). Even as the overall regional water cycle intensifies, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in snow and permafrost may lead to soil drying (*medium confidence*). Fire is projected to increase for the rest of this century across most tundra and boreal regions, while interactions between climate and shifting vegetation will influence future fire intensity and frequency (*medium confidence*). By 2050, 70% of Arctic infrastructure is located in regions at risk from permafrost thaw and subsidence; adaptation measures taken in advance could reduce costs arising from thaw and other climate-change related impacts such as increased flooding, precipitation, and freeze-thaw events by half (*medium confidence*). {3.4.1; 3.4.2; 3.4.3; 3.5.2}.

***Response options exist that can ameliorate the impacts of polar change, build resilience and allow time for effective mitigation measures. Institutional barriers presently limit their efficacy.***

**Responding to climate change in polar regions will be more effective if attention to reducing immediate risks (short-term adaptation) is concurrent with long-term planning that builds resilience to address expected and unexpected impacts (*high confidence*).** Emphasis on short-term adaptation to specific problems will ultimately not succeed in reducing the risks and vulnerabilities to society given the scale, complexity and uncertainty of climate change. Moving toward a dual focus of short- and long-term adaptation involves knowledge co-production, linking knowledge with decision-making and implementing ecosystem-based stewardship, which involves the transformation of many existing institutions (*high confidence*). {3.5.4}

**Innovative tools and practices in polar resource management and planning show strong potential in improving society's capacity to respond to climate change (*high confidence*).** Networks of protected areas, participatory scenario analysis, decision-support systems, community-based ecological monitoring that draws on local and indigenous knowledge, and self-assessments of community resilience contribute to

strategic plans for sustaining biodiversity and limit risk to human livelihoods and wellbeing. Such practices are most effective when linked closely to the policy process. Experimenting, assessing, and continually refining practices while strengthening the links with decision making has the potential to ready society for the expected and unexpected impacts of climate change (*high confidence*). {3.5.1, 3.5.2, 3.5.4}

**Institutional arrangements that provide for strong multiscale linkages with Arctic local communities can benefit from including indigenous knowledge and local knowledge in the formulation of adaptation strategies (*high confidence*).** The tightly-coupled relationship of northern local communities and their environment provide an opportunity to better understand climate change and its effects, support adaptation and limit unintended consequences. Enabling conditions for the involvement of local communities in climate adaptation planning include investments in human capital, engagement processes for knowledge co-production, and systems of adaptive governance. {3.5.3}

**The capacity of governance systems in polar regions to respond to climate change has strengthened recently, but the development of these systems is not sufficiently rapid or robust to address the challenges and risks to societies posed by projected changes (*high confidence*).** Human responses to climate change in the polar regions occur in a fragmented governance landscape. Climate change, new polar interests from outside the regions, and an increasingly-active role played by informal organisations are compelling stronger coordination and integration between different levels and sectors of governance. The governance landscape is currently not sufficiently equipped to address cascading risks and uncertainty in an integrated and precautionary way within existing legal and policy frameworks (*high confidence*). {3.5.3, 3.5.4}

#### TS.4 Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities

This chapter assesses past and future contributions to global, regional and extreme sea level changes, associated risk to low-lying islands, coasts, cities, and settlements, and response options and pathways to resilience and sustainable development along the coast.

**Global mean sea level (GMSL) is rising (*virtually certain*) and accelerating (*high confidence*).** The sum of glacier and ice sheet contributions is now the dominant source of GMSL rise (*very high confidence*). GMSL from tide gauges and altimetry observations increased from 1.4 mm yr<sup>-1</sup> over the period 1901–1990 to 2.1 mm yr<sup>-1</sup> over the period 1970–2015 to 3.2 mm yr<sup>-1</sup> over the period 1993–2015 to 3.6 mm yr<sup>-1</sup> over the period 2005–2015 (*high confidence*). The dominant cause of global mean sea level rise since 1970 is anthropogenic forcing (*high confidence*) (4.2.2.1.6, 4.2.2.5).

**Global mean sea level was considerably higher than today during past climate states that were slightly warmer than preindustrial, including the Last Interglacial (LIG; 129–116 thousand years ago), when global mean surface temperature was 0.5°C to 1.0°C warmer, and the mid-Pliocene Warm Period (mPWP; ~3.3 to 3.0 million years ago), 2°–4° C warmer. Despite the modest global warmth of the Last Interglacial, Greenland and Antarctic ice sheets contributed 6–9 m to GMSL (*high confidence*), but not more than 10 m (*medium confidence*). Based on new understanding about geological constraints since AR5, 25 m is a plausible upper bound on GMSL during the mid-Pliocene Warm Period (*low confidence*).** Ongoing uncertainties in paleo sea-level reconstructions and modeling hamper conclusions regarding the total magnitudes and rates of past sea level rise. Furthermore, the long (multi-millennial) timescales of these past climate and sea level changes, and regional climate influences from changes in Earth's orbital configuration and climate system feedbacks, lead to *low confidence* in direct comparisons with near-term future changes. (4.2.2, 4.2.2.1, 4.2.2.5, CCB-5, Supplementary Material (SM) 4.1)

**Non-climatic anthropogenic drivers, including recent and historical demographic and settlement trends and anthropogenic subsidence, have played an important role in increasing low-lying coastal communities' exposure and vulnerability to sea level rise and extreme sea level events (*very high confidence*).** In coastal deltas, for example, these drivers have altered freshwater and sediment availability (*high confidence*). In low-lying coastal areas more broadly, human-induced changes can be rapid and modify coastlines over short periods of time, outpacing the effects of SLR (*high confidence*). Adaptation can be undertaken in the short- to medium-term by targeting local drivers of exposure and vulnerability,

notwithstanding uncertainty about local SLR impacts in coming decades and beyond (*high confidence*; 4.2.2.4, 4.3.1, 4.3.2.2, 4.3.2.2., 4.3.2.3).

**Coastal ecosystems are already impacted by the combination of sea level rise, other climate-related ocean changes, and adverse effects from human activities on ocean and land (*high confidence*).** **Attributing such impacts to sea level rise, however, remains challenging due to the influence of other climate-related and non-climatic drivers such as infrastructure development and human-induced habitat degradation (*high confidence*).** Coastal ecosystems, including saltmarshes, mangroves, vegetated dunes and sandy beaches, can build vertically and expand laterally in response to SLR, though this capacity varies across sites (*high confidence*). These ecosystems provide important services that include coastal protection and habitat for diverse biota. However, as a consequence of human actions that fragment wetland habitats and restrict landward migration, coastal ecosystems progressively lose their ability to adapt to climate-induced changes and provide ecosystem services, including acting as protective barriers (*high confidence*; 4.3.2.3).

**Coastal risk is dynamic and increased by widely observed changes in coastal infrastructure, community livelihoods, agriculture and habitability (*high confidence*).** **As with coastal ecosystems, attribution of observed changes and associated risk to sea level rise remains challenging.** Drivers and processes inhibiting attribution include demographic, resource- and land-use changes, and anthropogenic subsidence (4.3.3, 4.3.4).

**A diversity of adaptation responses to coastal impacts and risks have been implemented around the world, but mostly as a reaction to current coastal risk or experienced disasters (*high confidence*).** Hard coastal protection measures (dikes, embankments, sea walls, surge barriers) are widespread, providing predictable levels of safety in North West Europe, East Asia, and around many coastal cities and deltas. Ecosystem-based adaptation is continuing to gain traction worldwide, providing multiple co-benefits, but there is still *low agreement* on its cost and long-term effectiveness. Advance, which refers to the creation of new land by building into the sea (e.g., land reclamation), has a long history in most areas where there are dense coastal populations. Accommodation measures, such as early warning systems for extreme sea level events, are widespread. Retreat is observed but largely restricted to small communities or carried out for the purpose of creating new wetland habitat (4.4.2.3, 4.4.2.4, 4.4.2.5).

## Projections

**Future rise in global mean sea level caused by thermal expansion, melting of glaciers and ice sheets, and land water storage changes, is strongly dependent on which RCP emission scenario is followed.** **Sea level rise at the end of the century is projected to be faster under all scenarios, including those compatible with achieving the long-term temperature goal set out in the Paris Agreement. GMSL will rise between 0.43 m (0.29–0.59 m, *likely* range) (RCP2.6) and 0.84 m (0.61–1.10 m, *likely* range) (RCP8.5) by 2100 (*medium confidence*) relative to 1986–2005.** Beyond 2100, sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the Greenland and Antarctic ice sheets (4.2.3.5), and will remain elevated for thousands of years (*high confidence*). For RCP8.5, estimates for 2100 are higher and the uncertainty range larger than in AR5. Antarctica could contribute up to 28 cm of sea level rise (RCP8.5, upper end of *likely* range) by the end of the century (*medium confidence*). Estimates of sea level rise higher than the *likely* range are also provided here for decision makers with low risk tolerance (SR1.5, 4.1, 4.2.3.2).

**Under RCP8.5, the rate of sea level rise will be 15 mm yr<sup>-1</sup> (10–20 mm yr<sup>-1</sup>, *likely* range) in 2100, and could exceed several cm yr<sup>-1</sup> in the 22nd century.** These high rates challenge the implementation of adaptation measures that involve a long lead-time, but this has not yet been studied in detail (4.2.3.2, 4.4.2.2.3).

**Processes controlling the timing of future ice-shelf loss and the extent of ice sheet instabilities could increase Antarctica's contribution to sea level rise to values higher than the *likely* range on century and longer time-scales (*low confidence*).** Evolution of the Antarctic Ice Sheet beyond the end of the 21st

century is characterized by deep uncertainty<sup>7</sup> as ice sheet models lack realistic representations of some of the underlying physical processes. The few model studies available addressing timescales of centuries to millennia indicate multi-meter rise in sea level for RCP8.5 (*medium confidence*). There is *low confidence* in threshold temperatures for ice sheet instabilities and the rates of GMSL rise they can produce. (Cross-Chapter Box 5 in Chapter 1, Cross-Chapter Box 8 in Chapter 3, and Sections 4.1, 4.2.3.1.1, 4.2.3.1.2, 4.2.3.6).

**Sea level does not and will not rise uniformly. Thermal expansion, ocean dynamics and land ice loss contributions will generate regional departures of about  $\pm 30\%$  around the GMSL rise. Local anthropogenic subsidence and change in wave height and period are important contributors to future changes in relative sea level (RSL) at the coast (*high confidence*).** Subsidence caused by human activities is currently the most important cause of RSL change in many delta regions. In addition, changes in wave height and period at some locations have larger effects on coastal flooding than RSL change (*medium confidence*). While the comparative importance of climate-driven RSL rise will increase over time, these findings on anthropogenic subsidence and waves imply that a consideration of local processes is critical for projections of sea level impacts at local scales (*high confidence*; 4.2.1.6, 4.2.2.4).

**Due to projected global mean sea level rise, extreme sea level events (ESLs) that are historically rare (for example, today's hundred-year event) will become common by 2100 under all RCPs (*high confidence*).** Many low-lying megacities and small islands at almost all latitudes will experience such events annually by 2050 (4.2.3.4). Greenhouse gas mitigation envisioned in low-emission scenarios (e.g., RCP2.6) is expected to sharply reduce but not eliminate risk to low-lying coasts and islands from SLR and ESL events. Low-emission scenarios lead to slower rates of SLR and allow for a wider range of adaptation options. For the first half of the 21st century differences in ESL events among the scenarios are small, facilitating adaptation planning (4.2.2.5, Figure TS.6).

**Non-climatic anthropogenic drivers will continue to increase the exposure and vulnerability of coastal communities to future sea level rise and extreme sea level events in the absence of major adaptation efforts compared to today (*high confidence*).** (4.3.4, Cross-Chapter Box 9).

**The expected impacts of sea level rise on coastal ecosystems over the course of the century include habitat contraction, loss of functionality and biodiversity, and lateral and inland migration. Impacts will be exacerbated in cases of land reclamation and where anthropogenic barriers prevent inland migration of marshes and mangroves and limit the availability and re-location of sediment (*high confidence*).** Under favorable conditions, marshes and mangroves have been found to keep pace with fast rates of SLR (e.g., > 10mm/year), but this capacity varies significantly depending on factors such as wave exposure of the location, tidal range, sediment trapping, overall sediment availability, and coastal squeeze (*high confidence*) (4.3.3.5.1).

**In the absence of adaptation, more intense and frequent extreme sea level events, together with trends in coastal development will increase expected annual flood damages by 2-3 orders of magnitude by 2100 (*high confidence*).** However, well-designed coastal protection is very effective in reducing expected damages and cost efficient for urban and densely populated regions, but generally unaffordable for rural and poorer areas (*high confidence*). Effective protection requires investments on the order of tens to several hundreds of billions of US\$ per year globally (*high confidence*). While investments are generally cost efficient for densely populated and urban areas (*high confidence*), rural and poorer areas will be challenged to afford such investments with relative annual costs for some small island states amounting to several percent of GDP (*high confidence*). Even with well-designed hard protection, the risk of possibly disastrous consequences in the event of failure of defenses remains (4.3.4, 4.4.2.2, 4.4.3.2, Cross-Chapter Box 9).

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<sup>7</sup> Statements about uncertainty in section 4.2 are contingent upon the RCP or other emissions assumptions that accompany them. In 4.4, the entirety of information facing a decision maker is taken into consideration, including the unknown path of future emissions, in assessing uncertainty. Depending on which perspective is chosen, uncertainty may or may not be characterized as “deep”.

**Risk related to sea level rise (including erosion, flooding and salinization) is expected to significantly increase by the end of this century along all low-lying coasts in the absence of major additional adaptation efforts (very high confidence).** While only urban atoll islands and some Arctic communities are expected to experience high risk relative to today in a low emission pathway, high to very high risks are expected in all low-lying coastal settings at the upper end of the *likely* range for high emission pathways (*medium confidence*). However, the transition from moderate to high and from high to very high risk will vary from one coastal setting to another (*high confidence*). While a slower rate of SLR enables greater opportunities for adapting, adaptation benefits are also expected to vary between coastal settings. Although ambitious adaptation will not necessarily eradicate end-century SLR risk (*medium confidence*), it will help to buy time in many locations and therefore help to lay a robust foundation for adaptation beyond 2100. (4.1.3, 4.3.4, Box 4.1, SM4.2).

### Choosing and Implementing Responses.

**All types of responses to sea-level rise, including protection, accommodation, ecosystem-based adaptation, advance and retreat, have important and synergistic roles to play in an integrated and sequenced response to sea-level rise (high confidence).** Hard protection and advance (building into the sea) is economically efficient in most urban contexts facing land scarcity (*high confidence*), but can lead to increased exposure in the long term. Where sufficient space is available, ecosystem-based adaptation can both reduce coastal risks and provide multiple other benefits (*medium confidence*). Accommodation such as flood-proofing buildings and early warning systems for ESL events are often both low-cost and highly cost-efficient in all contexts (*high confidence*). Where coastal risks are already high, and population size and density are low, or in the aftermath of a coastal disaster, retreat may be especially effective, albeit socially, culturally, and politically challenging (4.4.2.2, 4.4.2.3, 4.4.2.4, 4.4.2.5, 4.4.2.6, 4.4.3).

**Technical limits to hard protection are expected to be reached under high emission scenarios (RCP8.5) beyond 2100 (high confidence) and biophysical limits to ecosystem-based adaptation may arise during the 21st century, but economic and social barriers arise well before (medium confidence).** Economic challenges to hard protection increase with higher sea levels and will make adaptation unaffordable before technical limits are reached (*high confidence*). Drivers other than SLR are expected to contribute more to biophysical limits of ecosystem-based adaptation. For corals, limits may be reached during this century, due to ocean acidification and ocean warming, and for tidal wetlands due to pollution and infrastructure limiting their inland migration. Limits to accommodation are expected to occur well before limits to protection occur. Limits to retreat are uncertain, reflecting research gaps. Social barriers (i.e., governance challenges) to adaptation are already encountered (4.4.2.2, 4.4.2.3., 4.4.2.3.2, 4.4.2.5, 4.4.2.6, 4.4.3., Cross-Chapter Box 9).

**Choosing and implementing responses to sea level rise presents society with profound governance challenges and difficult social choices, which are inherently political and value-laden (high confidence).** The large uncertainties about post 2050 SLR, and the substantial impact expected, challenge established planning and decision-making practises and introduce the need for coordination within and between governance levels and policy domains. SLR responses also raise equity concerns about marginalising those most vulnerable and could potentially spark or compound social conflict (*high confidence*). Choosing and implementing responses is further challenged through a lack of resources, vexing trade-offs between safety, conservation and economic development, multiple ways of framing the “SLR problem”, power relations, and various coastal stakeholders having conflicting interests in the future development of heavily used coastal zones (*high confidence*) (4.4.2, 4.4.3).

**Despite the large uncertainties about post 2050 sea level rise, adaptation decisions can be made now, facilitated by using decision analysis methods specifically designed to address uncertainty (high confidence).** These methods favour flexible responses (i.e., those that can be adapted over time) and periodically adjust decisions (i.e., adaptive decision making). They use robustness criteria (i.e., effectiveness across a range of circumstances) for evaluating alternative responses instead of standard expected utility criteria (*high confidence*). One example is adaptation pathway analysis, which has emerged as a low-cost tool to assess long-term coastal responses as sequences of adaptive decisions in the face of dynamic coastal risk characterized by deep uncertainty (*medium evidence, high agreement*). The range of sea level rise to be considered in decisions depends on the risk tolerance of stakeholders, with stakeholders whose risk tolerance is low also considering sea level rise higher than the *likely* range (4.1, 4.4.4.3).

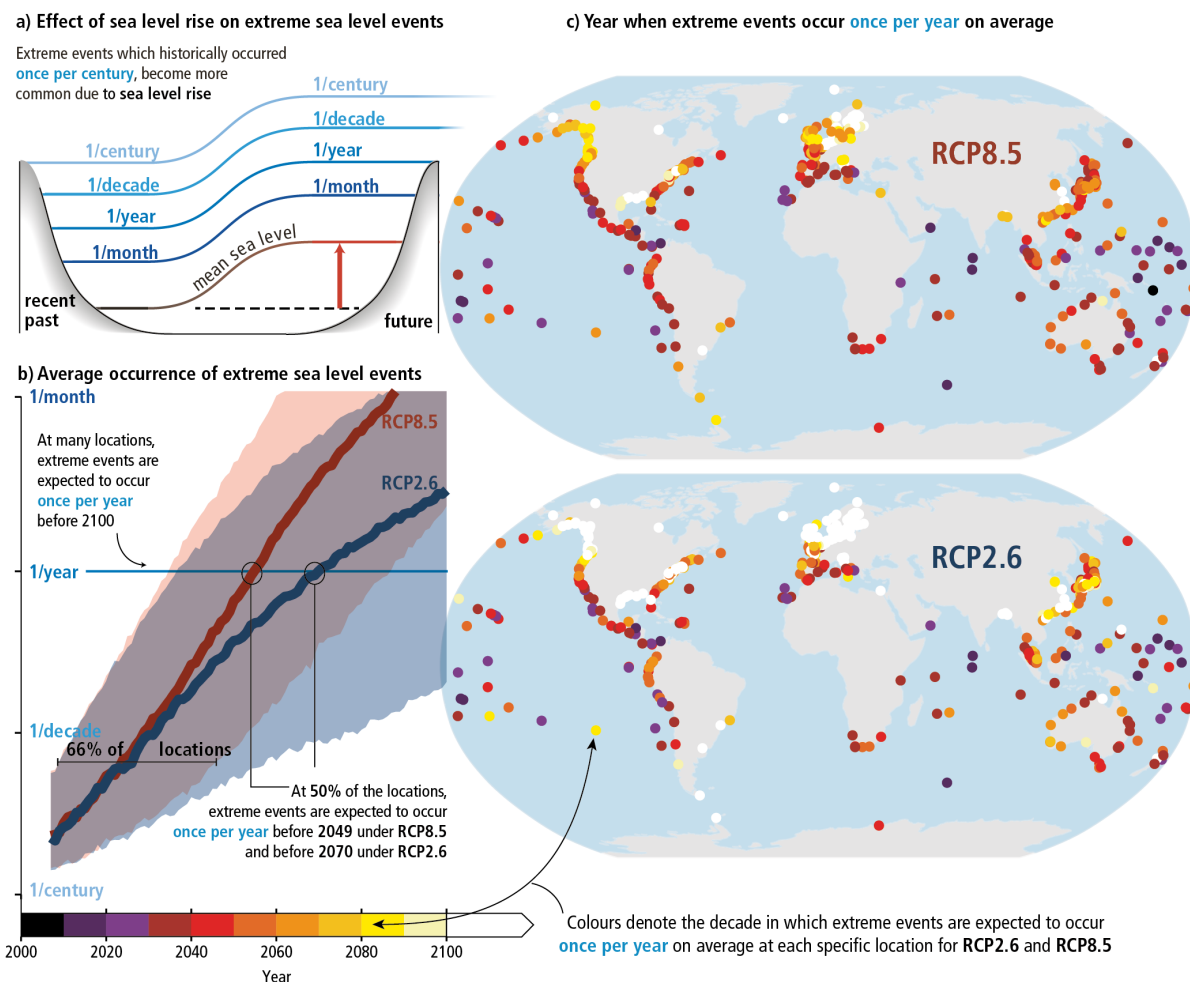


**Adaptation experience to date demonstrates that using a locally appropriate combination of decision analysis, land-use planning, public participation and conflict resolution approaches can help to address the governance challenges faced in responding to SLR (*high confidence*).** Effective SLR responses depend, first, on taking a long-term perspective when making short-term decisions, explicitly accounting for uncertainty of locality-specific risks beyond 2050 (*high confidence*), and building governance capabilities to tackle the complexity of SLR risk (*medium evidence, high agreement*). Second, improved coordination of SLR responses across scales, sectors and policy domains can help to address SLR impacts and risk (*high confidence*). Third, prioritising consideration of social vulnerability and equity underpins efforts to promote fair and just climate resilience and sustainable development (*high confidence*), and can be helped by creating safe community arenas for meaningful public deliberation and conflict resolution (*medium evidence, high agreement*). Finally, public awareness and understanding about SLR risks and responses can be improved by drawing on local, indigenous and scientific knowledge systems, together with social learning about locality-specific SLR risk and response potential (*high confidence*)(4.4.4.2, 4.4.5, Table 4.9, Figure TS.7).

**Achieving the United Nations Sustainable Development Goals and charting Climate Resilient Development Pathways depends in part on ambitious and sustained mitigation efforts to contain SLR coupled with effective adaptation actions to reduce SLR impacts and risk (*medium evidence, high agreement*).**

## Extreme sea level rise

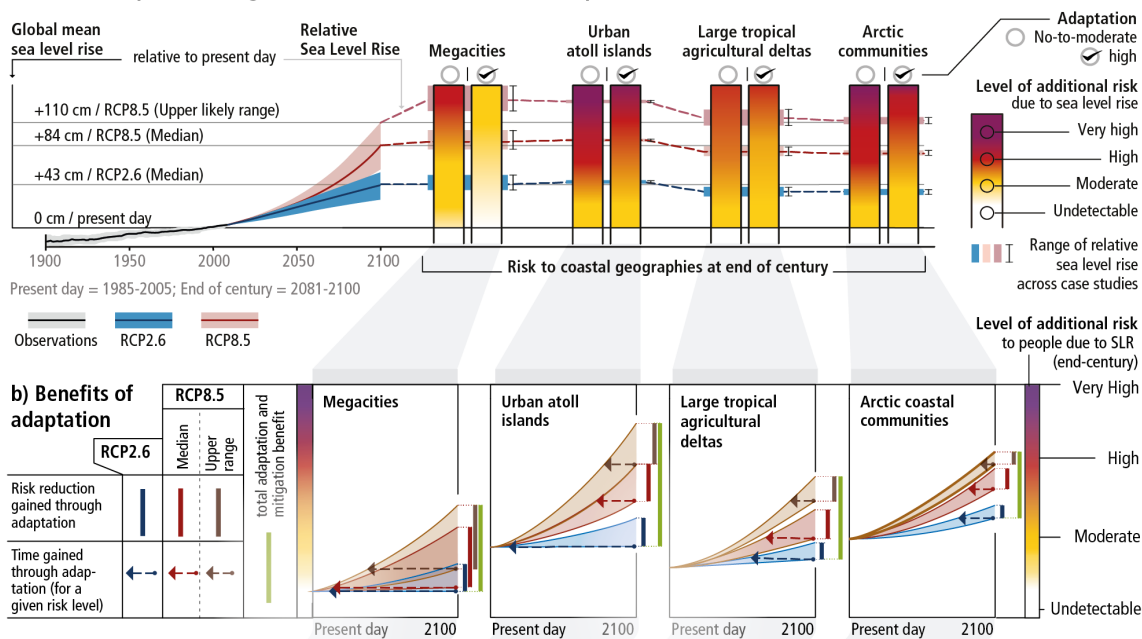
Due to projected global mean sea level rise, extreme water level events that are historically rare (e.g., those that, in the past, were induced by intense surges) will become common. For many coastal locations, this will occur during the 21st century, leading to severe flooding in the absence of strong adaptation (*high confidence*). Under all RCPs, low-lying islands will experience such events annually by 2050 {4.2.3}, Figure 4.12. Under RCP8.5, most inhabited coastlines will experience these events annually before 2100.



**Figure TS.6:** The effect of mean (average) sea level rise on extreme sea level events at coastal locations. Extreme sea level events refer to coastal water levels which occurred on average once per century during recent past (1986-2005). a) Illustration of extreme sea level events and their average occurrence in the recent past and the future. As a consequence of mean sea level rise, the extreme sea levels will be reached more frequently in the future. b) The average occurrence of extreme sea level events at 439 coastal locations (shown in c)) projected from mean sea level rise under high (Representative Concentration Pathway RCP8.5) and low (RCP2.6) greenhouse gas emission pathways. The solid lines indicate the median of all locations; the shading denotes the 17-83 percentiles. The horizontal lines mark the years when the average occurrence of extreme sea level events is once per decade and once per year. c) The year in which extreme events are expected to occur once per year on average for individual coastal locations. The darker the circle, the earlier this is projected. White circles (33% of locations under RCP2.6 and 10% under RCP8.5) indicate that extreme sea level events are not expected to occur once per year by 2100. {4.2.3, Figure 4.12}

## Sea level associated risk triggering adaptive responses

### a) Risk development during sea level rise with and without adaptation



### c) Response options for building climate resilient coastal communities

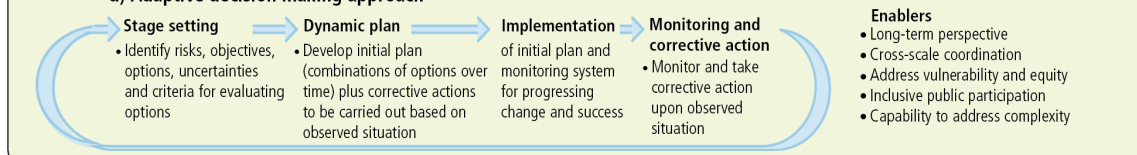
Confidence levels: ●●●● = Very High ●●● = High ●● = Medium ● = Low

Responses {4.4.2}		Effectiveness*	Advantages	Co-benefits**	Drawbacks	Economic efficiency	Governance challenges
Protection	Hard protection	Up to several meters of SLR ●●●	Predictable levels of safety ●●●	Multifunctional dikes	Flooding/erosion elsewhere, Destruction of habitat through coastal squeeze, lock-in, disaster in case of failure	High for urban coasts, low for rural coast	Long-term finance; Trade-offs between conservation, safety and tourism goals, Distributional conflicts
	Sediment-based	Depends on sediment availability	High flexibility	Beach preservation for tourism	Destruction of habitat	High if tourism revenues are high	Distributional conflicts
Ecosystem-based adaptation	Coral	Conservation	Opportunity for community involvement	Carbon sequestration, tourism, fishery productivity, water quality, food, medicine, fuel/construction, cultural	Long-term effectiveness questionable	Limited evidence on benefit-cost ratios; Depends on population density and the availability of land	Permits difficult to obtain. Lack of finance, lack of enforcement of conservation policies
		Restoration			High cost, only suitable for local application.		
	Wetland	Conservation			Global change impacts continue, safety levels less predictable. Development benefits not realised		
		Restoration			Medium to High cost, safety levels less predictable, a lot of land required		
Advance		Up to several meters of SLR ●●●	Predictable levels of safety ●●●	Generates land and land sale revenues	Groundwater salinisation, erosion, loss of coastal ecosystems/ human habitat	Very high for urban coasts	Social conflicts: New land access and distribution
Accommodation <sup>++</sup>		Very effective for small SLR	Mature technology; deposited sediments can raise elevation	Maintains landscape connectivity	Does not prevent flooding/impacts	Very high for early warning systems and building-scale measures)	Effective institutional arrangements (Early warning)
Managed retreat <sup>#</sup>		Very high <sup>***</sup> ●●●	Risks can be eliminated completely <sup>***</sup>	Optional improved services <sup>+</sup> , economy, jobs.	Loss of social cohesion, cultural identity, well-being. Possibly depressed services <sup>+</sup> , economy, jobs.	Limited evidence	Unpopular topic, high reputational risk for policy makers, unclear legal status of refugees

<sup>+</sup> health, education, housing; <sup>++</sup> Flood-proof houses, early warning systems, etc.; <sup>+++</sup> but limited by ocean acidification/warming; <sup>#</sup> Migration, displacement, relocation;

\*technical/biophysical limits; \*\* beyond risk reduction; \*\*\*if sufficient safe land is available

### d) Adaptive decision making approach



**Figure TS.7:** Risk related to sea level rise for low-lying coastal areas, benefits of adaptation, response options and adaptive decision-making to address them. Panel a) describes global mean sea level rise (GMSL) scenarios and related risk to archetypal local geographies. This assessment focusses on the additional risks due to sea level rise (SLR) and does not account for changes in extreme event climatology. The left side of panel a) describes GMSL observations for the present day and projections under Representative Concentration Pathways RCP2.6 and RCP8.5 until the end of the century (relative to 1986–2005), as assessed in Chapter 4. Relative sea level (RSL) changes at specific geographies are represented in the right hand side of panel a) {4.2, 4.3.4, SI4.2}. Only Arctic communities remote from regions of rapid glacial-isostatic emergence have been selected for this assessment. The risk assessment presented in panel a) distinguishes between two adaptation scenarios: “No-to-moderate adaptation” represents a business-as-usual scenario where no major additional adaptation efforts compared to today are implemented (i.e. neither further significant action nor new types of actions). “High adaptation” represents an ambitious combination of both incremental and transformational adaptation that leads to significant additional efforts compared to today. Adaptation implemented at its full potential is assumed here, i.e. the extent of adaptation that is technologically possible, with little financial, social and political barriers. Panel b) builds on the risk assessment in panel a) to describe risk reduction benefits from adaptation to be expected by 2100 for each SLR scenario (vertical blue, red and brown bars) as well as from combined mitigation and adaptation (vertical green bars). Panel b) also shows the time gained through adaptation (horizontal blue, red and brown bars): implementing adaptation will help reduce risk but will not necessarily eradicate risk (i.e. residual risks must be considered). Panel c) Risk related to sea level rise for low-lying coastal areas, benefits of adaptation, response options and adaptive decision-making to address risk. Panel c) describes and evaluates the options for adaptation to sea level change. Panel d) presents steps of an adaptive decision-making approach as well as key enablers of adaptation {4.4.4}.

## TS.5 Changing Ocean, Marine Ecosystems, and Dependent Communities

The ocean is essential for all aspects of human well-being and livelihood. It provides key services like climate regulation, through the energy budget, carbon cycle and nutrient cycle. The ocean is the home of biodiversity ranging from microbes to marine mammals that form a wide variety of ecosystems in open pelagic and coastal ocean.

### Observations: Climate-related trends, impacts, adaptation

**Carbon emissions from human activities are causing ocean warming, acidification, and oxygen loss with some evidence of changes in nutrient cycling and primary production. The warming ocean is affecting marine organisms at multiple trophic levels, impacting fisheries with implications for food production and human communities. Concerns regarding the effectiveness of existing ocean and fisheries governance have already been reported, highlighting the need for timely mitigation and adaptation responses.**

**The ocean has warmed unabated since 2005, continuing the clear multi-decadal ocean warming trends documented in the IPCC Fifth Assessment Report (AR5).** The warming trend is further confirmed by the improved ocean temperature measurements over the last decade. The 0–700 m and 700–2000 m layers of the ocean have warmed at rates of  $5.31 \pm 0.48$  and  $4.02 \pm 0.97$  ZJ yr<sup>-1</sup> from 2005 to 2017. The long-term trend for 0–700 m and 700–2000 m layers have warmed  $4.35 \pm 0.8$  and  $2.25 \pm 0.64$  ZJ yr<sup>-1</sup> from 1970 to 2017 and is attributed to anthropogenic influences. It is *likely* the ocean warming has continued in the abyssal and deep ocean below 2000m (southern hemisphere and Southern Ocean). {1.8.1, 1.2, 5.2.2}

**It is *likely* that the rate of ocean warming has increased since 1993.** The 0–700 m and 700–2000 m layers of the ocean have warmed by  $3.22 \pm 1.61$  ZJ and  $0.97 \pm 0.64$  ZJ from 1970 to 1993, and  $6.28 \pm 0.48$  ZJ and  $3.86 \pm 2.09$  ZJ from 1993 to 2017. This represents at least a two-fold increase in heat uptake. {Table 5.1, 5.2.2}

**The upper ocean is *very likely* to have been stratifying since 1970.** Observed warming and high latitude freshening are making the surface ocean less dense over time relative to the deeper ocean (*high confidence*) and inhibiting the exchange between surface and deep waters. The upper 200m stratification increase is in the *very likely* range of between 2.18% and 2.42% from 1970 to 2017. {5.2.2}

**Multiple datasets and models show that the rate of ocean uptake of atmospheric CO<sub>2</sub> has continued to strengthen in the recent two decades in response to the increasing concentration of CO<sub>2</sub> in the atmosphere.** The *very likely* range for ocean uptake is between 20-30% of total anthropogenic emissions in the recent two decades. Evidence is growing that the ocean carbon sink is dynamic on decadal timescales, especially in the Southern Ocean, which has affected the total global ocean carbon sink (*medium confidence*). {5.2.2.3}

**The ocean is continuing to acidify in response to ongoing ocean carbon uptake.** The open ocean surface water pH is observed to be declining (*virtually certain*) by a *very likely* range of 0.017 to 0.027 pH units per decade since the late 1980s across individual time-series observations longer than 15 years. The anthropogenic pH signal is *very likely* to have emerged for three-quarters of the near-surface open ocean prior to 1950 and it is *very likely* that over 95 % of the near-surface open ocean has already been affected. These changes in pH have reduced the stability of mineral forms of calcium carbonate due to a lowering of carbonate ion concentrations, most notably in the upwelling and high latitude regions of the ocean. {5.2.2.3, Box 5.1}

**There is a growing consensus that the open ocean is losing oxygen overall with a *very likely* loss of 0.5 to 3.3% between 1970-2010 from the ocean surface to 1000 m (*medium confidence*).** Globally, the oxygen loss due to warming is reinforced by other processes associated with ocean physics and biogeochemistry, which cause the majority of the observed oxygen decline (*high confidence*). The oxygen minimum zones are expanding by a *very likely* range of 3-8%, most notably in the tropical oceans, but there is substantial decadal variability that affects the attribution of the overall oxygen declines to human activity in tropical regions (*high confidence*). {5.2.2.4, Figure TS.5}

**In response to ocean warming and increased stratification, open ocean nutrient cycles are being perturbed and there is *high confidence* that this is having a regionally variable impact on primary producers.** There is currently *low confidence* in appraising past open ocean productivity trends, including those determined by satellites, due to newly identified region-specific drivers of microbial growth and the lack of corroborating *in situ* time series datasets. {5.2.2.5, 5.2.2.6}

**Ocean warming has contributed to observed changes in biogeography of organisms ranging from phytoplankton to marine mammals (*high confidence*), consequently changing community composition (*high confidence*), and in some cases, altering interactions between organisms (*medium confidence*).** Observed rate of range shifts since the 1950s and its *very likely* range are estimated to be 51.5±33.3 km per decade and 29.0±15.5 km per decade for organisms in the epipelagic and seafloor ecosystems, respectively. The direction of the majority of the shifts of epipelagic organisms are consistent with a response to warming (*high confidence*). {5.2.3, 5.3}

**Warming-induced range expansion of tropical species to higher latitudes has led to increased grazing on some coral reefs, rocky reefs, seagrass meadows and epipelagic ecosystems, leading to altered ecosystem structure (*medium confidence*).** Warming, sea level rise, and enhanced loads of nutrients and sediments in deltas have contributed to salinization and deoxygenation in estuaries (*high confidence*), and have caused up-stream redistribution of benthic and pelagic species according to their tolerance limits (*medium confidence*). {5.3.4, 5.3.5, 5.3.6, 5.2.3}

**Fisheries catches and their composition in many regions are already impacted by the effects of warming and changing primary production on growth, reproduction and survival of fish stocks (*high confidence*).** Ocean warming and changes in primary production in the 20<sup>th</sup> century are related to changes in productivity of many fish stocks (*high confidence*), with an average decrease of approximately 3% per decade in population replenishment and 4.1% (*very likely* range of 9.0% decline to 0.3% increase) in maximum catch potential (*robust evidence, low agreement* between fish stocks, *medium confidence*). Species composition of fisheries catches since the 1970s in many shelf seas ecosystems of the world is increasing dominated by warm-water species (*medium confidence*). {5.2.3, 5.4.1}

**Warming-induced changes in spatial distribution and abundance of fish stocks have already challenged the management of some important fisheries and their economic benefits (*high***

**confidence).** For existing international and national ocean and fisheries governance, there are concerns about the reduced effectiveness to achieve mandated ecological, economic, and social objectives because of observed climate impacts on fisheries resources (*high confidence*). {5.4.2, 5.5.2}

**Coastal ecosystems are observed to be under stress from ocean warming and sea level rise that are exacerbated by non-climatic pressures from human activities on ocean and land (*high confidence*).** Global wetland area has declined by nearly 50% relative to pre-industrial level as a result of warming, sea level rise, extreme climate events and other human impacts (*medium confidence*). Warming-related mangrove encroachment into subtropical saltmarshes has been observed in the past 50 years (*high confidence*). Distributions of seagrass meadows and kelp forests are contracting at low-latitudes that is attributable to warming (*high confidence*), and in some areas a loss of 36-43% following heat waves (*medium confidence*). Inundation, coastline erosion and salinization are causing inland shifts in plant species distributions, which has been accelerating in the last decades (*medium confidence*). Warming has increased the frequency of large-scale coral bleaching events, causing worldwide reef degradation since 1997-1998 with cases of shifts to algal-dominated reefs (*high confidence*). Sessile calcified organisms (e.g. barnacles, mussels) in intertidal rocky shores are highly sensitive to extreme temperature events and acidification (*high confidence*), a reduction in their biodiversity and abundance have been observed in naturally-acidified rocky reef ecosystems (*medium confidence*). Increased nutrient and organic matter loads in estuaries since the 1970s have exacerbated the effects of warming on bacterial respiration and eutrophication, leading to expansion of hypoxic areas (*high confidence*). {5.3.1, 5.3.2, 5.3.4, 5.3.6}

**Coastal and near-shore ecosystems including saltmarshes, mangroves, and vegetated dunes in sandy beaches have a varying capacity to build vertically and expand laterally in response to sea-level rise.** These ecosystems provide important services including coastal protection, carbon sequestration and habitat for diverse biota (*high confidence*). The carbon emission associated with the loss of vegetated coastal ecosystems is estimated to be 0.04–1.46 Gt C yr<sup>-1</sup> (*high confidence*). The natural capacity of ecosystems to adapt to climate impacts may be limited by human activities that fragment wetland habitats and restrict landward migration (*high confidence*). {5.3.2, 5.3.3, 5.4.1, 5.5.1}

**Three out of the four major Eastern Boundary Upwelling Ecosystems (EBUS) have shown large-scale wind intensification in the past 60 years (*high confidence*).** However, the interaction of coastal warming and local winds may have affected upwelling strength, with the direction of changes varies between and within EBUS (*low confidence*). Increasing trends in ocean acidification and deoxygenation are observed in the two Pacific (California Current and Humboldt Current) EBUS in the last few decades (*high confidence*), although there is *low confidence* to distinguish anthropogenic forcing from internal climate variability. The expanding California EBUS oxygen minimum zone has altered ecosystem structure and fisheries catches (*medium confidence*). {Box 5.3}

**Since the early 1980s, the occurrence of harmful algal blooms (HABs) and pathogenic organisms (e.g. *Vibrio*) has increased in coastal areas in response to warming, deoxygenation and eutrophication, with negative impacts on food provisioning, tourism, the economy and human health (*high confidence*).** These impacts depend on species-specific responses to the interactive effects of climate change and other human drivers (e.g. pollution). Human communities in poorly monitored areas are among the most vulnerable to these biological hazards (*medium confidence*). {Box 5.4, 5.4.2}

**Many frameworks for climate-resilient coastal adaptation have been developed since AR5, with substantial variations in approach between and within countries, and across development status (*high confidence*).** Few studies have assessed the success of implementing these frameworks due to the time-lag between implementation, monitoring, evaluation and reporting (*medium confidence*). {5.5.2}

## **Projections: scenarios and time horizons**

**Climate models project significant changes in the ocean state over the coming century. Under the high emissions scenario (RCP8.5) the impacts by 2090 are substantially larger and more widespread than for the low emissions scenario (RCP2.6) throughout the surface and deep ocean, including: warming (*virtually certain*); ocean acidification (*virtually certain*); decreased stability of mineral forms of calcite**

**(virtually certain); oxygen loss (very likely); reduced near-surface nutrients (likely as not); decreased net-primary productivity (high confidence); reduced fish production (likely) and loss of key ecosystems services (medium confidence) that are important for human wellbeing and sustainable development. {5.2.2, Box 5.1, 5.2.3, 5.2.4, 5.4}**

**By 2100 the ocean is very likely to warm by 2 to 4 times as much for low emissions (RCP2.6) and 5 to 7 times as much for the high emissions scenario (RCP8.5) compared with the observed changes since 1970.** The 0–2000 m layer of the ocean is projected to warm by a further 2150 ZJ (*very likely* range 1710 to 2790 ZJ) between 2017 and 2100 for the RCP8.5 scenario. The 0–2000 m layer is projected to warm by 900 ZJ (*very likely* range 650 to 1340 ZJ) by 2100 for the RCP2.6 scenario, and the overall warming of the ocean will continue this century even after radiative forcing and mean surface temperatures stabilize (*high confidence*). {5.2.2.2}

**The upper ocean will continue to stratify.** By the end of the century the annual mean stratification of the top 200 m (averaged between 60°S and 60°N relative to the 1986 to 2005 period) is projected to increase in the *very likely* range of 1 to 9% and 12 to 30% for RCP2.6 and RCP8.5 respectively. {5.2.2.2}

**It is very likely that the majority of coastal regions will experience statistically significant changes in tidal amplitudes over the course of the 21st century.** The sign and amplitude of local changes to tides are *very likely* to be impacted by both human coastal adaptation measures and climate drivers. {5.2.2.2.3}

**It is virtually certain that surface ocean pH will decline, by 0.036–0.042 or 0.287–0.29 pH units by 2081–2100, relative to 2006–2015, for the RCP2.6 or RCP8.5 scenarios, respectively.** These pH changes are *very likely* to cause the Arctic and Southern Oceans, as well as the North Pacific and Northwestern Atlantic Oceans to become corrosive for the major mineral forms of calcium carbonate under RCP8.5, but these changes are *virtually certain* to be avoided under the RCP2.6 scenario. There is increasing evidence of an increase in the seasonal exposure to acidified conditions in the future (*high confidence*), with a *very likely* increase in the amplitude of seasonal cycle of hydrogen ion concentrations of 71–90% by 2100, relative to 2000 for the RCP8.5 scenario, especially at high latitudes. {5.2.2.3}

**Oxygen is projected to decline further.** Globally, the oxygen content of the ocean is *very likely* to decline by 3.2–3.7% by 2081–2100, relative to 2006–2015, for the RCP8.5 scenario or by 1.6–2.0% for the RCP2.6 scenario. The volume of the oceans oxygen minimum zones is projected to grow by a *very likely* range of 7.0±5.6% by 2100 during the RCP8.5 scenario, relative to 1850–1900. The climate signal of oxygen loss will *very likely* emerge from the historical climate by 2050 with a *very likely* range of 59–80% of ocean area being affected by 2031–2050 and rising with a *very likely* range of 79–91% by 2081–2100 (RCP8.5 emissions scenario). The emergence of oxygen loss is *very likely* smaller in area for the RCP2.6 scenario in the 21<sup>st</sup> century and by 2090 the emerged area is declining. {5.2.2.4, Box 5.1 Figure 1}

**Overall, nitrate concentrations in the upper 100m are very likely to decline by 9–14 % across CMIP5 models by 2081–2100, relative to 2006–2015, in response to increased stratification for RCP8.5, with medium confidence in these projections due to the limited evidence of past changes that can be robustly understood and reproduced by models.** There is *low confidence* regarding projected increases in surface ocean iron levels due to systemic uncertainties in these models. {5.2.2.5}

**Climate models project that net primary productivity will very likely decline by 4–11% for RCP8.5 by 2081–2100, relative to 2006–2015.** The decline is due to the combined effects of warming, stratification, light, nutrients and predation and will show regional variations between low and high latitudes (*low confidence*). The tropical ocean NPP will *very likely* decline by 7–16% for RCP8.5, with *medium confidence* as there are improved constraints from historical variability in this region. Globally, the sinking flux of organic matter from the upper ocean into the ocean interior is *very likely* to decrease by 9–16% for RCP8.5 in response to increased stratification and reduced nutrient supply, especially in tropical regions (*medium confidence*), which will reduce organic carbon supply to deep sea ecosystems (*high confidence*). The reduction in food supply to the deep sea is projected to lead to a 5–6% reduction in biomass of benthic biota over more than 97% of the abyssal seafloor by 2100. {5.2.2.6, 5.2.4.2, Figure TS.8}



**New ocean states for a broad suite of climate indices will progressively emerge over a substantial fractions of the ocean in the coming century (relative to past internal ocean variability), with ESMs showing an ordered emergence of first pH, followed by SST, interior oxygen, upper ocean nutrient levels and finally NPP.** The anthropogenic pH signal has *very likely* emerged for three quarters of the ocean prior to 1950, with little difference between scenarios. Oxygen changes will *very likely* emerge over 59-80% of the ocean area by 2031-2050 and rises to 79-91% by 2081-2100 (RCP8.5 emissions scenario). The rate and extent of these effects for all variables remain detectable over 30% of the ocean surface in the RCP2.6 scenario, but are much lower than for RCP8.5. {Box 5.1, Box 5.1 Figure 1}

**Simulated ocean warming and changes in net primary production during the 21st century are projected to alter community structure of marine organisms (*high confidence*), reduce global marine animal biomass (*medium confidence*) and the maximum potential catches of fish stocks (*medium confidence*) with regional differences in the direction and magnitude of changes (*high confidence*).** The global biomass of marine animals, including those that contribute to fisheries, is projected to decrease with a *very likely* range under RCP2.6 and RCP8.5 of  $4.3 \pm 2.0\%$  and  $15.0 \pm 5.9\%$ , respectively, by 2080–2099 relative to 1986–2005. The maximum catch potential is projected to decrease by 2.8% to 9.1% (RCP2.6) and 16.2% to 25.5% (RCP8.5) in the 21st century. {5.4.1}

**Projected decreases in global marine animal biomass and fish catch potential could elevate the risk of impacts on income, livelihood and food security of the dependent human communities (*medium confidence*).** Projected climate change impacts on fisheries also increase the risk of potential conflicts among fishery area users and authorities or between two different communities within the same country (*medium confidence*), exacerbated through competing resource exploitation from international actors and mal-adapted policies (*low confidence*). {5.2.3, 5.4, 5.5.3}

**Projected decrease in upper ocean export of organic carbon to the deep seafloor is expected to result in a loss of animal biomass on the deep seafloor by 5.2% to 17.6% by 2090-2100 compared to the present (2006-2015) under RCP8.5 with regional variations (*medium confidence*).** Some increases are projected in the polar regions, due to enhanced stratification in the surface ocean, reduced primary production and shifts towards small phytoplankton (*medium confidence*). The projected impacts on biomass in the abyssal seafloor are larger under RCP8.5 than RCP4.5 (*very likely*). The increase in climatic hazards beyond thresholds of tolerance of deep-sea organisms will increase the risk of loss of biodiversity and impacts on functioning of deep water column and seafloor that is important to support ecosystem services, such as carbon sequestration (*medium confidence*). {5.2.4}

**Structure and functions of all types of coastal ecosystems will continue to be at moderate to high risk under the RCP2.6 scenario (*medium confidence*) and will face high to very high risk under the RCP8.5 scenario (*high confidence*) by 2100.** Seagrass meadows (*high confidence*), kelp forests (*high confidence*) and coral reefs (*very high confidence*) will face high to very high risk already at temperatures  $1.5^\circ\text{C}$  of global warming (*high confidence*). Intertidal rocky shores are also expected to be at very high risk (transition above  $3^\circ\text{C}$ ) under the RCP8.5 scenario (*medium confidence*). These ecosystems have low to moderate adaptive capacity, as they are highly sensitive to ocean temperatures and acidification. The ecosystems with moderate to high risk (transition above  $1.8^\circ\text{C}$ ) under future emissions scenarios are mangrove forests, sandy beaches, estuaries and saltmarshes (*medium confidence*). Estuaries and sandy beaches are subject to highly dynamic hydrological and geomorphological processes, giving them more natural adaptive capacity to climate hazards. In these systems, sediment relocation, soil accretion and landward expansion of vegetation may initially mitigate against flooding and habitat loss, but saltmarshes, in particular, will be at very high risk in the context of sea level rise and extreme climate-driven erosion under RCP8.5. {5.3, Figure 5.16}

**Expected coastal ecosystem responses over the 21st century are habitat contraction, migration and loss of biodiversity and functionality.** Pervasive human coastal disturbances will limit natural ecosystem adaptation to climate hazards (*high confidence*). Global coastal wetlands will lose between 20-90% of their area depending on emissions scenario with impacts on their contributions to carbon sequestration and coastal protection (*high confidence*). Kelp forests at low-latitudes and temperate seagrass meadows will continue to retreat as a result of intensified extreme temperatures, and their low dispersal ability will elevate the risk of local extinction under RCP8.5 (*high confidence*). Intertidal rocky shores will continue to be affected by ocean acidification, warming, and extreme heat exposure during low tide emersion, causing reduction of

calcareous species and loss of ecosystem biodiversity and complexity shifting towards algae dominated habitats (*high confidence*). Salinization and expansion of hypoxic conditions will intensify in eutrophic estuaries, especially in mid and high latitudes with microtidal regimes (*high confidence*). Sandy beach ecosystems will increasingly be at risk of eroding, reducing the habitable area for dependent organisms (*high confidence*). {5.3, 5.4.1}

**Almost all coral reefs will degrade from their current state, even if global warming remains below 2°C (very high confidence), and the remaining shallow coral reef communities will differ in species composition and diversity from present reefs (very high confidence).** These declines in coral reef health will greatly diminish the services they provide to society, such as food provision (*high confidence*), coastal protection (*high confidence*) and tourism (*medium confidence*). {5.3.4, 5.4.1}

**Multiple hazards of warming, deoxygenation, aragonite under-saturation and decrease in flux of organic carbon from the surface ocean will decrease calcification and exacerbate the bioerosion and dissolution of the non-living component of cold-water coral.** Habitat-forming, cold-water corals will be vulnerable where temperature and oxygen exceed the species' thresholds (*medium confidence*). Reduced particulate food supply is projected to be experienced by 95% of cold-water coral ecosystems by 2100 under RCP8.5 relative to the present, leading to a *very likely* range of 8.6±2% biomass loss (*medium confidence*). {5.2.4, Box 5.2}

**Anthropogenic changes in Eastern Boundary Upwelling Ecosystems (EBUS) will emerge primarily in the second half of the 21st century (medium confidence).** EBUS will be impacted by climate change in different ways, with strong regional variability with consequences for fisheries, recreation and climate regulation (*medium confidence*). The Pacific EBUS are projected to have calcium carbonate undersaturation in surface waters within a few decades under RCP8.5 (*high confidence*); combined with warming and decreasing oxygen levels, this will increase the impacts on shellfish larvae, benthic invertebrates and demersal fishes (*high confidence*) and related fisheries and aquaculture (*medium confidence*). The inherent natural variability of EBUS, together with uncertainties in present and future trends in the intensity and seasonality of upwelling, coastal warming and stratification, primary production and biogeochemistry of source waters, poses large challenges in projecting the response of EBUS to climate change and to the adaptation of governance of biodiversity conservation and living marine resources in EBUS (*high confidence*). {Box 5.3}

**Climate change impacts on ecosystems and their goods and services threatens key cultural dimensions of lives and livelihoods.** These threats include erosion of Indigenous and non-indigenous culture, their knowledge about the ocean and knowledge transmission, reduced access to traditional food, loss of opportunities for aesthetic and spiritual appreciation of the ecosystems, and marine recreational activities (*medium confidence*). Ultimately, these can lead to the loss of part of people's cultural identity and values beyond the rate at which identity and values can be adjusted or substituted (*medium confidence*). {5.4.2}

**Climate change increases the exposure and bioaccumulation of contaminants such as persistent organic pollutants and mercury (medium confidence), and their risk of impacts on marine ecosystems and seafood safety (high agreement, medium evidence, medium confidence).** Such risks are particularly large for top predators and for human communities that have high consumption on these organisms, including coastal Indigenous communities (*medium confidence*). {5.4.2}

**B1.18 Shifting distributions of fish stocks between governance jurisdictions will increase the risk of potential conflicts among fishery area users and authorities or between two different communities within the same country (medium confidence).** These fishery governance related risks are widespread under high emissions scenarios with regional hotspots (*medium confidence*), and highlight the limits of existing natural resource management frameworks for addressing ecosystem change (*high confidence*). {5.2.5, 5.4.2.1.3, 5.5, 5.5.2}

**Response options to enhance resilience**

**There is clear evidence for observed climate change impacts throughout the ocean with consequences for human communities and require options to reduce risks and impacts. Coastal blue carbon can contribute to mitigation for many nations but its global scope is modest (offset of < 2% of current emissions) (*likely*). Some ocean indices are expected to emerge earlier than others (e.g., warming, acidification and effects on fish stocks) and could therefore be used to prioritise planning and building resilience. The survival of some keystone ecosystems (e.g., coral reefs) are at risk, while governance structures are not well-matched to the spatial and temporal scale of climate change impacts on ocean systems. Ecosystem restoration may be able to locally reduce climate risks (*medium confidence*) but at relatively high cost and effectiveness limited to low emissions scenarios and to less sensitive systems (*high confidence*). {5.2, 5.3, 5.4, 5.5}**

**Coastal blue carbon ecosystems, such as mangroves, salt marshes and seagrasses, can help reduce the risks and impacts of climate change, with multiple co-benefits.** Some 151 countries around the world contain at least one of these coastal blue carbon ecosystems and 71 countries contain all three. Below-ground carbon storage in vegetated marine habitats can be up to 1000 tC ha<sup>-1</sup>, much higher than most terrestrial ecosystems (*high confidence*). Successful implementation of measures to maintain and promote carbon storage in such coastal ecosystems could assist several countries in achieving a balance between emissions and removals of greenhouse gases (*medium confidence*). Conservation of these habitats would also sustain the wide range of ecosystem services they provide and assist with climate adaptation through improving critical habitats for biodiversity, enhancing local fisheries production, and protecting coastal communities from sea level rise and storm events (*high confidence*). The climate mitigation effectiveness of other natural carbon removal processes in coastal waters, such as seaweed ecosystems and proposed non-biological marine CO<sub>2</sub> removal methods, are smaller or currently have higher associated uncertainties. Seaweed aquaculture warrants further research attention. {5.5.1.1, 5.5.1.1, 5.5.1, 5.5.2, 5.5.1.1.3, 5.5.1.1.4}

**The potential climatic benefits of blue carbon ecosystems can only be a very modest addition to, and not a replacement for, the very rapid reduction of greenhouse gas emissions.** The maximum global mitigation benefits of cost-effective coastal wetland restoration is *unlikely* to be more than 2% of current total emissions from all sources. Nevertheless, the protection and enhancement of coastal blue carbon can be an important contribution to both mitigation and adaptation at the national scale. The feasibility of climate mitigation by open ocean fertilization of productivity is limited to negligible, due to the likely decadal-scale return to the atmosphere of nearly all the extra carbon removed, associated difficulties in carbon accounting, risks of unintended side effects and low acceptability. Other human interventions to enhance marine carbon uptake, e.g., ocean alkalisation (enhanced weathering), would also have governance challenges, with the increased risk of undesirable ecological consequences (*high confidence*). {5.5.1.2}

**Socio-institutional adaptation responses are more frequently reported in the literature than ecosystem-based and built-infrastructure approaches.** Hard engineering responses are more effective when supported by ecosystem-based adaptation approaches (*high agreement*), and both approaches are enhanced by combining with socio-institutional approaches for adaptation (*high confidence*). Stakeholder engagement is necessary (*robust evidence, high agreement*). {5.5.2}

**Ecosystem Based Adaptation is a cost-effective coastal protection tool that can have many co-benefits, including supporting livelihoods, contributing to carbon sequestration and the provision of a range of other valuable ecosystem services (*high confidence*).** Such adaptation does, however, assume that the climate can be stabilised. Under changing climatic conditions there are limits to the effectiveness of ecosystem based adaptation, and these limits are currently difficult to determine. {5.5.2.1}

**Socio-institutional adaptation responses, including community-based adaptation, capacity-building, participatory processes, institutional support for adaptation planning and support mechanisms for communities are important tools to address climate change impacts (*high confidence*).** For fisheries management, improving coordination of integrated coastal management and marine protected areas have emerged in the literature as important adaptation governance responses (*robust evidence, medium agreement*). {5.5.2.2, 5.5.2.6}

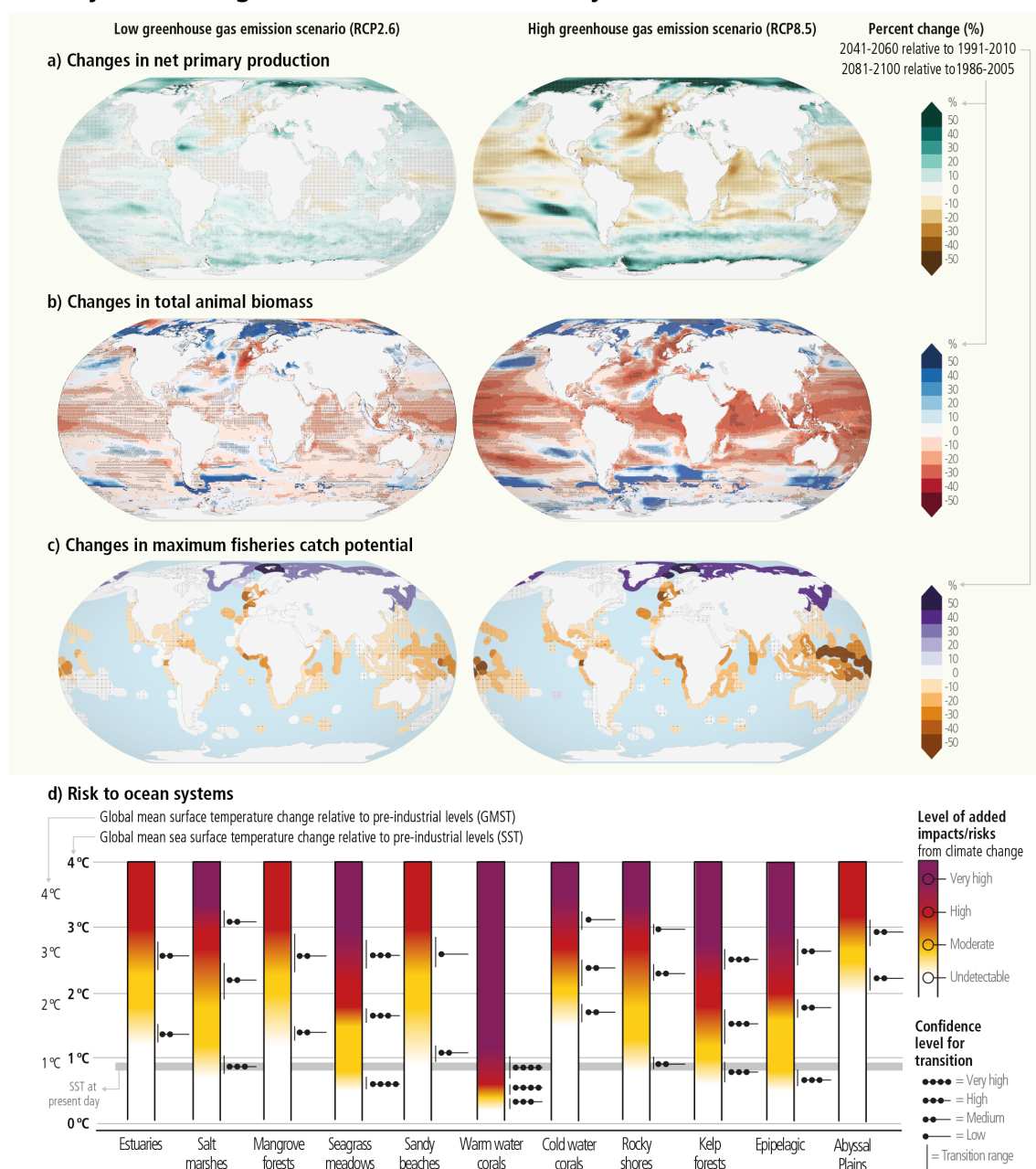
**Observed widespread decline in warm water corals has led to the consideration of alternative restoration approaches to enhance climate-resilience.** Approaches, such as 'coral reef gardening' have

been tested, and ecological engineering and other approaches such as assisted evolution, colonization and chimerism are being researched for reef restoration. However, the effectiveness of these approaches to increase resilience to climate stressors and their large-scale implementation for reef restoration will be limited unless warming and ocean acidification are rapidly controlled (*high confidence*). {Box 5.5, 5.5.2}

**Existing ocean governance structures are already facing multi-dimensional, scale-related challenges because of climate change. This trend of increasing complexity will continue (*high confidence*).** The mechanisms for the governance of marine Areas Beyond National Jurisdiction, such as ocean acidification, would benefit from further development (*high confidence*). There is also scope to increase the overall effectiveness of international and national ocean governance regimes by increasing cooperation, integration and widening participation (*medium confidence*). Diverse adaptations of ocean-related governance are being tried, and some are producing promising results. However, rigorous evaluation is needed of the effectiveness of these adaptations in achieving their goals. {5.5.3}

**There are a broad range of identified barriers and limits for adaptation to climate change in ecosystems and human systems (*high confidence*).** Limitations include the space that ecosystems require, non-climatic drivers and human impacts that need to be addressed as part of the adaptation response, the lowering of adaptive capacity of ecosystems because of climate change, and the slower ecosystem recovery rates relative to the recurrence of climate impacts, availability of technology, knowledge and financial support, and existing governance structures (*medium confidence*). {5.5.2}

## Projected changes and risks for ocean ecosystems



**Figure TS.8:** Projected changes and risks for selected ocean regions under low (left, Representative Concentration Pathway RCP2.6) and high (right, RCP8.5) greenhouse gas emission scenarios. Projected average changes (%) in a) depth integrated net primary production based on outputs from the Coupled Model Intercomparison Project 5 (CMIP 5) by 2081-2100, relative to 1986-2005. b) total animal biomass (including fishes and invertebrates) based on the average outputs from 10 sets of projections from the Fisheries and Marine Ecosystems Impact Model Intercomparison Project by 2081-2100, relative to 1986-2005. c) maximum fisheries catch potential in shelf seas based on the average outputs from two fisheries and marine ecosystem models by 2041-2060 relative to 1991-2010. Shaded areas indicate regions where models agree in the direction of change for: a) and b) at least three quarters of model projections, c) the two models. d) Risk assessments for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. ‘Present day’ is 2006-2015. Impacts and risks are shown in relation to changes in global mean surface temperature (left vertical axis) and global mean sea surface temperature (right axis) relative to pre-industrial levels. The relationship between global mean surface and sea surface temperature used here is based on RCP8.5 simulations {Figure SPM.1}. Impact and risk levels do not consider risk reduction strategies such as societal adaptation, or future changes in non-climatic hazards. In the polar regions, the projected change in (b) total animal biomass and (c) fisheries catch potential have *low confidence* due to uncertainties associated with multiple interacting drivers and ecosystem responses in the Arctic and Antarctic regions that are not fully-resolved in the global-scale models. {5.2, 5.3, 5.2.5, 5.3.7, SM5.5, SM5.7, Figure 5.16, Cross Chapter Box 1 in Chapter 1 Table CCB1}.

## TS.6 Extremes, Abrupt Changes and Managing Risks

This chapter assesses extremes and abrupt or irreversible changes in the ocean and cryosphere in a changing climate, to identify regional hot spots, cascading effects, their impacts on human and natural systems, and sustainable and resilient risk management strategies. It is not comprehensive in terms of the systems assessed and some information on extremes, abrupt and irreversible changes, in particular for the cryosphere, may be found in other chapters

### Ongoing and Emerging Changes in the Ocean and Cryosphere, and their Impacts on Ecosystems and Human Societies

**Anthropogenic climate change has increased precipitation, winds and extreme sea level events associated with a number of observed tropical- and extra-tropical cyclones (*high confidence*).** For example, studies have shown that the rainfall intensity of tropical cyclone Harvey increased by at least 8% due to climate change. {6.3, Table 6.2, Figure 6.2, Box 6.1}. In the Northern Hemisphere mid-latitudes, there is *low confidence* in links between Arctic amplification, blocking events and various types of weather extremes in recent decades. {6.3}

**Anthropogenic climate change may have contributed to a poleward migration of maximum tropical cyclone intensity in the western North Pacific in recent decades related to anthropogenically-forced tropical expansion (*low confidence*)** There is emerging evidence for a number of regional changes in tropical cyclone behaviour such as an increase in annual global proportion of Category 4 or 5 tropical cyclones in recent decades, severe tropical cyclones occurring in the Arabian Sea and making landfall in East and Southeast Asia, increasing in frequency of moderately large US storm surge events since 1923 and the decreasing frequency of severe TCs making landfall in eastern Australia since the late 1800s, but *low confidence* that these represent detectable anthropogenic signals. {6.3}

**Extreme wave heights across the globe have increased by around 5% over the past three decades (*medium confidence*).** {6.3}

**Marine heatwaves, periods of extremely high ocean temperatures, have negatively impacted marine organisms and ecosystems in all ocean basins over the last two decades, including critical foundation species such as corals, seagrasses and kelps (*very high confidence*).** Satellite observations reveal that marine heatwaves have *very likely* doubled in frequency between 1982 and 2016, and that they have also become longer-lasting, more intense and extensive. Between 2006 and 2015, 84% to 90% (*very likely range*) of all globally occurring marine heatwaves are attributable to the temperature increase since 1850-1900. {6.4, Figures 6.3-6.4}

**Both paleoclimate and modern observations suggest that the strongest El Niño and La Niña events since the pre-industrial have occurred during the last fifty years (*medium confidence*).** There have been three occurrences of extreme El Niño events during the modern observational period (1982–83, 1997–98, 2015–16), all characterised by pronounced rainfall in the normally dry equatorial east Pacific. There have been two occurrences of extreme La Niña (1988–89, 1998–99). El Niño and La Niña variability during the last 50 years is unusually high compared with average variability during the last millennium. {6.5, Figure 6.5}

**The equatorial Pacific trade wind system experienced an unprecedented intensification during 2001–2014, resulting in enhanced ocean heat transport from the Pacific to the Indian Ocean, influencing the rate of global temperature change (*medium confidence*).** In the last two-decades, total water transport from the Pacific to the Indian Ocean by the Indonesian Throughflow, and the Indian Ocean to Atlantic Ocean has increased (*high confidence*). Increased Indonesian Throughflow has been linked to Pacific cooling trends and basin-wide warming trends in the Indian Ocean. Pacific sea surface temperature cooling trends and strengthened trade winds have been linked to an anomalously warm tropical Atlantic. {6.6, Figure 6.7}

**Modern observations, climate simulations and paleoclimate reconstructions suggest that the Atlantic Meridional Overturning Circulation (AMOC) has weakened since the preindustrial (*medium confidence*). Nevertheless, there is insufficient evidence yet to quantify a *likely* range of the magnitude of the change {6.7, Figure 6.8}.**

**Climate change is modifying multiple types of climate-related events or hazards in terms of occurrence, intensity and periodicity. It increases the likelihood of compound hazards that comprise simultaneously or sequentially occurring events to cause extreme impacts in natural and human systems. Compound events in turn trigger cascading impacts (*high confidence*). Three case studies are presented in the chapter, (i) Tasmania's Summer of 2015/16, (ii) The Coral Triangle and (ii) Hurricanes of 2017. {6.8, Box 6.1}**

### **Projections of Ocean and Cryosphere Change and Hazards to Ecosystems and Human Society Under Low and High Emission Futures**

**An increase in the average intensity of tropical cyclones, and the associated average precipitation rates is projected for a 2°C global temperature rise (*medium confidence*), although there is *low confidence* in future frequency changes at the global scale. Rising sea levels will contribute to higher extreme sea levels associated with tropical cyclones in the future (*very high confidence*). Projections show that the proportion of Category 4 and 5 TCs will increase (*medium confidence*). Such changes will affect storm surge frequency and intensity, and impact coastal infrastructure and mortality. {6.3}**

**Wave heights are projected to increase across the Southern Ocean, tropical eastern Pacific and Baltic Sea and decrease over the North Atlantic and Mediterranean Sea under RCP 4.5 and RCP 8.5 (*high confidence*). There is still limited knowledge on projected wave period and direction. Accounting for the multiple contributions of waves, tides, storm surges and sea level rise, probabilistic projections of extreme sea levels predict the global average 100-year extreme sea level to *very likely* increase by 34–76 cm and 58–172 cm, under RCP4.5 and RCP8.5, respectively between 2000 and 2100. {6.3}**

**Marine heatwaves will further increase in frequency, duration, spatial extent and intensity under future global warming (*very high confidence*) pushing some marine organisms, fisheries and ecosystems beyond the limits of their resilience, with cascading impacts on economies and societies (*high confidence*). Globally, the frequency of marine heatwaves is *very likely* to increase by a factor of 46–55 by 2081–2100 under the RCP8.5 scenario and by a factor of 16–24 under the RCP2.6 scenario, relative to the 1850–1900 reference period. These future trends in MHW frequency can largely be explained by increases in mean ocean temperature. The largest changes in the frequency of marine heatwaves are projected for the Arctic Ocean and the tropical ocean (*medium confidence*). {6.4}**

**Extreme El Niño and La Niña events are *likely* to occur more frequently with global warming and are *likely* to intensify existing impacts, with drier or wetter responses in several regions across the globe, even at relatively low levels of future global warming (*medium confidence*). {6.5, Figure 6.5}**

**Lack of long-term sustained Indian and Pacific ocean observations, and inadequacies in the ability of climate models to simulate the magnitude of trade wind decadal variability and the inter-ocean link, mean there is *low confidence* in future projections of the trade wind system. {6.6, Figure 6.7}**

**The AMOC will *very likely* weaken over the 21st century (*high confidence*), although a collapse is *very unlikely* (*medium confidence*). Nevertheless, a substantial weakening of the AMOC remains a *physically plausible scenario*. Such a weakening would strongly impact natural and human systems, leading to a decrease in marine productivity in the North Atlantic, more winter storms in Europe, a reduction in Sahelian and South Asian summer rainfall, a decrease in the number of tropical cyclones in the Atlantic, and an increase in regional sea-level around the Atlantic especially along the northeast coast of North America (*medium confidence*). Such impacts would be superimposed on the global warming signal. {6.7, Figure 6.8}**



**Impacts from further changes in tropical and extra-tropical cyclones, marine heatwaves, extreme El Niño and La Niña events and other extremes will exceed the limits of resilience and adaptation of ecosystems and people, leading to unavoidable loss and damage (*medium confidence*). {6.9.2}**

### **Strengthening the Global Responses in the Context of Sustainable Development Goals and Charting Climate Resilient Development Pathways for Oceans and Cryosphere**

There is *medium confidence* that including extremes and abrupt changes, such as AMOC weakening, ice-sheet collapse (WAIS and GIS), leads to a several-fold increase in the cost of carbon emissions (*medium confidence*). If carbon emissions decline, the risk of extremes and abrupt changes are reduced, creating co-benefits. {6.8.5}

For tropical and extratropical cyclones, investment in disaster risk reduction, flood management (ecosystem and engineered) and early warning systems decreases economic loss (*medium confidence*), but such investments may be hindered by limited local capacities, such as increased losses and mortality from extreme winds and storm surges in less-developed countries despite adaptation efforts. There is emerging evidence of increasing risks for locations impacted by unprecedented storm trajectories (*low confidence*). Managing the risk from such changing storm trajectories and intensity proves challenging because of the difficulties of early warning and its receptivity by the affected population (*high confidence*). {6.3, 6.9}

Limiting global warming would reduce the risk of impacts of marine heatwaves, but critical thresholds for some ecosystems (e.g. kelp forests, coral reefs) will be reached at relatively low levels of future global warming (*high confidence*). Early warning systems, producing skillful forecasts of marine heatwaves, can further help to reduce the vulnerability in the areas of fisheries, tourism and conservation, but are yet unproven at large scale (*medium confidence*). {6.4}

Sustained long-term monitoring and improved forecasts can be used in managing the risks of extreme El Niño and La Niña events associated with human health, agriculture, fisheries, coral reefs, aquaculture, wildfire, drought and flood management (*high confidence*). {6.5}

Extreme change in the trade wind system and its impacts on global variability, biogeochemistry, ecosystems as well as society have not been adequately understood and represent significant knowledge gaps. {6.6}

By 2300, an AMOC collapse is *as likely as not* for high emission pathway and *very unlikely* for lower ones, highlighting that an AMOC collapse can be avoided in the long term by CO<sub>2</sub> mitigation (*medium confidence*). Nevertheless, the human impact of these physical changes have not been sufficiently quantified and there are considerable knowledge gaps in adaptation responses to a substantial AMOC weakening. {6.7}

The ratio between risk reduction investment and reduction of damages of extreme events varies. Investing in preparation and prevention against the impacts from extreme events is *very likely* less than the cost of impacts and recovery (*medium confidence*). Coupling insurance mechanisms with risk reduction measures can enhance the cost-effectiveness of adapting to climate change (*medium confidence*). {6.9}

Climate change adaptation and disaster risk reduction require capacity building and an integrated approach to ensure trade-offs between short- and long-term gains in dealing with the uncertainty of increasing extreme events, abrupt changes, and cascading impacts at different geographic scales (*high confidence*). {6.9}

Limiting the risk from the impact of extreme events and abrupt changes leads to successful adaptation to climate change with the presence of well-coordinated climate-affected sectors and disaster management relevant agencies (*high confidence*). Transformative governance inclusive of successful integration of disaster risk management and climate change adaptation, empowerment of vulnerable

**groups, and accountability of governmental decisions promotes climate-resilient development pathways (*high confidence*). {6.9}**

### **TS.7 Low Lying Islands and Coasts (Integrative Cross-Chapter Box)**

Ocean and cryosphere changes already impact Low-Lying Islands and Coasts (LLIC), including Small Island Developing States, with cascading and compounding risks. Disproportionately higher risks are expected in the course of the 21st century. Reinforcing the findings of the IPCC Special Report on Global Warming of 1.5°C, vulnerable human communities, especially those in coral reef environments and polar regions, may exceed adaptation limits well before the end of this century and even in a low greenhouse gas emission pathway (*high confidence*). Depending on the effectiveness of 21st century mitigation and adaptation pathways under all emission scenarios, most of the low-lying regions around the world may face adaptation limits beyond 2100, due to the long-term commitment of sea level rise (*medium confidence*). LLIC host around 11% of the global population, generate about 14% of the global Gross Domestic Product and comprise many world cultural heritage sites. LLIC already experience climate-related ocean and cryosphere changes (*high confidence*), and they share both commonalities in their exposure and vulnerability to climate change (e.g., low elevation, human disturbances to terrestrial and marine ecosystems), and context-specificities (e.g., variable ecosystem climate sensitivities and risk perceptions by populations). Options to adapt to rising seas, e.g., range from hard engineering to ecosystem-based measures, and from securing current settings to relocating people, built assets and activities. Effective combinations of measures vary across geographies (cities and megacities, small islands, deltas, Arctic coasts), and reflect the scale of observed and projected impacts, ecosystems' and societies' adaptive capacity, and the existence of transformational governance (*high confidence*) {Sections 3.5.3, 4.4.2 to 4.4.5, 5.5.2, 6.8, 6.9, Cross-Chapter Box 2 in Chapter 1}.