Chapter 6: Extremes, Abrupt Changes and Managing Risks

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Executive Summary

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.

Event attribution methods have shown how elevated sea surface temperatures and sea level due to anthropogenic climate change have impacted a number of observed tropical and extratropical cyclones (TCs and ETCs) and contributed to increased precipitation, winds and extreme sea level events including storm surges (*high confidence*[1]). In the future, tropical cyclones will *likely*[2] be of slightly higher intensity globally and have higher rainfall rates *(medium confidence).* While some resilience plans exist to prepare for these storms, more effort is required to further develop and implement such plans. Projections show that the proportion of Category 4&5 TCs will increase (*medium confidence*) although there is *low confidence* in future frequency changes for all TCs at the global scale. Rising sea levels will contribute to higher storm surges associated with TCs in the future (*high confidence*). The uncertainty surrounding the future characteristics of TCs in terms of track (e.g., poleward shift), intensity, or frequency create difficulties for implementing early warning and evacuation procedures. Coordination problems among disaster response organizations also persist. Reductions in vulnerability to storm surges have been documented, and can continue to mitigate some future impacts. {6.3, Table 6.2, Figure 6.2}

Marine heatwaves (MHWs) have *very likely* doubled in frequency since the early 1980s (*high confidence*) with one quarter of the worlds' oceans experiencing either the longest or most intense events on record in 2015 and 2016. Today, about 90% of the observed MHWs have an anthropogenic component and some recent MHWs are unprecedented with respect to preindustrial conditions (*medium confidence*). MHWs will *very likely* increase in frequency (*high confidence*), duration, spatial extent and intensity under future global warming, pushing marine organisms, fisheries and ecosystems beyond the limits of their resilience (*medium confidence*), especially those with reduced mobility such as coral reefs (*high confidence*). MHWs have occurred in all ocean basins over the last few decades with detrimental impacts on coral reefs and other marine ecosystems, and cascading impacts on economies and societies. A one-in-hundred-day event at preindustrial levels is projected to become a one-in-six-day event at 1.5°C global warming and a one-in-three-day event at 3.5°C global warming (*medium confidence*). The largest changes in the frequency of MHWs are projected for the Arctic Ocean and the western tropical Pacific (*medium confidence*). Skilful forecasts of MHWs can help in reducing vulnerability in the areas of fishery management, conservation and tourism. {6.4, Figures 6.3 and 6.4}

Extreme El Niño and La Niña events are *likely* to occur more frequently in the future, even at relatively low levels of future global warming (*medium confidence*). Warning systems exist and can be adapted and improved to manage the risks associated with extreme El Niño and La Niña events. 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 (the definition of an extreme El Niño event). There have been two occurrences of extreme La Niña (1988–89, 1998–99). It is currently unknown if there has been an anthropogenic influence on observed El Niño Southern Oscillation (ENSO) events and impacts. Little is known about the combined impacts of modes of climate variability and mean climate change in future projections. {6.5, Figures 6.5 and 6.6}

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[1] FOOTNOTE: 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 1.9.3 and Figure 1.4 for more details).

[2] FOOTNOTE: 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%, 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 1.9.3 and Figure 1.4 for more details).

The equatorial Pacific trade wind system has experienced extreme variability in the last two decades, influencing global-scale climate and contributing to the 'global warming hiatus' (*medium confidence*). In the last two-decades, total water transport from the Pacific to the Indian Ocean (Indonesian Throughflow), and the Indian Ocean to Atlantic Ocean has increased *(high confidence*). Increased Indonesian Throughflow (ITF) has been attributed to Pacific cooling and basin-wide warming in the Indian Ocean. Pacific sea surface temperature cooling trends and strengthened trade winds have been linked to an anomalously warm tropical Atlantic. Climate models fail to simulate the magnitude of trade wind decadal variability and the Atlantic-Pacific link. It has not been possible to attribute the extreme Pacific trade wind variations to either natural or anthropogenic factors. {6.6, Figure 6.7}

The Atlantic Meridional Overturning Circulation (AMOC) will *very likely* weaken over the 21st century under all Representative Concentration Pathways (RCP) scenarios. An abrupt transition or collapse of the AMOC during the 21st century is *very unlikely* but remains a physically plausible high-impact scenario. A substantial weakening of the AMOC would lead to wide spread impacts on surface climate, in turn affecting natural and human systems. Expected impacts include more winter storms in Europe; a reduction in Sahelian rainfall and associated millet and sorghum production; a decrease in the Asian summer monsoon; 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. Observations show a slight weakening AMOC trend over the years 2004–2017, but this is not distinguishable from natural variability. Some AMOC reconstructions based on sea surface temperature fingerprints and proxies suggest a more substantial weakening over the entire historical era (*low confidence*). There are more models available since the AR5 assessment that simulate an abrupt weakening under future RCP scenarios, although this does not change the AR5 assessment that abrupt AMOC change in the 21st century is *very unlikely*. Literature on adaptation responses to an AMOC rapid weakening or collapse is scarce. The human and economic impacts of these physical changes have not been sufficiently quantified. {6.7, Figures 6.8–6.10}

A new tipping element, the Subpolar Gyre System (SPG) in the North Atlantic, has been identified in some climate models (*medium confidence*). It involves an abrupt cooling of the North Atlantic SPG on a shorter, decadal time scale than the AMOC decline, but with smaller potential climate impacts. These mainly oppose the general warming trend in the North Atlantic bordering region at the decadal time scale, but could also increase the frequency of extreme summer heatwaves in Europe (*low confidence*). {6.7}

Climate change is increasingly exacerbating extreme events and causing multiple hazards that often comprise compound or sequential characteristics. In turn, these elements are interacting with community vulnerability and exposure to trigger compound risk and cascading impacts *(high confidence).* Three examples of recent compound events and cascading risks include: (i) Tasmania's summer of 2015/16; (ii) combined threats on the 'Coral Triangle' biodiversity and their ecological and societal influences; and (iii) the 2017 Atlantic Hurricane season. These indicate how extreme climate events are being influenced by anthropogenic climate change and are contributing to compound risk and cascading impacts *(high confidence)* {6.8.5}. 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 v*ery likely* less than the cost of impacts and recovery (*medium confidence).* {6.8}

Transformative governance and sustainable resilient pathways require alternative political/legal/institutional frameworks and participatory stakeholder integration that addresses combined climate change adaptation and disaster risk reduction (*medium confidence*). Integrating climate change adaptation and disaster risk management faces problems relating to: a lack of coordination among different government agencies; trade-offs between short- and long-term gains; varying local goals; and lack of training. Specific and integrated management measures such as large-scale early warning systems, or global monitoring and forecasting systems, can help to address the uncertainty of increasing extreme events and abrupt changes at different geographic scales. Place-based local risk management measures influenced by hazard experience, institutional structures, and cultural values are constrained by available resources and social vulnerabilities. The evidence-base for the locations and size of economic and social impacts from extreme and abrupt changes is sparse, which hinders decision-makers from adequately assessing risks and developing adaptation options. Improvements in credibility, trust, and reliability in institutions and scientific information on unexpected extremes and abrupt changes are crucial for countries to prepare for such uncertainties and enhance resilience (*medium confidence*). {6.9}

6.1 Introduction

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. While not comprehensive in terms of discussing all such phenomena, it addresses a number of issues that are prominent in both the policy area and in the scientific literature.

Building on the SREX (IPCC, 2012) and AR5 (IPCC, 2013; IPCC, 2014) assessments, for each of the topics addressed, we provide an assessment of:

- Key processes and feedbacks, observations, detection and attribution, projections;
- Impacts on human and natural systems, including confounding factors;
- Monitoring and early warning systems;
- Risk management and adaptation, sustainable and resilient pathways.

The chapter is organised in terms of the space- and time-scales of different phenomena. We move from small-scale tropical cyclones, which last for days-weeks, to the global-scale Atlantic Meridional Overturning Circulation (AMOC), which has time scales of decades to centuries. A common risk framework is adopted, based on that used in AR5 and introduced in Chapter 1 (Figure 6.1).

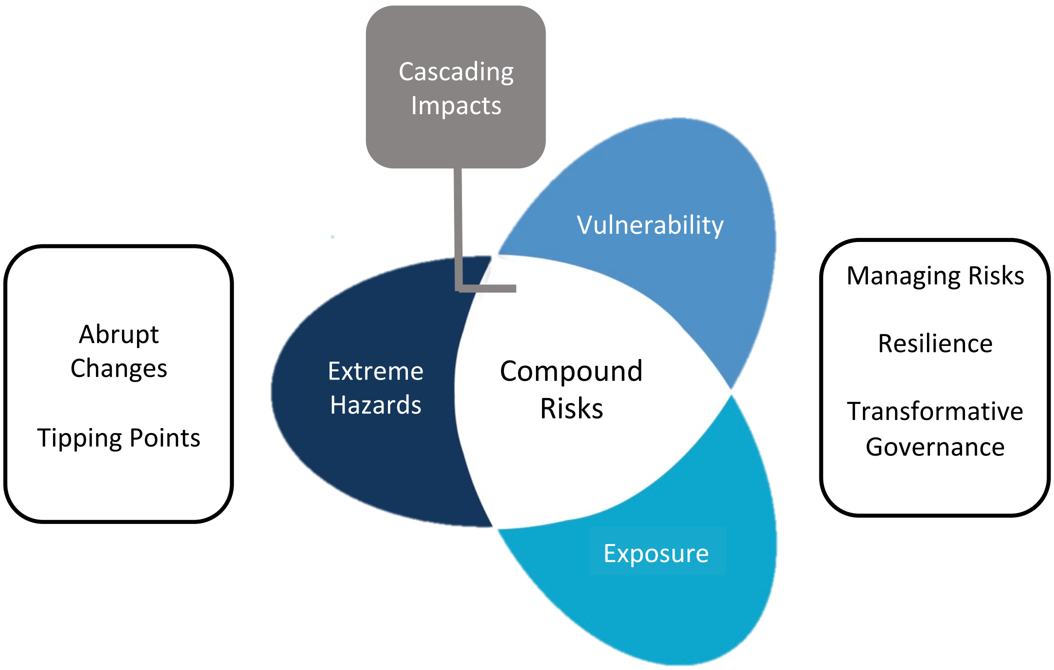


Figure 6.1: Framework used in this chapter (see discussion in Chapter 1). Extremes discussed are; tropical and extratropical cyclones (Section 6.3); marine heatwaves (Section 6.4), extreme El Niño and La Niña events (Section 6.5); and extreme oceanic decadal variability (Section 6.6). Examples of abrupt events, irreversibility and tipping points discussed are the Atlantic Meridional Overturning Circulation and Sub-polar Gyre system (Section 6.7). Section 6.2 also collects examples of such events from the rest of the SROCC. Cascading risks are discussed in section 6.8 and three examples of compound events are given in Box 6.1. Section 6.9 discusses options for managing risks including enhancing resilience, disaster risk reduction and the transformative governance required.

While much of what is discussed within the chapter concerns the ocean, we also summarise extreme and abrupt events in the cryosphere in section 6.2, drawing information from the previous five chapters where the main assessment of those phenomena may be found. The context of the assessment provided here and equivalent assessment provided in the SR15 report is discussed in Chapter 1.

6.1.1 Definitions of Principal Terms

In discussing concepts such as abrupt changes, irreversibility, tipping points and extreme events it is important to define precisely what is meant by those terms. The following definitions are therefore adopted (based on either AR5 or the SR15 Glossary):

Abrupt climate change: A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems.

Extreme weather/climate event: An extreme event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called an extreme event may vary from place to place. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., high temperature, drought, or total rainfall over a season).

Irreversibility: A perturbed state of a dynamical system is defined as irreversible on a given timescale, if the recovery timescale from this state due to natural processes is significantly longer than the time it takes for the system to reach this perturbed state. In the context of this report, the recovery time scale of interest is hundreds to thousands of years.

Tipping point: A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the climate system, it refers to a critical threshold when global or regional climate changes from one stable state to another stable state.

These above three terms generally refer to aspects of the physical climate system. Here we extend their definitions to natural and human systems. For example, there may be gradual physical climate change which causes an irreversible changes in an ecosystem. An adaptation tipping point could be reached when an adaptation option no longer remains effective. There may be a tipping point within a governance structure.

We also introduce two new key terms relevant for discussing risks.

Compound Risk arises from the interaction of hazards, which may be characterised by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors.

Cascading impacts can occur, when societal or infrastructural capacities are exceeded. Initially, vulnerability may be low because critical services and infrastructure required by exposed sectors of society are available. However, vulnerability increases with subsequent events as these services and infrastructure fail.

6.2 Summary of Abrupt Changes, Irreversibility and Tipping Points

Some potentially abrupt or irreversible events are assessed in other chapters hence Table 6.1 presents a cross-chapter summary of those. Subsection numbers indicate where detailed information may be found.

Table 6.1: Cross-chapter assessment of abrupt and irreversible phenomena related to the ocean and cryosphere. The column on the far right of the table indicates the likelihood of an abrupt/irreversible change based on the assessed literature which, in general, assesses RCP scenarios. Assessments of likelihood and confidence are made according to IPCC guidance on uncertainties.

Change in system component	Potentially abrupt	Irreversibility if forcing reversed (time	Impacts on natural and human systems; global *vs.* regional *vs.* local	Projected likelihood and/or confidence level in 21st century

		scales indicated)		under scenarios considered
Ocean				
Atlantic Meridional Overturning Circulation (AMOC) collapse (Section 6.7)	Yes	Unknown	Widespread; increased winter storms in Europe, reduced Sahelian rainfall and agricultural capacity, variations in tropical storms, increased sea levels on Atlantic coasts	*Very unlikely*, but a physically-plausible scenario
Sub-polar gyre cooling (Section 6.7)	Yes	Irreversible within decades	Similar to AMOC impacts but considerably smaller.	*Medium confidence*
Marine heatwaves increase (Section 6.4)	Yes	Yes	Coral reef bleaching, loss of biodiversity and ecosystem services, harmful algal blooms	*Very likely (high confidence)*
Arctic sea-ice retreat (Section 3.3)	Yes	Reversible within years to decades	Coastal erosion in Arctic (may take longer to reverse), impact on mid-latitude storms (*low confidence*); rise in Arctic winter temperatures (*high confidence*)	*Very likely (high confidence)*
Methane release from ocean subsurface hydrates (Section 5.2)	No	Reversible	Further increased global temperatures	*Low confidence*
Ocean deoxygenation and hypoxic events (Section 5.2)	Yes	Irreversible for centuries to millennia at depth	Major changes in ocean productivity, biodiversity and biogeochemical cycles	*Very likely (high confidence)*
Ocean acidification (Section 5.2)	Yes	Reversible at surface, but irreversible for millennia at depth	Growth, development, calcification, survival and abundance of species; e.g., from algae to fish	*Very likely (high confidence)*
Cryosphere				
Methane release from permafrost (Section 3.4)	Yes	Reversible	Further increased global temperatures	*Low confidence*
CO_2 release from permafrost (Section 3.4)	Yes	Irreversible for millennia	Further increased global temperatures	*Low confidence*
Partial West-Antarctic Ice sheet collapse (Cross Chapter Box 2 in Chapter 1, Section 4.2)	Yes (late 21st century, RCP8.5)	Irreversible for millennia	Significant contribution to sea-level rise and ocean salinity	*Low confidence*
Greenland Ice sheet decay (Cross Chapter Box 2 in Chapter 1, Section 4.2)	No	Irreversible for millennia	Significant contribution to sea-level rise, shipping (icebergs)	*Low confidence*
Ice-shelf collapses (Cross Chapter Box 2 in Chapter 1, Sections 3.3, 4.2}	Yes	Irreversible for centuries	May lead to sea-level rise from contributing glaciers. Some shelves more prone than others.	*Likely (medium confidence)*
Glacier avalanches, surges, and collapses (Section 2.3)	Yes	Variable	Local hazard; may accelerate sea level rise; local iceberg production; local ecosystems	*Low confidence* for increase in frequency/magnitude
Strong shrinkage or disappearance of individual glaciers (Sections 2.2, 3.3)	Yes	Reversible within decades to centuries	Regional impact on water resources, tourism, ecosystems and global sea level	*Very likely (high confidence)*
Landslides related to glaciers and permafrost, glacier lake outbursts (Section 2.3)	Yes	Irreversible for rock slopes; reversible	Local direct impact on humans, land use, infrastructure (hazard), and ecosystems	*Likely (medium confidence) for increase in frequency*

		within decades to centuries for glaciers, debris and lakes		
Rapid permafrost thermokarst (Section 2.2)	Yes	Unknown	Local and regional impacts on infrastructure, mobility and hydrology, ecosystems	*Very likely (high confidence)*
Permafrost ground water changes (Section 2.3)	Yes	Unknown	Local impacts on groundwater flows	*Likely (medium confidence)*
Change in biodiversity in high mountain areas (Section 2.4)	Yes	In many cases irreversible (e.g., extinction of species)	Local impacts on ecosystems and ecosystem services	*Very likely (high confidence)*
Switch to different state in glacier-fed river communities and related loss of endemic species (Section 2.3)	Yes	In many cases irreversible (e.g., extinction of species)	Local impacts on ecosystems and ecosystem services	*Likely (medium confidence)*

6.3 Changes in Tracks, Intensity, and Frequency of Tropical and Extratropical Cyclones and Associated Sea Surface Dynamics

6.3.1 Introduction

Severe tropical cyclones (TCs) and extratropical cyclones (ETCs) pose major threats to society, infrastructure and marine activities due to damaging winds, heavy rainfall, and associated storm surges and ocean waves. Reductions in cyclone speeds can increase rainfall totals over a given region thereby exacerbating flood risk (Kossin, 2018) while wave heights can be amplified along the tracks of rapidly moving cyclones (e.g., Moon et al., 2015a). The size of the storm determines its impact area on the underlying land or ocean region. Sequencing of extreme weather and climate events is important since the frequency that they occur in a given location can affect the ability of communities and the natural environment to recover before subsequent storm occurrence. Climate variability such as El Niño Southern Oscillation (ENSO) has a strong influence on regional TC incidence (Walsh et al., 2016). Changes in large-scale circulation patterns due to climate change may alter environment variables related to TC genesis and track (Sharmila and Walsh, 2018), thereby exposing regions to new or more frequent hazards.

IPCC AR5 concluded that there was *low confidence* in any long-term increases in TC activity globally and in attribution of global changes to any particular cause (Hartmann et al., 2013). Based on process understanding and agreement in 21st century projections, the IPCC AR5 concluded that is *likely* that the global TC frequency will either decrease or remain essentially unchanged, while global mean TC maximum wind speed and precipitation rates will *likely* increase although there is *low confidence* in region-specific projections of frequency and intensity. The AR5 concluded that circulation features have moved poleward since the 1970s, associated with a widening of the tropical belt, a poleward shift of storm tracks and jet streams, and contractions of the northern polar vortex and the Southern Ocean westerly wind belts. However it is noted that natural modes of variability on interannual to decadal time scales prevent the detection of a clear climate change signal (Hartmann et al., 2013).

AR5 also concluded that there is *medium confidence* that mean significant wave height has increased in the North Atlantic north of 45°N based on ship observations and reanalysis-forced wave model hindcasts. Extreme sea level events have increased since 1970, mainly due to a rise in mean sea levels (MSLs) over this period (Rhein et al., 2013). There is *medium confidence* that mid-latitude jets will move 1–2 degrees further poleward by the end of the 21st century under RCP8.5 in both hemispheres with weaker shifts in the Northern Hemisphere. In the Southern Hemisphere during austral summer, the poleward movement of the mid-latitude westerlies under climate change is projected to be partially offset by stratospheric ozone recovery. There is *low confidence* in projections of Northern Hemisphere storm tracks particularly in the

North Atlantic. Tropical expansion is *likely* to continue causing wider tropical regions and poleward movement of the subtropical dry zones (Collins et al., 2013). In the southern hemisphere, it is *likely* that enhanced wind speeds will cause an increase in annual mean significant wave heights. Wave swells generated in the Southern Ocean may also affect wave heights, periods and directions in adjacent ocean basins. The projected reduction in sea-ice extent in the Arctic Ocean will increase wave heights and wave-season length (Church et al., 2013).

6.3.2 Recent Anomalous Extreme Climate Events and their Causes

The ability to attribute extreme events to climate change is important for awareness-building, decision making and adaptation planning. Therefore, a major scientific focus in recent years has been on the development of methodologies for event attribution (Stott et al., 2016). Annual reports dedicated to extreme event attribution (Peterson et al., 2012; Peterson et al., 2013; Herring et al., 2014; Herring et al., 2015; Herring et al., 2018) have helped stimulate studies that adopt recognised methods for extreme event attribution. The increasing pool of studies allows different approaches to be contrasted and builds consensus on the role of climate change when individual climate events are studied by multiple teams using different methods. The findings of the studies show that the role of climate change in ocean and cryospheric extreme events is strengthening through time. Three studies in the most recent annual report on explaining extreme events (Imada et al., 2018; Knutson et al., 2018; Walsh et al., 2018) found that temperature extremes that occurred in 2016 fell outside the range of natural variability, (i.e., could not have occurred without climate change) – see also Section 6.4. Studies are also emerging that undertake 'impacts attribution' to determine whether the climate change influence on the extreme event can be tied to changes in the risk of the socio-economic or environmental impacts (Herring et al., 2018).

The attribution of changes in the observed statistics of extremes are generally addressed using well-established detection-attribution methods. In contrast, record-breaking weather and climate events are by definition unique, and can be expected to occur with or without climate change as the observed record lengthens. Therefore, event attribution begins with the premise that the climate is changing, the goal being to determine statistically how much climate change has contributed to the severity of the event (Trenberth et al., 2015; Shepherd, 2016).

The important role the ocean has in influencing atmospheric and oceanic extreme events is becoming increasingly apparent across the globe although some regions including Africa and the Pacific have had relatively fewer studies undertaken, possibly reflecting the lack of capacity or imperative by regional and national technical institutions. Events include marine heatwaves and associated coral bleaching events (e.g., Lewis and Mallela, 2018), tropical and extratropical cyclones (e.g., Murakami et al., 2015; Takagi and Esteban, 2016; van Oldenborgh et al., 2017), storm surges (Sweet et al., 2013), wave swell events (Hoeke et al., 2013; Wadey et al., 2017) and changes in the cryosphere including sea ice (Guemas et al., 2013; Zhang and Knutson, 2013).

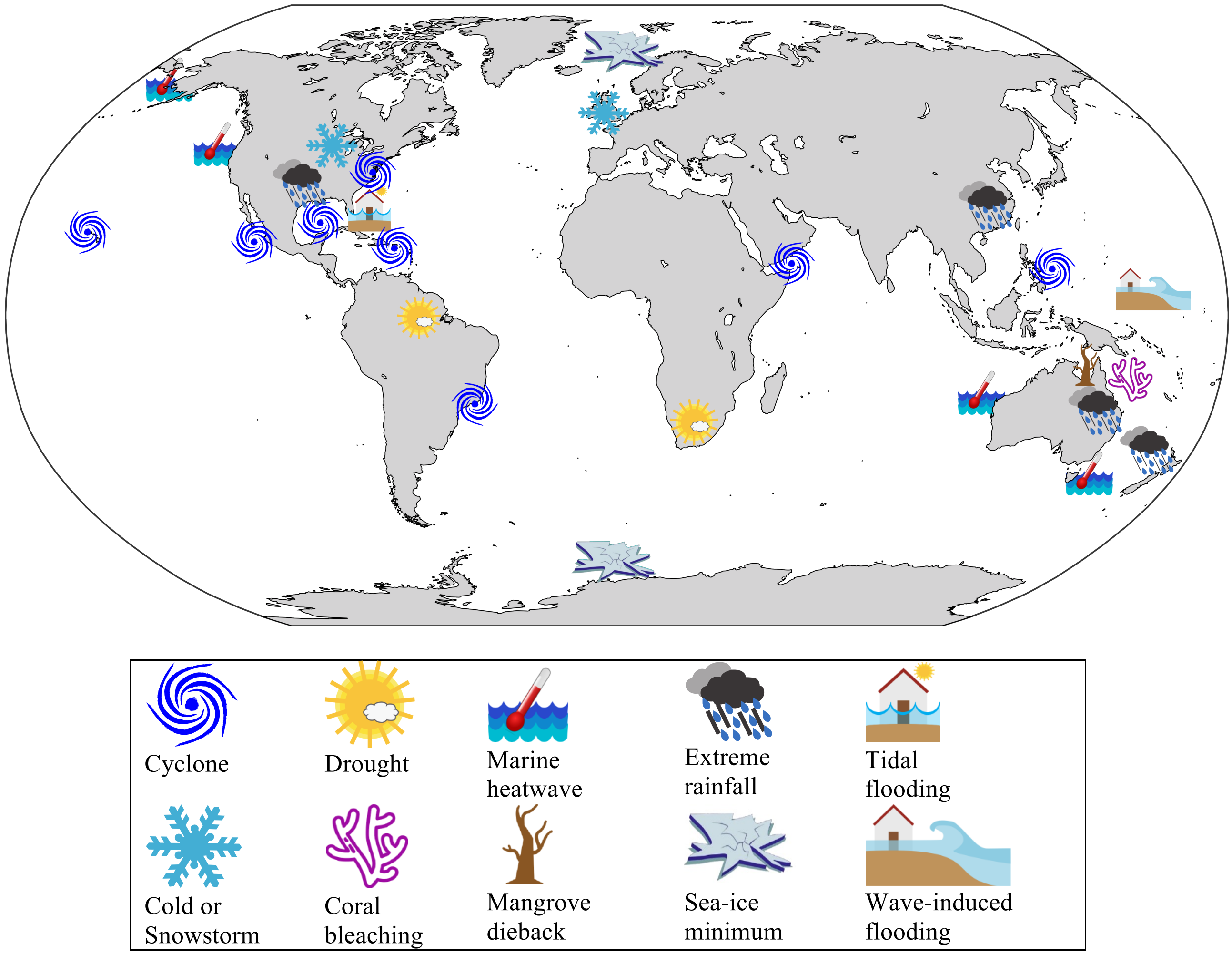
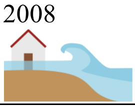


Figure 6.2: Locations where extreme events with an identified link to ocean changes have been discussed in Table 6.2.

Table 6.2: A selection of record-breaking extreme events with links to oceans and cryosphere. In many of these studies the method of event attribution has been used to estimate the role of climate change using either a probabilistic approach (using ensembles of climate models to assess how much more likely the event has become with anthropogenic climate change compared to a world without) or a storyline approach which examines the components of the climate system that contribute to the events and how changes in the climate system affect them (Shepherd, 2016). (Adapted and updated from Coumou and Rahmstorf, 2012)

Year/type of hazard	Region	Severe hazard	Impact, costs	Attribution to anthropogenic climate change
2004 	South Atlantic	First hurricane in the South Atlantic since 1970	Three deaths, USD 425 million damage (McTaggart-Cowan et al., 2006)	Increasing trend to positive Southern Annular Mode (SAM) could favour the synoptic conditions for such events in the future (Pezza and Simmonds, 2005)
2005 	North Atlantic	Record number of tropical storms, hurricanes and Category 5 hurricanes since 1970	Costliest US natural disaster, 1,836 deaths and USD 30 billion in direct economic costs in Louisiana due to Hurricane Katrina (Link, 2010)	Trend in sea surface temperature (SST) due to global warming contributed to half of the total SST anomaly. Atlantic Multidecadal Variability (AMV) and the after-effects of the 2004–2005 El Niño also played a role (Trenberth and Shea, 2006)
2008 	Western Pacific Islands	North Pacific-generated wave-swell event	Wave-induced inundation in islands of 6 Pacific nations (Kiribati, Marshall Islands,	Event shown to have been made more extreme compared to other historical

			Micronesia, Nauru, Papua New Guinea, Solomon Islands), salt water flooding of food and water supplies in Kosrae, Micronesia, 1408 houses damaged and 63,000 people affected across 8 provinces in Papua New Guinea (Hoeke et al., 2013)	events due to La Niña and sea level rise (Hoeke et al., 2013)
2010 	Southern Amazon	Widespread drought in the Amazon led to lowest river levels of major Amazon tributaries on record (Marengo et al., 2011)	Relative to the long-term mean, the 2010 drought resulted in a reduction in biomass carbon uptake of 1.1 Pg C, compared to 1.6 Pg C for the 2005 event which was driven by an increase in biomass mortality (Feldpausch et al., 2016)	Model-based attribution indicates human influences and SST natural variability increased probabilities of the 2010 severe drought in the South Amazon region whereas aerosol emissions had little effect (Shiogama et al., 2013)
2010–2011 	Eastern Australia	Wettest spring since 1900 (Leonard et al., 2014)	Brisbane flooding in January 2011, costing 23 lives and an estimated USD 2.55 billion (van den Honert and McAneney, 2011)	Based on La Niña SSTs during satellite era, La Niña alone is insufficient to explain total rainfall. 25% of rainfall was attributed to SST trend in region (Evans and Boyer-Souchet, 2012)
2011 	Western North Pacific	Tropical Storm Washi (also known as TS Sendong) was world's deadliest storm in 2011	Fatalities: >1,250, injured: 2,002, missing: 1,049 (Rasquinho et al., 2013) socio-economic costs: USD 63.3 million (Espinueva et al., 2012)	No attribution done; disaster was the outcome of interplay of climatic, environmental and social factors (Espinueva et al., 2012)
2011 	Western Australia	February-March record breaking heat wave in Ningaloo reef up to 5°C warmer than normal (Feng et al., 2013)	Widespread coral bleaching and fish kills	Warming of poleward-flowing Leeuwin Current in Austral summer forced by oceanic and atmospheric teleconnections associated with the 2010–2011 La Niña (Feng et al., 2013). Conditions increased since 1970's by negative Interdecadal Pacific Oscillation (IPO) and anthropogenic global warming (Feng et al., 2015)
2011 	Golden Bay, New Zealand	In December, Extreme two-day total rainfall was experienced (one in 500-year event)	In town of Takaka, 453 mm was recorded in 24 hours and 674 mm in 48 hours	Model based attribution indicated total moisture available for precipitation in Golden Bay, New Zealand was 1–5% higher due to anthropogenic emissions (Dean et al., 2013)
2012 	Arctic	Arctic sea-ice minimum		Model-based attribution indicated the exceptional 2012 sea-ice loss was due to sea-ice memory and positive feedback of warm atmospheric conditions, both contributing approximately equally (Guemas et al., 2013) and *extremely unlikely* to have occurred due to internal climate variability alone based on observations

				and model-based attribution (Zhang and Knutson, 2013)
2012	US East coast	Hurricane Sandy	Repair & mitigation expenditures funded at USD 60.2 billion. Losses of fishing vessels estimated at USD 52.0 million (Sainsbury et al., 2018)	Relative sea level rise (SLR) shown to have increased probabilities of exceeding peak impact elevations since the mid-20th century (Sweet et al., 2013; Lackmann, 2015)
2013	UK	Severely cold 2013 winter		Model based attribution study found odds of an extremely cold spring had been reduced 30 times by anthropogenic climate change (Christidis et al., 2013)
2013	Western North Pacific	Strongest and fastest Super Typhoon Haiyan (Category 5) in the region	Deadliest and most expensive natural disaster in the Philippines (Fatality: 6,245; Injured: 28,626; Missing: 1,039). Damage to mangroves was still apparent 18 months after the storm (Sainsbury et al., 2018)	Occurred in a season with remarkably warm SSTs, (David et al., 2013; Takagi and Esteban, 2016). Ocean heat content and sea levels had increased since 1998 due to the negative Pacific Decadal Oscillation (PDO) phase but impacts were worsened by thermodynamic effects on SSTs and SLR due to climate change (Trenberth et al., 2015)
2014	Western Tropical and Northeast Pacific Ocean	Global SST during 2014 was the highest over observational records without the influence of a strong El Niño		During the 2014 calendar year and summer, human influence has increased the probability of regional high SST extremes over the western tropical and northeast Pacific Ocean. Natural internal variability also played a role (Weller et al., 2015)
2014	Hawaiian hurricane season	Extremely active hurricane season in the eastern and central Pacific Ocean, particularly around Hawaii		Anthropogenic forcing could have contributed to the unusually large number of hurricanes in Hawaii in 2015, in combination with the moderately favourable condition of the El Niño event (Murakami et al., 2015)
2014	Arabian Sea	Cyclone Nilofar was the first severe tropical cyclone to be recorded in the Arabian Sea in post-monsoon cyclone season (Murakami et al., 2017)	Cyclone did not make landfall but produced heavy rainfall on western Indian coasts (Bhutto et al., 2017)	Anthropogenic global warming has been shown to have increased the probability of post-monsoon tropical cyclones over the Arabian Sea (Murakami et al., 2017)
2014	Northland New Zealand	Extreme 5-day rainfall in Northland	NZD 18.8 million in insurance claims	Extreme 5-day rainfall over Northland, New Zealand is seen to be influenced by human-induced climate change (Rosier et al., 2015)

2015 	North America		Several intense snowstorms resulting to power outages and large economic losses	Reduced Arctic sea ice and anomalous SSTs may have contributed to the anomalous meander of the jet stream, and could contribute to enlarge probability of such extreme cold spells over North America (Bellprat et al., 2016)
2015 	Arctic	Record Low Northern Hemisphere Sea Ice Extent in March 2015	March NH sea ice content reached the lowest winter maximum in 2015	Record low in NH sea ice maximum could not have been reached without human-induced change in climate, with the surface atmospheric conditions on average contributing 54% to the change (Fuckar et al., 2016)
2015 	Florida	Sixth largest flood in Virginia Key, Florida since 1994, with the 5 highest in response to hurricanes	Flooding in several Miami-region communities with 0.57 m of ocean water on a sunny day	The probability of a 0.57 m flood has increased by 500% (Sweet et al., 2016)
2015/2016 	Ethiopia and Southern Africa	One of the worst droughts in 50 years, also intensified flash droughts characterized by severe heatwaves	A 9-million tonne cereal deficit resulted in more than 28 million in need of humanitarian aid	Anthropogenic warming contributed substantially to the very warm 2015/16 El Niño SSTs, land local air temperatures thereby reducing Northern Ethiopia and Southern Africa rainfall and runoff (Funk et al., 2018; Yuan et al., 2018)
2015 	Eastern North Pacific	TC Patricia, most intense and rapidly intensifying storm in the Western Hemisphere with an estimated MSL pressure of 872 hPa (Rogers et al., 2017). It intensified rapidly into a Category 5 (Diamond and Schreck, 2016)	Forecasting the rapid intensity change observed in Patricia is currently beyond weather forecasting capabilities (Rogers et al., 2017). Approximately 9000 homes and agricultural croplands, including banana crops, were damaged by wind and rain from Patricia that made landfall near Jalisco, Mexico (Diamond and Schreck, 2016)	A near-record El Niño combined with a positive Pacific Meridional Mode provided extremely record SSTs and low vertical wind shear that fuelled the 2015 eastern North Pacific hurricane season to near-record levels (Collins et al., 2016)
2015 	Arabian Sea, Somalia and Yemen	Cyclones Chapala and Megh occurred within a week of each other and both tracked westward across Socotra Island and Yemen. Rainfall from Chapala was 7 times the annual average	Death toll in Yemen from Chapala and Megh was 8 and 20 respectively, Thousands of houses and businesses damaged or destroyed by both cyclones and fishing disrupted. The coastal town of Al Mukalla experienced a 10 m storm surge that destroyed the seafront (Kruk, 2016). Flooding in Somalia led to thousands of livestock killed and damage to infrastructure (IFRC, 2016)	Anthropogenic global warming has been shown to have increased the probability of post-monsoon tropical cyclones over the Arabian Sea (Murakami et al., 2017)

2015/2016	Northern Australia	1000 km of mangrove tidal wetland dieback	More than 74,000 ha of mangrove vegetation affected with potential flow-on consequences to Gulf of Carpentaria fishing industry worth AUD 30 million per year due to loss of loss of recruitment habitat	Attributed to anomalously high temperatures and low rainfall and low sea levels associated with El Niño (Duke et al., 2017)
2015/2016	Eastern Australia	Marine heatwave in eastern Tasmania	Disease outbreaks in farmed shellfish, mortality in wild shellfish and species found further south than previously recorded (see Box 6.1)	The intensity and most notably the duration of the marine heatwave was unprecedented and both aspects had a clear human signature (Oliver et al., 2017)
2016	central Equatorial Pacific, California Current	Record warm SSTs	Impacted the 2015–2016 El Niño event. Caused a major outbreak of a toxic algal bloom along the US West Coast leading to impacts on fisheries (McCabe et al., 2016)	Record warm ocean temperatures during the 2015/16 El Niño appear to partly reflect an anthropogenic influence (Jacox et al., 2018; Newman et al., 2018)
2016	Arctic	Highly anomalous Arctic warmth during November-December	Arctic sea ice content was at record low levels	Would not have been possible without anthropogenic forcing (Kam et al., 2018)
2016	Alaska. Bering Sea/Gulf of Alaska, Northern Australia	Marine heatwaves	Impacts on marine ecosystems	Data suggest human-induced climate change (Oliver et al., 2018b; Walsh et al., 2018)
2016	Eastern China	Super cold surge	Extreme weather brought by the cold surge caused significant impacts on > 1 billion people in China in terms of transportation and electricity transmission systems, agriculture and human health	This cold surge would have been stronger if there was no anthropogenic warming (Qian et al., 2018; Sun and Miao, 2018)
2016	Antarctic	Springtime low record of sea ice extent	Antarctic sea ice extent decreased at a record rate 46% faster than the mean rate and 18% faster than any spring rate in the satellite era	The signature of a human-induced warming is too early to tell (Turner et al., 2017)
2016	Great Barrier Reef, Australia	Extended period of heat stress	Extensive coral bleaching	Anthropogenic greenhouse gas (GHG) emission increased the risk of coral bleaching through anomalously high SSTs and accumulation of heat stress (Lewis and Mallela, 2018)
2017	Western North Atlantic	Hurricanes Harvey, Irma and Maria	Extensive impacts (see Box 6.1)	Rainfall intensity in Harvey attributed to climate change (Emanuel, 2017; Risser and Wehner, 2017; van Oldenborgh et al., 2017; see Box 6.1)
2017	Europe	Storm Ophelia	Largest ever recorded hurricane in East Atlantic; extreme winds and coastal erosion in Ireland	Very rare event, in line with projections of stronger cyclones in Europe (Haarsma et al., 2013)

6.3.3 Changes in Storms and Associated Sea-surface Dynamics

6.3.3.1 Tropical Cyclones

Notable developments since IPCC AR5 Bindoff et al. (2013) and Knutson et al. (2010) include a further simulation study on the possible influence of aerosols on multidecadal tropical storm variability in the Atlantic basin (Dunstone et al., 2013). Kossin et al. (2014) identified a poleward expansion of the latitudes of maximum TC intensity in recent decades, which has been linked to an anthropogenically-forced tropical expansion (Sharmila and Walsh, 2018) and a continued poleward shift of cyclones projected over the western north Pacific in a warmer climate (Kossin et al., 2016). There have been more TC dynamical or statistical/dynamical downscaling studies and higher resolution General Circulation Model (GCM) experiments that support the IPCC AR5 projections of future TC activity (e.g., Emanuel, 2013; Manganello et al., 2014; Knutson et al., 2015; Murakami et al., 2015; Roberts et al., 2015; Wehner et al., 2015; Yamada et al., 2017); more studies of storm surge (e.g., Lin et al., 2012; Garner et al., 2017) and storm size (Kim et al., 2014; Knutson et al., 2015; Yamada et al., 2017) under climate warming scenarios. Emanuel (2013) was notable for a projected increase in global TC frequency, at variance with most other TC frequency projections and with previous assessments.

Although warming oceans are expected to increase TC activity, the increased mixing to the surface of cooler subsurface water can have a limiting effect on cyclone development, which may reduce the projected intensification of TCs in the future because of greater thermal stratification of the upper ocean in CMIP5 models under global warming (Huang et al., 2015). The effect of such increased thermal stratification is expected to reduce the intensification of TCs by roughly 10–15% compared to previous projections (Emanuel, 2015; Tuleya et al., 2016). Furthermore, a strengthening effect of reduced near-surface salinity on TC intensification has been suggested (Balaguru et al., 2015), which would have an influence opposite to the thermal stratification effect. In summary, coupled ocean-atmosphere models still robustly project an increase of TC intensity with climate warming, even using updated estimates of thermal stratification change.

The expected detectability of climate change signals in hurricane activity and some proposed reasons for the lack of detection of intensity changes to date has been further explored (Sobel et al., 2016). New studies have used event attribution to explore attribution of certain individual TC events or anomalous seasonal cyclone activity events to anthropogenic forcing (Lackmann, 2015; Murakami et al., 2015; Takayabu et al., 2015; Zhang et al., 2016; Emanuel, 2017). Risser and Wehner (2017) and van Oldenborgh et al. (2017) concluded that for the Hurricane Harvey event, there is a detectable human influence on extreme precipitation in the Houston area, although their detection analysis is for extreme precipitation in general and not specifically for TC-related precipitation.

There have been a number of studies exploring future track changes of TCs under climate warming scenarios (Li et al., 2010; Kim and Cai, 2014; Manganello et al., 2014; Knutson et al., 2015; Murakami et al., 2015; Roberts et al., 2015; Wehner et al., 2015; Nakamura et al., 2017; Park et al., 2017; Sugi et al., 2017; Yamada et al., 2017; Yoshida et al., 2017; Zhang et al., 2017a). While it is difficult to identify a robust consensus of projected change in TC tracks, several of the studies found either poleward or eastward expansion of TC occurrence over the North Pacific region resulting in greater storm occurrence in the central North Pacific.

There are now several studies exploring the impact of anthropogenic warming on TC size characteristics (e.g., Kim and Cai, 2014; Knutson et al., 2015; Yamada et al., 2017). The projected TC size changes are approximately 10% or less, and vary in sign between basins and studies. These provide preliminary findings on this issue, which future studies will continue to investigate.

Taking the above into account, the following is a summary assessment of TC detection and attribution. In agreement with IPCC AR5 (Bindoff et al., 2013) there is *medium confidence* that a reduction in aerosol forcing over the North Atlantic has contributed to the observed increase in TC activity since the 1970s. This recent rise in activity was apparently the latest in a series of low-frequency increases and decreases occurring over the 20th century, thought to be due in part to aerosol forcing variations (Dunstone et al., 2013). Kossin et al. (2016) showed that the observed poleward migration of the latitude of maximum TC intensity in the western North Pacific is unusual compared to expected natural variability and therefore there is *low-to-medium confidence* that this change represents a detectable climate change contribution from anthropogenic forcing. They relate this to the poleward expansion of the tropical circulation with climate warming (e.g., Bindoff et al., 2013). Additional studies of observed long-term TC changes, may represent emerging anthropogenic signals, but still with *low confidence*. These include: i) decreasing frequency of severe TCs that make landfall in eastern Australia since the late 1800s (Callaghan and Power, 2011); ii) increase in frequency of moderately large US storm surge events since 1923 (Grinsted et al., 2012); iii) recent increase of extremely severe cyclonic storms over the Arabian Sea in the post-monsoon season (Murakami et al., 2017) and intense TCs that make landfall in East and Southeast Asia in recent decades (Mei and Xie, 2016; Li et al., 2017); and iv) increase in annual global proportion of hurricanes reaching Category 4 or 5 intensity in recent decades (Holland and Bruyère, 2014). While an anthropogenic influence on extreme precipitation in general has been detected over global land regions (Bindoff et al., 2013), and recently in some specific regions affected by hurricanes (Risser and Wehner, 2017; van Oldenborgh et al., 2017) an anthropogenic climate change has not yet been detected specifically for hurricane precipitation rates. The lack of confident climate change detection for most TC metrics continues to limit confidence in both future projections and in the attribution of past changes and events, since TC attribution in most published studies is generally being inferred without support from a confident climate change detection.

Tropical cyclone projections for the late 21st century are summarized as follows: 1) sea level rise over the coming century will lead to higher storm surge levels for the TCs that do occur, assuming all other factors are unchanged (*high confidence*). 2) There is *medium confidence* that the proportion of TCs that reach Category 4–5 levels will increase, that the average intensity of TCs will increase (by roughly 1–10%, assuming a 2 degree global temperature rise), and that average tropical cyclone precipitation rates (for a given storm) will increase by at least 7% per degree Celsius sea surface temperature (SST) warming, owing to higher atmospheric water vapour content. 3) There is *low confidence* in how global TC frequency or the global frequency of very intense (Category 4–5) storms will change, although most modelling studies project some decrease in global TC frequency.

6.3.3.2 Extratropical Cyclones and Blocking

Extratropical cyclones (ETCs) form in the midlatitudes of the North Atlantic, North Pacific and Southern oceans, and the Mediterranean Sea. The storm track regions are characterised by large surface equator-to-pole temperature gradients and baroclinic instability. Jet streams influence the direction and speed of movement of ETCs in this region. Projecting future changes to ETCs is challenging because the thermodynamic responses to anthropogenic radiative forcing factors, such as CO_2 and ozone changes, tend to have opposing influences on storm tracks. Surface shortwave cloud radiative changes increase the equator-to-pole temperature gradient whereas longwave cloud radiative changes reduce it (Shaw et al., 2016).

A sensitivity study based on the CMIP3 General Circulation Model (GCM) multimodel ensemble finds that projected changes to the Northern Hemisphere extratropical storm track particularly in the northern North Atlantic is more strongly associated with changes in the lower rather than upper tropospheric equator-to-pole temperature difference (Harvey et al., 2015). For the Southern Hemisphere (SH) the total number of SH ETCs in a CMIP5 GCM multimodel ensemble of future climate simulations decreased, whereas the number of strong ETCs increased in most models and in the ensemble mean. This was associated with a general poleward shift related to both tropical upper tropospheric warming and shifting meridional sea surface temperature gradients in the Southern Ocean (Grieger et al., 2014). The poleward movement of baroclinic instability and associated storm formation over the observational period due to external radiative forcing, are projected to continue, with associated declining rainfall trends in the midlatitudes and positive trends further polewards (Frederiksen et al., 2017). The findings of the new studies on ETCs are generally consistent with those assessed in the AR5 and do not change the AR5 assessment provided in section 6.3.1.

The term 'blocking' refers to an extratropical weather system that is characterised by a quasi-stationary anticyclone that interrupts the usual westerly flow and/or storm tracks for up to a week or more (Woollings et al., 2018). The persistence of a blocking event can lead to a range of regional weather extremes such as heatwaves in summer or severe cold in winter associated with reduced cloud cover in the anticyclonic region. Such conditions can also enhance particulate matter concentrations in winter and photochemically-induced surface ozone during spring and summer. Dry conditions that contribute to drought can also occur in the vicinity of the anticyclone whereas extreme rainfall can occur along the paths that storms are deflected to by the blocking anticyclone. For example, a link between sea-ice loss in the Arctic and drought in California has been identified where sea-ice changes lead to a reorganization of tropical convection which triggers enhanced anticyclonic activity over the North Pacific (Cvijanovic et al., 2017). Local boundary layer and soil moisture feedbacks can also help to maintain block persistence pointing to a need for climate models to well-represent boundary layer processes. The different definitions of blocking, its poor representation in climate models and the incomplete understanding of the dynamical mechanisms responsible for blocking lead to *low confidence* in projections of future changes (Woollings et al., 2018).

6.3.3.3 Waves and Extreme Sea Levels

The results of several new global wave climate projection studies are consistent with those presented in IPCC AR5. Mentaschi et al. (2017) project up to a 30% increase in 100-year return level wave energy flux (the rate of transfer of wave energy) for the majority of coastal areas in the southern temperate zone, and a projected decrease in wave energy flux for most Northern Hemisphere coastal areas. The most significant long-term trends in extreme wave energy flux are explained by their relationship to climate indices (Arctic Oscillation, El Niño Southern Oscillation and North Atlantic Oscillation). Wang et al. (2014b) assessed the climate change signal and uncertainty in a 20-member ensemble of wave height simulations, and found model uncertainty (intermodel variability) is significant globally, being about 10 times as large as the variability between RCP4.5 and RCP8.5 scenarios. In a study focussing on the western north Pacific wave climate, Shimura et al. (2015) associate projected regions of future change in wave climate with spatial variation of Sea Surface Temperatures (SSTs) in the tropical Pacific Ocean. A review of 91 published global and regional scale wind-wave climate projection studies found a consensus on a projected increase in significant wave height over the Southern Ocean, tropical eastern Pacific and Baltic Sea and decrease over the North Atlantic and Mediterranean Sea. They found little agreement between studies of projected changes over the Atlantic Ocean, southern Indian and eastern North Pacific Ocean and no regional agreement of projected changes to extreme wave height. It was noted that few studies focussed on wave direction change, which is important for shoreline response (Morim et al., 2018).

Significant developments have taken place since the AR5 to model storm surges and tides at the global scale. An unstructured global hydrodynamic modelling system has been developed with maximum coastal resolution of 5 km (Verlaan et al., 2015) and used to develop a global climatology of extreme sea levels due to the combination of storm surge and tide (Muis et al., 2016). A global study on the effect of Sea Level Rise (SLR) on astronomical tides reveals that for SLR scenarios from 0.5 m, to 10 m Mean High Water changes exceed ±10% of the imposed SLR at around 10% of coastal cities when coastlines are held fixed. However in coastal recession-permitting simulations, results indicate a reduction in tidal range due to changes in the period of oscillation of the basin under the changed coastline conditions (Pickering et al., 2017). A recent study on global probabilistic projections of extreme sea levels considering mean sea level, tides, wind-waves and storm surges shows that under RCP4.5 and RCP8.5, the global average 100-year extreme sea level is *very likely* to increase by 34–76 cm and 58–172 cm, respectively between 2000 and 2100 (Vousdoukas et al., 2018). Despite the advancements in global tide and surge modelling, using CMIP GCM multimodel ensembles to examine the effects of future weather and circulation changes on storm surges in a globally consistent way is still a challenge because of the *low confidence* in GCMs being able to represent small scale weather systems such as TCs. To date only a small number of higher resolution GCMs are able to produce credible cyclone climatologies (e.g., Murakami et al., 2012) although this will probably improve with further GCM development and increases to GCM resolution (Walsh et al., 2016).

New regional and local assessments of storm surges have been undertaken, with several also examining the role of other factors contributing to extreme sea levels such as waves and interannual variability of austral winter swell waves combined with high spring tides in the Gulf of Guinea (Melet et al., 2016) and the Maldives (Wadey et al., 2017). Multivariate statistical analysis and probabilistic modelling is used to show that flood risk in the northern Gulf of Mexico is higher than determined from short observational records (Wahl et al., 2016). A synthetic cyclone modelling approach has been used to evaluate probabilities of extreme water levels from tides and storm surge (storm tide) in Fiji (McInnes et al., 2014) and Samoa (McInnes et al., 2016) highlighting the spatial variation and the relative roles of climate variability and projected changes in TCs in storm tide heights. Higher resolution modelling for Apia, Samoa incorporating waves highlights that although SLR reduces wave setup and wind setup by 10–20%, during storm surges, it increases wave energy reaching the shore by up to 200% (Hoeke et al., 2015).

In the German Bight, Arns et al. (2015) show that under sea level rise, increases in extreme water levels occur due to a change in phase of tidal propagation; which more than compensates for a reduction in storm surge change due to deeper coastal sea levels. Vousdoukas et al. (2017) develop extreme sea level (ESL) projections for Europe that account for changes in waves and storm surge. By 2100 increases that are larger than MSL projections occur along the North Sea coasts of northern Germany and Denmark and the Baltic Sea coast, reaching 0.35 m towards the end of the century under RCP8.5, while little to negative change is found for the southern European coasts.

In the US, Garner et al. (2017) combine downscaled tropical cyclones, storm-surge models, and probabilistic sea-level rise projections to assess flood hazard associated with changing storm characteristics and sea-level rise in New York City from the preindustrial era to 2300. Compensation between increased storm intensity and offshore shifts in storm tracks causes minimal change in modelled storm-surge heights through 2300. However, projected sea-level rise leads to large increases in future overall flood heights associated with tropical cyclones in New York City. Consequently, flood height return periods that were ~500y during the preindustrial era have fallen to ~25y at present and are projected to fall to ~5y within the next three decades.

6.3.3.4 Compounding Factors

Of relevance to compounding hazards are regions where changes in the climate system could increase the likelihood or severity of multiple hazards, particularly in proximity to large population centres. In this context, western boundary current (WBC) regions are notable for their vulnerability to regional climate (Yang et al., 2016a). These regions experience cyclones of tropical origin in the warmer months and ETCs during the winter months. The warm SSTs are known to intensify cyclogenesis in the vicinity of the Gulf Stream (Booth et al., 2012), the Kuroshio (Hirata et al., 2016) and for the East Australian Current (EAC; Pepler et al., 2016a), and in turn influence severe rainfall, flooding and storm surges (Thompson et al., 2013; Oey and Chou, 2016; Pepler et al., 2016a). In one study WBC's were found to undergo an intensification and poleward expansion in all but the Gulf Stream where the weakening of the Atlantic Overturning Circulation (AMOC) cancelled this effect (Seager and Simpson, 2016; Yang et al., 2016a).

In terms of future projections, the WBC regions have been identified as areas of extreme regional sea level rise due to the effect of large ocean variability caused by ocean eddies (Brunnabend et al., 2017; Zhang et al., 2017b). Acknowledging the dual role of regional SLR and tropical cyclone frequency and intensity changes for future flood risk, Little et al. (2015) developed a flood index (FI) that takes account of local projected SLR along with TC frequency and intensity changes in a CMIP5 multi-model ensemble and find that relative to 1986–2005, the FI by 2080–2099 is 4–75 times higher for RCP2.6 (10–90th percentile range) and 35–350 times higher for RCP8.5. In terms of ETCs in the vicinity of the EAC, Pepler et al. (2016b) found a reduction in winter ETCs but an increase in the number of cyclones with heavy rainfall closest to the coast. Besides, using coastal water levels, fluvial flow and projected SLR in several US estuaries, Moftakhari et al. (2017) demonstrates that neglecting compounding effects of flood drivers can cause significant underestimation of projected failure probability.

Over the last decade, several efforts have been made to address long-term shoreline change driven by the compound effect of SLR, waves and mean sea level. Ranasinghe et al. (2012) presented the Probabilistic Coastline Recession (PCR) model, which provides probabilistic estimates of coastline recession in response to both storms and SLR in the 21st century. Dune recession is estimated for each storm considering the recovery between storms, which is obtained empirically. More recently, Toimil et al. (2017) developed a methodology to address shoreline change over this century due to the action of waves, storm surges, astronomical tides in combination with SLR. The methodology considers the generation of thousands of multi-variate hourly time series of waves and storm surges to reconstruct future shoreline evolution probabilistically. This enables to obtain robust estimates of extreme recessions and long-term coastline change. The model proposed by Vitousek et al. (2017) integrates longshore and cross-shore transport induced by GCM-projected waves and SLR, which allows it to be applied to both long and pocket sandy beaches. The analysis provides only one instance of what coastline change over the 21st century may be.

In summary, there have been considerable developments since the AR5 to understand past and future changes in TCs and ETCs. Significant advances have been made in hydrodynamic models for simulating storm surges and tides at global scale. Of relevance to compound hazards are several new studies that variously identify the WBCs as regions where potentially large future changes in sea level, TC and ETC intensity and associated storm surge and flooding rain could have large local impacts (*medium confidence*).

6.3.4 Impacts

As shown in previous assessments, increasing exposure is a major driver of increased cyclone risk (damages), as well as flood risk associated with cyclone rainfall and surge irrespective of whether there has been a signal from anthropogenic climate change (Handmer et al., 2012; Arent et al., 2014). Changes in TC trajectories are potentially a major source of increased risk, as the degree of vulnerability is typically much higher in locations that were previously not exposed to the hazard (Noy, 2016). TC Hayan's move to the south of the usual trajectories of TCs in the Western North Pacific basin (Yonson et al., 2018) made the evacuation more difficult as people were less willing to heed storm surge warnings they received.

Abrupt changes in impacts therefore are not only determined by changes in cyclone hazard, but also by the sensitivity or tipping points that are crossed in terms of flooding for instance, that can be driven by sea-level rise but also by changes in local exposure. The frequency of nuisance flooding along the US east coast is expected to accelerate further in the future (Sweet and Park, 2014). The loss of coral reefs and mangrove forests have also been shown to increase damages from storm surge events (e.g., Beck et al., 2018). Cyclones also affect marine life, habitats, and fishing. There is some evidence that fish may evacuate storm areas or be redistributed by storm waves and currents (FAO, 2018; Sainsbury et al., 2018). Other examples of damage to fisheries from cyclones and storm surges can be found in FAO (2018: Chapter V, Table 1).

With regard to property losses, according to most projections, increasing losses from more intense cyclones are not off-set by a possible reduction in frequency (Handmer et al., 2012). While the relation between aggregate damages and frequency may be linear, the relationship between intensity and damages is most probably highly non-linear; with research suggesting a 10% increase in wind-speed associated with a 30–40% increase in damages (e.g., Strobl, 2012). Investigations into the economic impact of past cyclone events is less common, as these are much more difficult to identify. Examples of such work include Strobl (2012) on hurricane impacts in the Caribbean, Haque and Jahan (2016) on TC Sidr in Bangladesh, Jakobsen (2012) on Hurricane Mitch in Nicaragua, and Taupo and Noy (2017) on TC Pam in Tuvalu. The relation between changes in tropical cyclones and property losses is complex, and there are indications that wind shear changes may have larger impact than changes in global temperatures (Wang and Toumi, 2016). With regard to loss of life, total fatalities and mortality from cyclone-related coastal flooding is globally declining, probably as a result of improved forecasting and evacuation (Paul, 2009; Lumbroso et al., 2017; Bouwer and Jonkman, 2018). A global analysis finds that despite adaptation efforts, further sea-level rise could increase storm surge mortality in many parts of the developing world (Lloyd et al., 2016).

An assessment of future changes in coastal impacts based on direct downscaling of indicators of flooding such as total water level and number of hours per year with breakwater overtopping over a given threshold for port operability is provided by Camus et al. (2017). These indicators are multivariable and include the combined effect of sea level rise, storm surge, astronomical tide and waves. Regional projected wave climate is downscaled from global multimodel projections from 30 CMIP5 model realizations. For example, projections by 2100 under the RCP8.5 scenario shows a spatial variability along the coast of Chile with port operability loss between 600–800 h yr^{-1} and around 200 h yr^{-1} relative to present (1979–2005) conditions. Although wave changes are included in projected overtopping distributions, future changes of operability are mainly due to the sea level rise contribution.

6.3.5 Risk Management and Adaptation

The most effective risk management strategy in the last few decades has been the development of early warning systems for cyclones (Hallegatte, 2013). Generally, however, a lack of familiarity with the changed nature of storms prevails. Storm surge, for example, has become the world's most deadly and destructive natural hazard (Needham et al., 2015). Powerful storms can sometimes generate record storm surges, such as in the cases of Cyclone Nargis and Typhoon Haiyan but surge warnings had been less well understood and followed because they had tended to be new or rare to the locality (Lagmay et al., 2015). A US study on storm surge warnings highlights the issue of the right timing to warn, as well as the difficulty in delivering accurate surge maps (Morrow et al., 2015). Previous experience with warnings that were not followed by hazard events show the "crying wolf" problem leading many to choose to ignore future warnings (Bostrom et al., 2018).

There is scant literature on the management of storms that follow less common trajectories. The most recent and relatively well-studied ones are Superstorm Sandy in 2012 in the US and Typhoon Haiyan in 2013 in the Philippines. These two storms were unexpected and people, having underestimated the levels of impact, ignored warnings and evacuation directives. In the case of Typhoon Haiyan, the dissemination of warnings via scripted text messages were ineffective without an explanation of the difference between Haiyan's accompanying storm surge and that of other 'normal' storms to which people were used to (Lejano et al., 2016). Negative experiences of previous evacuations also lead to the reluctance of authorities to issue mandatory evacuation orders, e.g., during Superstorm Sandy (Kulkarni et al., 2017). They contribute to a preventable high number of casualties (Dalisay and De Guzman, 2016).

Coordination of different organizations is typically cited as a problem in the immediate disaster response (Abramson and Redlener, 2013). The lack of coordination is seen among different government agencies, such as in the US between the Federal Emergency Management Agency and Housing and Urban Development (Olshansky and Johnson, 2014); between government and international and national nongovernmental organizations offering response services (Santiago et al., 2016); between the different non-governmental organizations where the institutional capacity of the government is weaker; and among the government and self-organized volunteers that use more flexible bottom-up tools such as participatory mapping and social media (Wridt et al., 2016).

After the storms, retreat or rebuild options exist. Buyout programs, a form of 'managed retreat' gained traction in recent years as a potential solution to reduce exposure to changing storm surge and flood risk. The decision to retreat or rebuild *in situ* depends, at least partially, on how communities have recovered in the past and therefore on the perceived success of a future recovery (Binder, 2014). However, political and jurisdictional conflicts between local, regional, and national government over land management responsibilities, lack of coordinated nation-wide adaptation plans, and clashes among individual and community needs have led to some buyouts becoming unpopular in the case of the program after Hurricane Sandy (Boet-Whitaker, 2017). Relocation (i.e., managed retreat) is often very controversial, and can incur significant political risk even when it is in principle voluntary (Gibbs et al., 2016), and is rarely implemented with much success at larger scales (Beine and Parsons, 2015; Hino et al., 2017). In addition, managed retreats are often fraught with legal, distributional and human-rights issues, as seen in the case of resettlements after Typhoon Haiyan (Thomas, 2015).

If rebuilding *in situ* is pursued after catastrophic events and without decreased exposure, it is often accompanied by actions that aim to reduce vulnerability in order to adapt to the increasing risk (Harman et al., 2013). In many cases, resilient designs and sustainable urban plans integrating climate change concerns, that are inclusive of vegetation barriers as coastal defences, are considered (Cheong et al., 2013; Saleh and Weinstein, 2016). But, often more hard-defence structures that are known to be less sustainable in the longer-term, but potentially more protective in the short-term, are constructed (Knowlton and Rotkin-Ellman, 2014; Rosenzweig and Solecki, 2014).

6.4 Marine Heatwaves and their Implications

IPCC WGI AR5 concluded that it is *virtually certain* that the surface and upper ocean (above 700 m) has warmed from 1971 to 2010 (Rhein et al., 2013), and that global ocean temperatures are projected to further increase during the 21st century (Collins et al., 2013). For an update on observed and projected long-term global changes in ocean temperature, the reader is referred to Chapter 5. In addition to the long-term ocean warming trend, changes in ocean temperatures also manifest in short-term extreme water temperatures, so-called marine heatwaves (MHWs). MHWs are characterized by ocean temperatures that are extremely warm for days to months (see SROCC Glossary; Hobday et al., 2016a), can extend up to thousands of kilometres (Scannell et al., 2016) and can penetrate multiple hundreds of metres into the deep ocean (Benthuysen et al., 2018). Unlike the effects of atmospheric heatwaves on terrestrial and human systems, and with the exception of tropical coral reef systems (Gatusso et al., 2014) and intertidal systems (Wethey et al., 2011), little focus has been given to MHWs and their effects on physical, natural and human systems in AR5 (IPCC, 2013; IPCC, 2014) and SREX (IPCC, 2012).

6.4.1 Observations and Key Processes, Detection and Attribution, Projections

6.4.1.1 Recent Documented Marine Heatwave Events and Key Driving Mechanisms

MHWs have been observed and documented in all ocean basins over the last few decades (Figure 6.3a). One of the first documented MHW was the “Mediterranean Sea 2003” MHW (Garrabou et al., 2009; Galli et al., 2017) with sea water temperatures 1°C–3°C above the climatological mean from June to August in 2003 (Olita et al., 2007). The “Western Australian 2011” MHW was characterized by record high SSTs of up to 5°C that persisted for more than 10 weeks in early 2011 from Ningaloo (22°S) to Cape Leeuwin (34°S) off the coast of Western Australia (Pearce and Feng, 2013; Wernberg et al., 2013; Benthuysen et al., 2014; Caputi et al., 2016; Perkins-Kirkpatrick et al., 2016). The “Northwest Atlantic 2012” MHW led to the highest SSTs recorded (1°C–3°C above normal) in 150 years of measurements in the first half of 2012 off the US East Coast from the Gulf of Maine to Cape Hatteras (Mills et al., 2013; Chen et al., 2014; Pershing et al., 2015; Zhou et al., 2015). Between 2013 and 2015, the Northeast Pacific had the largest MHW ever recorded (often called ‘The Blob’; Bond et al., 2015), with maximum SST anomalies of 6.2°C off Southern California (Jacox et al., 2016; Gentemann et al., 2017; Rudnick et al., 2017) and subsurface warm anomalies in the deep British Columbia Fjord that persisted through the beginning of 2018 (Jackson et al., 2018). The Gulf of Alaska experienced record-setting warming with peak SSTs of 6.1°C above the 1981–2010 climatology during the cold season of 2015/2016 (Walsh et al., 2017; Walsh et al., 2018). The “Tasman Sea 2015/16” MHW lasted for 251 days with maximum SSTs of 2.9°C above the 1982–2005 average (Oliver et al., 2014b; Oliver et al., 2017). The “Coastal Peruvian 2017” MHW developed in early 2017 with a strong shallow ocean warming of up to 10°C off the northern coast of Peru. MHWs also occurred over the western Pacific Warm Pool including the Coral Sea and the Indonesian-Australian Basin in 1998, 2010, 2014–2017 (Hughes et al., 2017b; Le Nohaïc et al., 2017; Benthuysen et al., 2018), and in the Yellow Sea in August 2016 with sea surface temperatures 2°C–7°C higher than normal (Korea Meteorological Administration, 2016; Kim and Han, 2017).

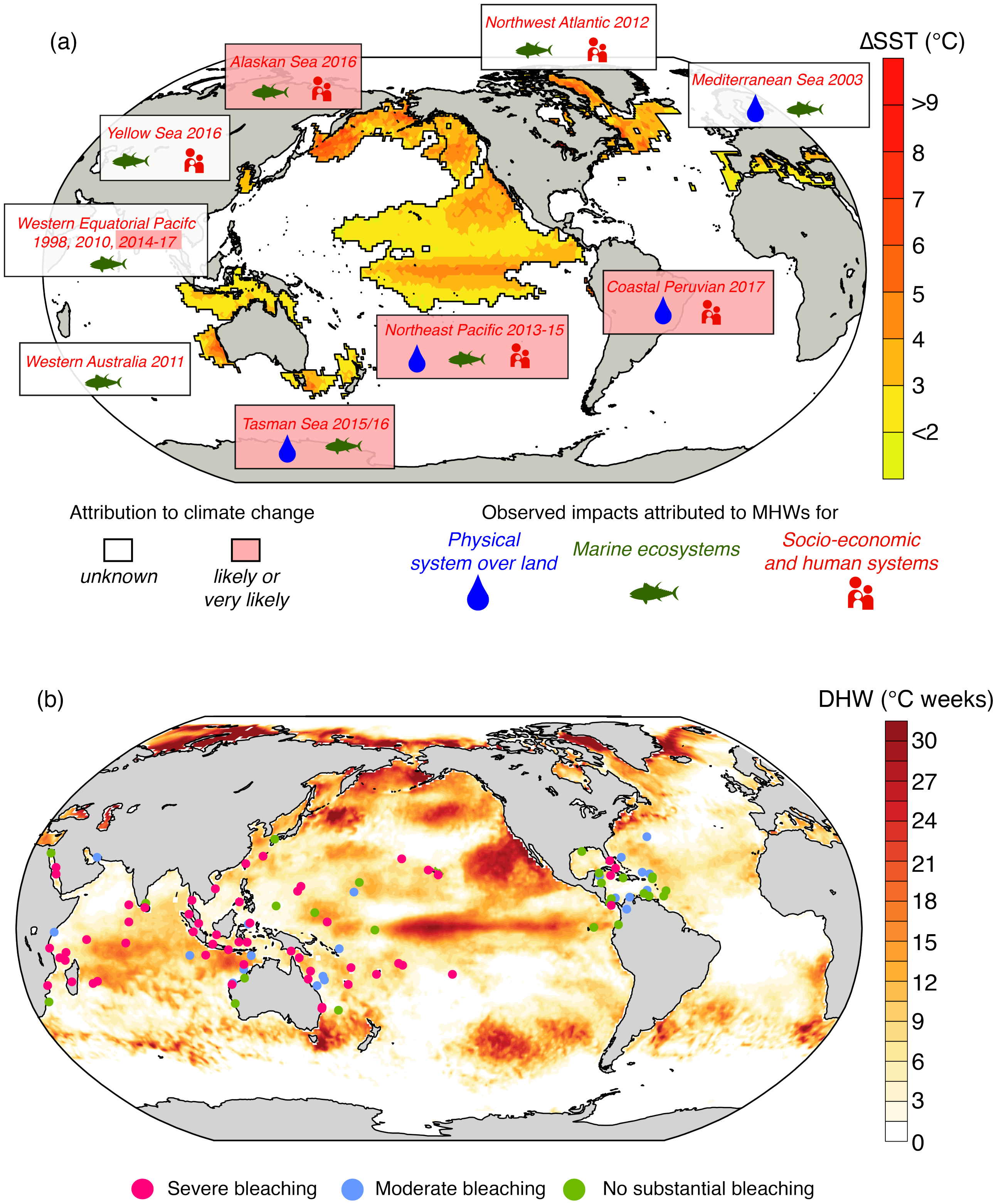


Figure 6.3: Recent marine heatwaves and their documented impacts. (a) Documented marine heatwaves (MHWs) over the last two decades and their impacts. The colour map shows the maximum sea surface temperature anomaly using the National Oceanic and Atmospheric Administration's (NOAA) daily Optimum Interpolation sea surface temperature dataset (Reynolds et al., 2007; Banzon et al., 2016). A MHW is defined specifically here as a set of spatially and temporally coherent grid points exceeding the 99th percentile. The 99th percentile is calculated over the 1982–2016 reference period after de-seasonalizing the data. Red shading of the boxes indicates if the likelihood of MHW occurrence has increased due to climate change, and symbols denote observed impacts on physical systems over land, marine ecosystems, and socio-economic and human systems. Figure is updated from Frölicher and Laufkötter (2018). (b) The record-warming years 2015 and 2016 and the global extent of mass bleaching of corals during these years. The colour map shows the Degree Heating Week (DHW) annual maximum over 2015 and 2016 from NOAA's Coral Reef Watch Daily Global 5 km Satellite Coral Bleaching Heat Stress Monitoring Product Suite v.3.1 (Liu et al.,

2014). The DWH is the most commonly used bleaching risk metric and is the accumulation of temperature anomalies exceeding the maximum of the local monthly mean sea surface temperature by 1°C. Symbols show 100 reef locations that are assessed in Hughes et al. (2018a) and indicate where severe bleaching affected more than 30% of corals (green circles), moderate bleaching affected less than 30% of corals (purple circles), and no substantial bleaching recorded (blue circles).

The dominant ocean and/or atmospheric processes leading to the build-up, persistence and decay of MHWs vary greatly among the individual MHWs and depend on the location and season of occurrence (Pearce and Feng, 2013). MHWs may be associated with large-scale modes of climate variability, such as ENSO, Indian Ocean Dipole, North Pacific Oscillation and North Atlantic Oscillation (Benthuysen et al., 2014; Bond et al., 2015; Chen et al., 2015b; Di Lorenzo and Mantua, 2016). These modes can change the strength, direction and location of ocean currents that build up areas of extreme warm waters, or they can change the air-sea heat fluxes, leading to a warming of the ocean surface from the atmosphere. For example, predominant La Niña conditions in 2010 and 2011 strengthened and shifted the Leeuwin Current southward along the west coast of Australia leading to the Western Australia 2011 MHW (Pearce and Feng, 2013; Kataoka et al., 2014). The Northeast Pacific 2013–2015 MHW emerged in 2013 in response to teleconnections between the North Pacific and the weak El Niño that drove strong positive sea level pressure anomalies across the Northeast Pacific inducing a smaller heat loss from the ocean (Bond et al., 2015; Di Lorenzo and Mantua, 2016) while low sea ice concentrations in the Arctic may have also played a role (Lee et al., 2015a). The build-up and decay of extreme warm SSTs may also be caused by small-scale atmospheric and oceanic forcing, such as ocean mesoscale eddies or local atmospheric weather (Carrigan and Puotinen, 2014; Schlegel et al., 2017a; Schlegel et al., 2017b). For example, the Tasman Sea 2015/16 MHW was caused by enhanced southward transport in the East Australian current driven by increased wind stress curl across the mid-latitude South Pacific (Oliver and Holbrook, 2014; Oliver et al., 2017) with local downwelling-favourable winds also having played a role for the subsurface intensification of the MHW (Schaeffer and Roughan, 2017). In addition, the 2016 MHW in the southern part of the Great Barrier Reef was mitigated by the extratropical cyclone Winston that passed over Fiji on February 20th. The cyclone caused strong winds, cloud cover and rain, which lowered sea surface temperature and prevented corals from bleaching (Hughes et al., 2017b).

6.4.1.2 Detection and Attribution of Marine Heatwave Events

The upper ocean has significantly warmed in most regions over the last few decades, with anthropogenic forcing *very likely* being the main driver (Bindoff et al., 2013). Concomitant with the long-term ocean warming trend, satellite observations and in-situ measurements reveal that MHWs have *very likely* increased since 1925 (Oliver et al., 2018a). Over the satellite period between 1982 and 2016, the number of MHW days exceeding the 99th percentile, calculated over the 1982–2016 period, has doubled globally, from about 2.5 to 5 heatwave-days per year (*high confidence*) (Frölicher et al., 2018; Oliver et al., 2018a). As a result of the record global warm sea surface temperatures in 2015 and 2016 (NOAA National Centers for Environmental Information, 2018), a quarter of the surface ocean experienced either the longest or most intense marine heatwave since 1982 in 2015/2016 (Hobday et al., 2016a; Figure 6.3b). Using a classification system to separate MHWs into categories (I-IV; depending on the level to which water temperature exceed local averages), Hobday et al. (2018) suggest that Category II MHW events have increased by 24 percent over the past 35 years. On a regional scale, MHWs have become more common in 38% of the world's coastal ocean over the last few decades (Lima and Wethey, 2012). In tropical reef systems, the interval between recurrent MHWs and associated coral bleaching events has diminished steadily since 1980 and is now only 6 years (it was 25 to 30 years in the early 1980s). The observed trend towards more frequent MHW days, defined relative to a fixed baseline period, is *very likely* due to long-term anthropogenic increase in mean ocean temperatures, with increases and decreases of MHW days during El Niño and La Niña years, respectively (Frölicher et al., 2018; Oliver et al., 2018a; Oliver et al., 2018b). This suggests that a further increase in the probability of MHWs under continued global warming can be expected (see section 6.4.1.3).

A few attribution studies have investigated if the likelihood of individual MHW events has changed to due anthropogenic warming (Weller et al., 2015). These studies show that most of the individual MHW events analysed have a clear human-induced signal (*medium confidence*) (Figure 6.3a). However, natural variability is still needed for the events to occur. On a global scale, about 90% of the occurrence of MHWs today are attributable to human-caused global warming (Fischer and Knutti, 2015; Frölicher et al., 2018). On a regional scale, the 2014 record-breaking high SST over the western tropical Pacific (Weller et al., 2015), the 2016 coral bleaching event in the Coral Sea (King et al., 2017), the Alaskan Sea 2016 MHW (Oliver et al., 2018b; Walsh et al., 2018), the MHW in Northern Australia in 2016 (Oliver et al., 2018b), the anomalously warm SST in the central equatorial Pacific in 2015/2016 and the extensive warming over the Great Barrier Reef in 2016 (Lewis and Mallela, 2018; Newman et al., 2018) have nearly been all fully attributed to anthropogenic forcing. In other words, such events are very rarely found or absent in preindustrial climate model simulations. In the California Current Large Marine Ecosystem, anthropogenic global warming also contributed to the increased likelihood of extreme ocean temperatures between 2014 and 2016 (Jacox et al., 2018), and the Northeast Pacific MHW in 2014 has become about five times more likely with human-caused global warming (Wang et al., 2014a; Kam et al., 2015; Weller et al., 2015). The duration and intensity of the MHW in the Tasmanian Sea were much more likely with anthropogenic climate change than without (Oliver et al., 2017).

6.4.1.3 Future Changes

Marine heatwaves will *very likely* increase in frequency, duration, spatial extent and intensity under future global warming (Oliver et al., 2017; Ramírez and Briones, 2017; Alexander et al., 2018; Darmaraki et al., 2018; Frölicher et al., 2018; Frölicher and Laufkötter, 2018). Projections based on twelve CMIP5 Earth system models suggest that, on global scale and under a global warming of 1.5°C relative to preindustrial levels, the probability of MHWs exceeding the preindustrial 99th percentile will increase by a factor of 16 (intermodel range: 11–24; Figure 6.4a; Frölicher et al., 2018). In other words, a one-in-hundred-day event at preindustrial levels is projected to become a one-in-six-day event at 1.5°C global warming. The probability of MHWs will increase by a factor of 23 (intermodel range: 16–31; a one in-four-day event) if warming is kept below 2°C, and by a factor of 41 (intermodel range: 36–45; a one in-two-day event) if warming is 3.5°C relative to preindustrial levels. The average spatial extent of a MHW is 21-times (15–29) bigger at 3.5°C global warming than at preindustrial; i.e., the typical spatial extent increases from $4.2 \cdot 10^5$ km^2 to $94.5 \cdot 10^5$ km^2; the duration is 112 days (92–129 days) and the maximum intensity is 2.5°C (2.1°C–2.9°C).

The changes in MHW characteristics will not be globally uniform. CMIP5 models project that the largest changes in the probability of MHWs will occur in the Arctic Ocean and the western tropical Pacific (Figure 6.4b), and that most of the Large Marine Ecosystems (Alexander et al., 2018; Frölicher et al., 2018) are projected also to experience large increase in the number of MHW days. In addition, MHW events in the Great Barrier Reef, such as the one associated with the bleaching in 2016, are projected to be at least twice as frequent under 2°C global warming than they are today (King et al., 2017). However, the projected changes at the regional to local scale are uncertain as CMIP5-type models produce different responses, due partly to issues of horizontal and vertical resolution. Only a few studies have used higher resolution models to assess the changes in MHW characteristics. For example, regional high-resolution coupled climate model simulations suggest that the Mediterranean Sea will experience at least one long lasting MHW every year by the end of the 21st century under the RCP8.5 scenario (Darmaraki et al., 2018), and eddy-resolving ocean model simulations project a further increase in the likelihood of extreme temperature events in the Tasman Sea (Oliver et al., 2014a; Oliver et al., 2015; Oliver et al., 2017).

Most of the global changes in the probability of MHWs, when defined relative to a fixed temperature climatology and using coarse resolution climate models, are driven by the global-scale shift in the mean ocean SST stemming from ocean warming (*medium confidence*) (Alexander et al., 2018; Frölicher et al., 2018). However, previously ice-covered regions, such as the Arctic Ocean, will exhibit larger SST variability under future global warming. This is because of an enhanced SST increase in summer due to sea-ice retreat, but SST remaining near the freezing point in winter (Carton et al., 2015; Alexander et al., 2018). When contrasting the changes in the probability of MHWs with land-based heatwaves (Fischer and Knutti, 2015), it is evident that MHWs are projected to occur more frequently (Frölicher et al., 2018; Frölicher and Laufkötter, 2018).

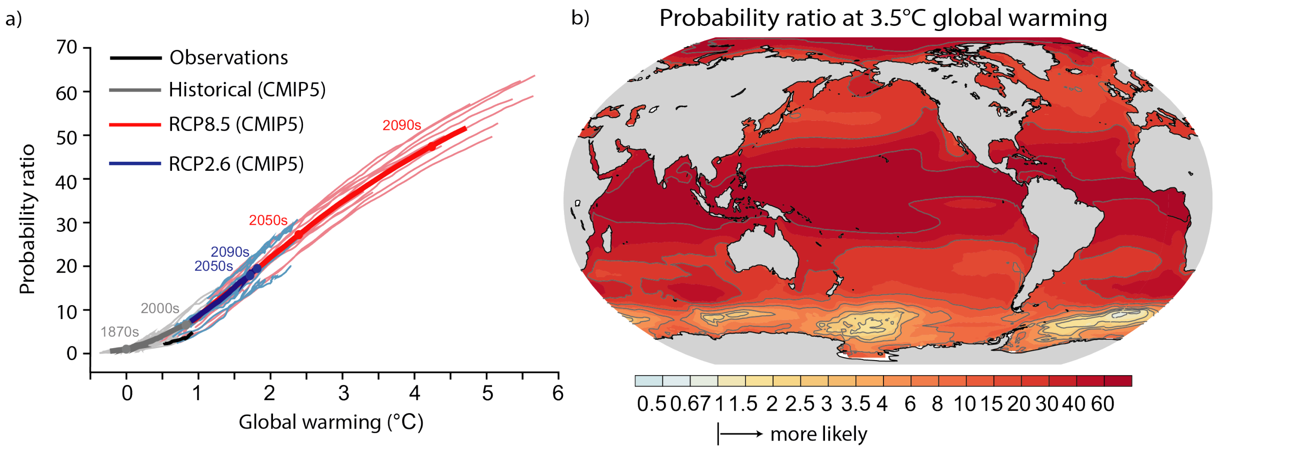


Figure 6.4: Global and regional changes in the probability of marine heatwave (MHW) days for different global warming levels relative to preindustrial conditions. (a) Changes in the probability of annual mean MHW days exceeding the 99th percentile of preindustrial local daily sea surface temperature for different levels of global surface atmospheric warming relative to pre-industrial conditions averaged over the ocean. The thinner lines represent individual projections from 12 CMIP5 models covering the 1861–2100 period, while the thicker lines represent the observations and the multi-model averages for the RCP8.5 and RCP2.6 scenarios, respectively. The simulated and observation-based time series are smoothed with a 30-year and 10-year running mean, respectively. (b) Simulated regional changes in the multi-model annual mean MHW days exceeding the preindustrial 99th percentile for a 3.5°C global warming level. The grey contours in (b) highlight the spatial pattern. Figure is modified from Frölicher et al. (2018).

6.4.2 Impacts on Physical, Natural and Human Systems

6.4.2.1 Impacts on Marine Organisms and Ecosystems

Recent marine heatwaves have strongly impacted marine ecosystems, including coral bleaching and mortality (Hughes et al., 2017b; Hughes et al., 2018a; Hughes et al., 2018b), shifts in species range (Smale and Wernberg, 2013), and local (Wernberg et al., 2013; Wernberg et al., 2016) and potentially global (Brainard et al., 2011) extinctions. However, our understanding of the response of marine organisms and ecosystems to MHWs, with the exception of coral reefs, is still limited and so far based on a few observations made during recent MHW events.

A growing number of studies have reported that MHWs negatively affect corals and coral reefs through bleaching, disease, and mortality (see chapter 5 for an extensive discussion on coral reefs and coral bleaching). The recent (2014–17) high ocean temperatures in the tropics and sub-tropics triggered a pan-tropical episode of unprecedented mass bleaching of corals (100s of km^2), the third global-scale event after 1997–98 and 2010 (Heron et al., 2016; Eakin et al., 2017; Hughes et al., 2017b; Eakin et al., 2018; Hughes et al., 2018a). The heat stress during this event was sufficient to cause bleaching at 75% of global reefs (Hughes et al., 2018a; Figure 6.3b) and mortality at 30% (Eakin et al., 2017), much more than any previously documented global bleaching event. In some locations, many reefs bleached extensively for the first time on record, and over half of the reefs bleached multiple times during the three-year event. However, there were distinct geographical variations in bleaching, mainly determined by the spatial pattern and magnitude of the MHW. For example, bleaching was extensive and severe in the northern regions of the Great Barrier Reef, with 93% of the northern Australian Great Barrier Reef coral suffering bleaching in 2016 (Hughes et al., 2017b), and impacts to corals were severe in the central equatorial Pacific at Jarvis with concomitant decreases in total reef fish biomass and seabirds. However, impacts were moderate only at nearby Howland, Baker and Kanton Islands (Brainard et al., 2018; Stuart-Smith et al., 2018).

Apart from strong impacts on corals, recent MHWs have demonstrated their potential impacts on other marine ecosystems (Ummenhofer and Meehl, 2017). Two of the best-studied MHWs with extensive ecological implications are the Western Australia 2011 MHW and the Northeast Pacific 2013-15 MHW. The Western Australia 2011 MHW resulted in an entire regime shift of the temperate reef ecosystem (Wernberg et al., 2013; Wernberg et al., 2016). The abundance of the dominant habitat-forming seaweeds *Scytohalia dorycara* and *Ecklonia radiata* became significantly reduced and *Ecklonia* kelp forest was replaced by small turf-forming algae with wide ranging impacts on associated sessile invertebrates and demersal fish. The sea grass *Amphibolis antarctica* in Shark Bay underwent defoliation after the MHW (Fraser et al., 2014) and together with the loss of other sea grass species lead to significant releases of organic carbon to the atmosphere (Arias-Ortiz et al., 2018). In addition, coral bleaching and effects on invertebrate fisheries were documented (Depczynski et al., 2013; Caputi et al., 2016). The Northeast Pacific 2013–2015 MHW also caused extensive alterations to open ocean and coastal ecosystems (Cavole et al., 2016). Impacts included increased mortality events of sea birds (Jones et al., 2018), salmon and marine mammals (Cavole et al., 2016), very low ocean primary productivity (Whitney, 2015; Jacox et al., 2016), an increase in warm-water copepod species (Di Lorenzo and Mantua, 2016), and novel species compositions (Peterson et al., 2017). In addition, a coast-wide bloom of the toxigenic diatom Pseudo-nitzschia resulted in the largest ever recorded outbreak of domoic acid poisoning along the North American west coast (McCabe et al., 2016). Stranded marine mammals had elevated toxins, which resulted in prolonged and geographically extensive closure of rock crab, razor clam, and crab fisheries.

Other MHWs also demonstrated the vulnerability of marine organisms to elevated ocean temperatures. The Northwest Atlantic 2012 MHW strongly impacted coastal ecosystems including a northward movement of warm-water species and local migrations of some species (e.g., lobsters) earlier in the season (Mills et al., 2013; Pershing et al., 2015). The Mediterranean Sea 2003 MHW lead to mass mortalities of macro-invertebrate species (Garrabou et al., 2009) and the Tasman Sea 2015/16 MHW had impacts on sessile, sedentary and cultured species in the shallow, near-shore environment including outbreaks of disease in commercially viable species (Oliver et al., 2017). *Vibrio* outbreaks were also observed in the Baltic Sea in response to elevated SSTs (Baker-Austin et al., 2013). The Alaskan Sea 2016 MHW favoured some phytoplankton species, leading to harmful algal blooms, shellfish poisoning events and mortality events in seabirds (Walsh et al., 2018)(see chapter 3 for more details). Also, lower-than-average size of multiple groundfish species were observed including pollock, Pacific cod, and Chinook salmon (Zador and Siddon, 2016). The Yellow Sea 2016 MHW killed a large number of marine species in part of the coastal and bay areas of South Korea (Korea Meteorological Administration, 2016). And the Coastal Peruvian 2017 MHW affected anchovies, which showed decreased fat content and early spawning as a reproductive strategy (IMPARPE, 2017), a behaviour usually seen during warm El Niño conditions (Ñiquen and Bouchon, 2004).

The examples described above indicate that a range of organisms and ecosystems can be impacted by MHWs. With MHWs predicted to increase with further climate warming, it is therefore *likely* that this will result in profound impacts on natural systems.

6.4.2.2 Impacts on the Physical System

Marine heatwaves can impact the weather patterns over land via teleconnections causing drought, heavy precipitation or heat wave events. The Northeast Pacific 2013–2015 MHW and the associated persistent atmospheric high-pressure ridge, for example, prevented normal winter storms from reaching the West Coast of the US and contributed to the drought conditions across the entire West Coast (Seager et al., 2015; Di Lorenzo and Mantua, 2016). The Tasman Sea 2015/16 MHW has increased the intensity of rainfall that caused flooding in northeast Tasmania in January 2016 (see Box 6.1) and the Coastal Peruvian 2017 MHW caused heavy rainfall and flooding on the west coast of tropical Southern American (ENFEN, 2017; Garreaud, 2018; Takahashi et al., 2018). Similarly, MHWs in the Mediterranean Sea can contribute to heatwaves (García-Herrera et al., 2010) and heavy precipitation events over central Europe (Messmer et al., 2017). Such physical changes may then also affect ecosystems on land (Reimer et al., 2015).

It should be noted that the effects of future changes in MHWs on weather patterns over land will depend not only on the MHW intensity but also on temperature gradients within the climate system, such as those associated with extreme ENSO events (see Section 6.5) or the mean climate (Jauregui and Takahashi, 2018). Therefore, it remains unclear how the projected increase in MHW intensity and frequency will impact the physical systems over land in the future.

6.4.2.3 Impacts on the Human System

Marine heatwaves can also lead to significant socio-economic ramifications when affecting aquaculture or important fishery species, or when triggering heavy rain or drought events on land (*medium confidence*).

The Northwest Atlantic 2012 MHW, for example, had major economic impacts on the US lobster industry (Mills et al., 2013), which is worth more than USD 620 million in 2015 (National Marine Fisheries Service, 2016). The MHW lead to changes in lobster fishing practices and harvest patterns, because the lobsters moved from the deep offshore waters into shallower coastal areas much earlier in the season than usual causing a rapid rise in lobster catch rates. Together with a supply chain bottleneck, the record catch outstripped market demand and contributed to a collapse in lobster prices (Mills et al., 2013). Even though high catch volumes were reported, the price collapse threatened the economic viability of many US and Canadian lobstermen. Economic impacts through changes in fisheries were also reported during the Northeast Pacific 2013–2015 MHW and the Alaskan Sea 2016 MHW. The Northeast Pacific 2013–2015 MHW lead to closing of both commercial and recreational fisheries resulting in millions of dollars in losses among fishing industries (Cavole et al., 2016). In addition, harmful algal blooms impacted not only tourism and recreation, but also other marine organisms (Berdalet et al., 2016; Du et al., 2016; McCabe et al., 2016) with cascading impacts on human health. The ingestion of such contaminated seafood products, the inhalation of aerosolized toxins or the skin contact with toxin-contaminated water may cause toxicity in humans. The ecological changes associated with the Alaskan Sea 2016 MHW impacted subsistence and commercial activities. Ice-based harvesting of seals, crabs and fish in western Alaska was delayed due to the lack of winter sea ice, which caused oyster farm closures.

MHWs can also impact the socio-economic and human system through changes to weather patterns. For example, heavy rain associated with the Coastal Peruvian 2017 MHW triggered numerous landslides and flooding, which resulted in a death toll of several hundred, widespread damage to infrastructure and civil works (United Nations, 2017).

6.4.3 Risk Management and Adaptation, Monitoring and Early Warning Systems

Risk management strategies to respond to MHWs include early warning systems as well as seasonal (weeks to months) and multi-annual predictions systems. Since 1997, the National Oceanic and Atmospheric Administration’s (NOAA) Coral Reef Watch has used SST satellite data to provide near real-time warning of coral bleaching (Liu et al., 2014). These satellite-based products, along with NOAA Coral Reef Watch’s 4-month coral bleaching outlook based on operational climate forecast models (Liu et al., 2018), and coral disease outbreak risk (Heron et al., 2010) provide critical guidance to coral reef managers, scientists, and other stakeholders (Tommasi et al., 2017b; Eakin et al., 2018). These products are also used to implement proactive bleaching response plans (Rosinski et al., 2017), brief stakeholders, and allocate monitoring resources in advance of bleaching events, such as the 2014–2017 global coral bleaching event (Eakin et al., 2017). For example, Thailand closed ten reefs for diving in advance of the bleaching peak in 2016, while Hawaii immediately began preparations of resources both to monitor the 2015 bleaching and to place specimens of rare corals in climate-controlled, onshore nurseries in response to these forecast systems (Tommasi et al., 2017b).

Seasonal SST predictions have also been used or will be used as early warning systems for multiple other ecosystems and fisheries in addition to coral reefs, including aquaculture, lobster, sardine, and tuna fisheries (Hobday et al., 2016b; Tommasi et al., 2017b). For example, seasonal forecasts of SST around Tasmania help farm managers of salmon aquaculture to prepare and respond to upcoming MHWs by changing stocking densities, varying feed mixes transferring fish to different locations in the farming region, and implementing disease management (Spillman and Hobday, 2014; Hobday et al., 2016b). Skilful multi-annual to decadal SST predictions may also improve many management and industry decisions, as well as long-term spatial planning decisions such as adjustments to quotas for internationally shared fish stocks (Tommasi et al., 2017a). It has been shown that global climate forecasts have significant skill in predicting occurrence of above average warm or cold SST events at decadal timescales in coastal areas (Tommasi et al., 2017a), but barriers to their widespread usage in fishery and aquaculture industry still exist (Tommasi et al., 2017b).

Even with a monitoring and prediction system in place, MHWs have developed without warning and had catastrophic effects. For example, governmental agencies, socioeconomic sectors, public health officials and citizens were not forewarned of the Coastal Peruvian 2017 MHW, despite a basin-wide monitoring system across the Pacific. The reason was partly due to an El Niño definition problem and a new government that may have hindered actions (Ramírez and Briones, 2017). Therefore, early warning systems should not only provide predictions of physical changes, but should also connect different institutions to assist decision makers in performing time-adaptive measures (Chang et al., 2013).

Monitoring and prediction systems are important and can be advanced by the use of common metrics to describe MHWs. So far, MHWs are often defined differently in the literature, and it is only recently that a categorizing scheme (Categories I to IV; based on the degree to which temperatures exceed the local climatology), similar to what is used for hurricanes, has been developed (Hobday et al., 2018). Such a categorizing scheme, can easily be applied to real data and predictions, and may facilitate comparison, public communication and familiarity with MHWs. Similar metrics (i.e., Degree Heating Weeks) have been used to identify ocean regions where conditions conducive to coral bleaching are developing.

6.5 Extreme ENSO Events and Other Modes of Interannual Climate Variability

6.5.1 Key Processes and Feedbacks, Observations, Detection and Attribution, Projections

6.5.1.1 Extreme El Niño, La Niña

IPCC AR5 (Christensen et al., 2013) and SREX do not provide a definition for an extreme El Niño but mention such events, especially in the context of the 1997/1998 El Niño and its impacts. SREX indicates that model projections of changes in ENSO variability and the frequency of El Niño events as a consequence of increased greenhouse gas concentrations are not consistent, and so there is *low confidence* in projections of changes in the phenomenon. Likewise, AR5 concluded that confidence in any specific change in ENSO variability in the 21st century is low. However, they did note that due to increased moisture availability, precipitation variability associated with ENSO is likely to intensify. There is limited body of literature that says anything about the impact of climate change on ENSO over the historical period.

Paleo-ENSO studies suggest that there were epochs of strong ENSO variability throughout the Holocene, with no evidence for a systematic trend in ENSO variance (Cobb et al., 2013) but with some indication that the ENSO variance over 1979–2009 has been much larger than that over 1590–1880 (McGregor et al., 2013). Further proxy evidence exists for changes in the mean state of the equatorial Pacific in the last 2000 years (Rustic et al., 2015; Henke et al., 2017). Simulations using an Earth System Model indicate significantly higher ENSO variance during 1645–1715 than during the 21st century warm period, though it is unclear whether these simulated changes are realistic (Keller et al., 2015). For the 20th century, the frequency and intensity of El Niño events were high during 1951–2000, in comparison with the 1901–1950 period (Lee and McPhaden, 2010; Roxy et al., 2014). Current observational records are not long enough to assert these changes with *high confidence* (Wittenberg, 2009; Stevenson et al., 2010).

Since SREX and AR5, a large El Niño event occurred in 2015/16. This has resulted in significant new literature regarding physical processes and impacts but there are no firm conclusions regarding the impact of climate change on the event. The SST anomaly peaked toward the central equatorial Pacific causing floods in many regions of the world such as those in the west coasts of the United States and other parts of North America, some parts of South America close to Argentina and Uruguay, the United Kingdom and China (Ward et al., 2014; Ward et al., 2016; Zhai et al., 2016; Scaife et al., 2017; Whan and Zwiers, 2017; Sun and Miao, 2018; Yuan et al., 2018).

The main new body of literature concerns future projections of the frequency of occurrence of extreme ENSO events with improved confidence (Cai et al., 2014a). In this report, we define extreme El Niño events as those El Niño events which are characterized by a pronounced eastward extension of the west Pacific warm pool and development of atmospheric convection, and hence a rainfall increase of greater than 5 mm per day during December-February (above 90th percentile), in the usually cold and dry equatorial eastern Pacific (Niño 3 region, 150°W–90°W, 5°S–5°N; Cai et al., 2014a)–such as the 1982/1983, 1997/1998 and 2015/2016 El Niños (Santoso et al., 2017; Figure 6.5).

The background long-term warming puts the 2015/2016 El Niño among the three warmest in the instrumental records (Huang et al., 2016; Santoso et al., 2017). The 2015/2016 event can be viewed as the first emergence of an extreme El Niño in the 21st century – one which satisfies the rainfall threshold definition, but not characterized by the eastward extension of the west Pacific warm pool (L'Heureux et al., 2017; Santoso et al., 2017).

A combination of strong ENSO and Indian Ocean Dipole (IOD) events lead to shifts in the Intertropical Convergence Zone (ITCZ; Freitas et al., 2017). El Niño events with strong eastern Pacific warming result in major shifts of the extreme equatorward swings of the South Pacific Convergence Zone (Borlace et al., 2014).

Based on the precipitation threshold, extreme El Niño frequency is projected to increase with the global mean temperatures with a doubling in the 21st century under RCP8.5, from about one event every 20 years during 1891–1990, to one every 10 years (Cai et al., 2014a; Figure 6.5). The increase in frequency continues for up to a century after global mean temperature has stabilized (Wang et al., 2017). Meanwhile, the La Niña events also tend to increase in frequency and double under RCP8.5 (Cai et al., 2015), but indicate no further significant changes after global mean temperatures have stabilized (Wang et al., 2017). Particularly concerning is that swings from extreme El Niño to extreme La Niña have been projected to occur more frequently under greenhouse warming (Cai et al., 2015). Further, CMIP5 models indicate that the risk of major rainfall disruptions has already increased for countries where the rainfall variability is linked to ENSO variability. This risk will remain elevated for the entire 21st century, even if substantial reductions in global greenhouse gas emissions are made. The increase in disruption risk is caused by anthropogenic warming that drives an increase in the frequency and magnitude of ENSO events and also by changes in background SST patterns (Power et al., 2013; Chung et al., 2014; Huang and Xie, 2015).

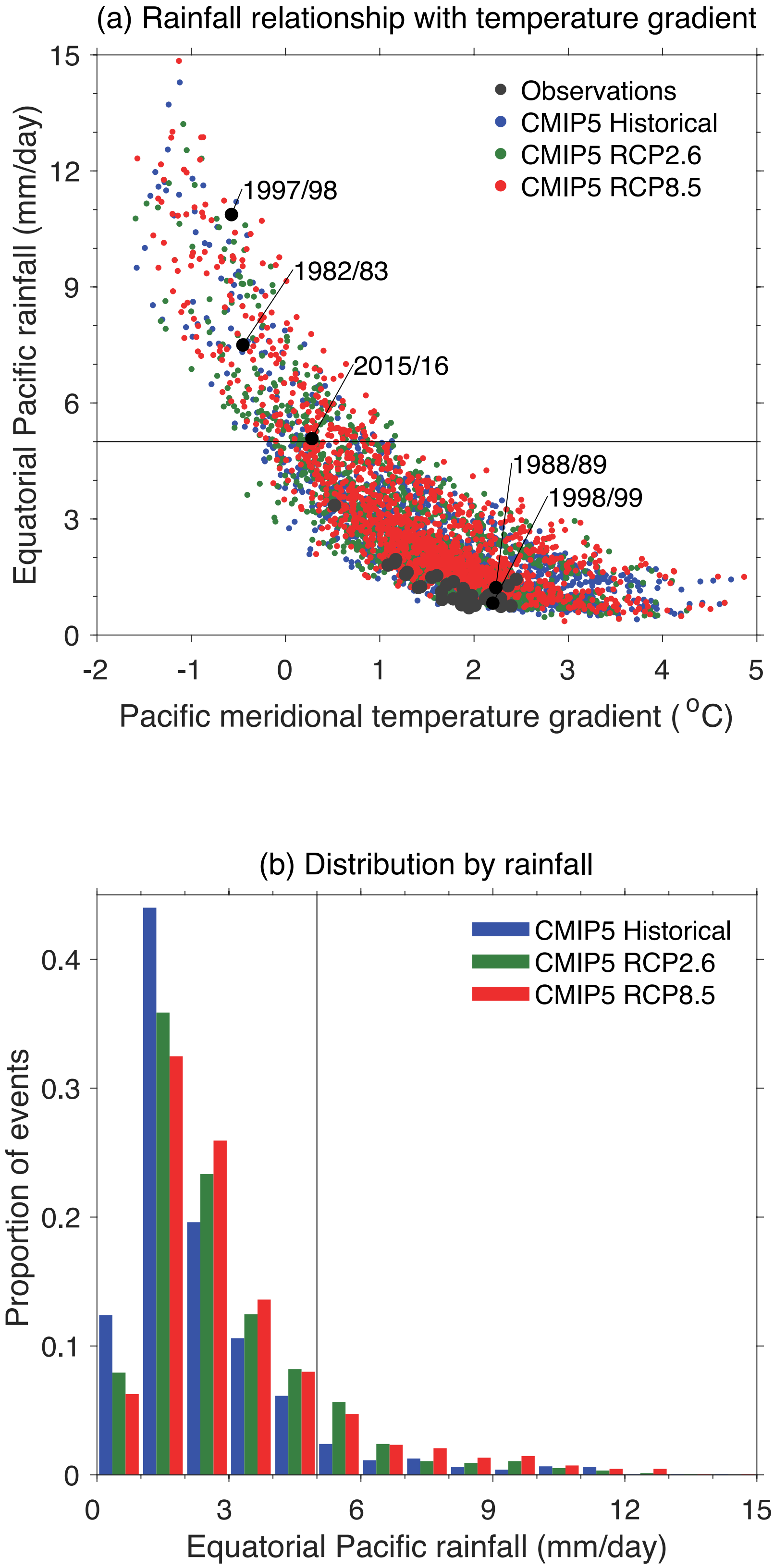


Figure 6.5: Frequency of extreme El Niño Southern Oscillation (ENSO) events, adapted from Cai et al. (2014a). In (a) the dots indicated Dec-Feb mean meridional sea surface temperature gradient (x-axis: 5°N–10°N, 210°E–270°E minus 2.5°S–2.5°N, 210°E–270°E) and equatorial Pacific anomalous rainfall (y-axis: 5°S–5°N, 210°E–270°E). Blue dots are from CMIP5 historical simulations, green dots from future RCP2.6 simulations and red dots from RCP8.5. Only output from those models that can simulate extreme El Niño events are shown. Black dots are from observations with extreme El Niño and extreme La Niña years indicated. The horizontal dashed line indicates the threshold of 5 mm per day for an extreme. The histograms in (b) show the relative frequency of events in historical (blue), RCP2.6 (green) and RCP8.5 simulations (red) highlighting the future increase in the frequency of extreme events.

6.5.1.2 Indian Ocean Basin-wide Warming and Changes in Indian Ocean Dipole (IOD) Events

The Indian Ocean has experienced consistent warming from the surface to 2000 m during 1960–2015, with most of the warming occurring in the upper 300 m (Cheng et al., 2015; Nieves et al., 2015; Cheng et al., 2017; Gnanaseelan et al., 2017). New historical ocean heat content (OHC) estimates show an abrupt increase in the Indian Ocean upper 700 m OHC after 1998, contributing to more than 28% of the global ocean heat gain, despite representing only about 12% of the global ocean area (Cheng et al., 2017). The tropical Indian Ocean SST has warmed by 1.04°C during 1950–2015, while the tropical SST warming is 0.83°C and the global SST warning is 0.65°C. More than 90% of the surface warming in the Indian Ocean has been attributed to changes in greenhouse gas emissions (Dong et al., 2014), with the heat redistributed in the basin via local ocean and atmospheric dynamics (Liu et al., 2015b), the Indonesian Throughflow (Susanto et al., 2012; Sprintall and Revelard, 2014; Lee et al., 2015b; Susanto and Song, 2015; Zhang et al., 2018), and the Walker circulation (Roxy et al., 2014; Abish et al., 2018).

The frequency of extreme positive IOD events is projected to increase by almost a factor of three, from one-in-seventeen-year event in the 20th century to a one-in-six-year event in the 21st century. However, the increase in IOD events is not linked to the change in the frequency of El Niño events but instead to mean state change—with weakening of both equatorial westerly winds and eastward oceanic currents in association with a faster warming in the western than the eastern equatorial Indian Ocean (Cai et al., 2014b).

6.5.2 Impacts on Human and Natural Systems, and Confounding Factors

Both ENSO and the IOD and other modes of variability are known to have widespread impacts on natural and human systems throughout the tropics and into some mid-latitude and polar regions and the occurrence of the extreme 2015/16 El Niño has produced a large body of literature. Impacts include tropical cyclone activity (Yonekura and Hall, 2014; Zhang and Guan, 2014; Wang and Liu, 2016; Zhan, 2017), marine ecosystems (Sanseverino et al., 2016; Mogollon and Calil, 2017; Ohman, 2017), bleaching of corals (Hughes et al., 2017a; Hughes et al., 2017b), forest fires (Christidis et al., 2018; Tett et al., 2018), air quality (Koplitz et al., 2015; Chang et al., 2016; Zhai et al., 2016), glacial growth and retreat (Thompson et al., 2017), human and animal diseases (Wendel, 2015; Caminade et al., 2017), agriculture (Iizumi et al., 2014) and destruction of property (French and Mechler, 2017). It is *likely* that the mosquito-borne Zika virus outbreaks over the South American continent during 2015–2016 were fuelled by the warm temperatures during the extreme El Niño event (Caminade et al., 2017). Nevertheless, much of what has been written does not concern how climate change may have altered such an impact, nor how such impacts might change in the future with increasing frequency of extreme ENSO events. Rather than provide an extensive assessment of the extensive literature on generic impacts of modes of variability, or the impacts of specific events, we highlight here some studies that have attempted to assess the joint impact of mean change and variability.

As a response to rising global ocean SSTs and partially due to extreme El Niño events, the northern hemisphere summer monsoon showed substantial intensification during 1979–2011, with an increase in rainfall by 9.5% per degree Celcius of global warming (Wang et al., 2013). However, the Indian summer monsoon circulation and rainfall exhibits a statistically significant weakening since the 1950s. This weakening has been hypothesised to be a response to the Indian Ocean basin-wide warming (Mishra et al., 2012; Roxy et al., 2015) and also to increased aerosol emissions (Guo et al., 2016) and changes in land use (Paul et al., 2016). Warming in the north Indian Ocean, especially the Arabian Sea, has resulted in increasing fluctuations in the southwest monsoon winds and a three-fold increase in extreme rainfall events across central India (Roxy et al., 2017). The frequency and duration of heatwaves have increased over the Indian subcontinent, and these events are associated with the Indian Ocean basin-wide warming and frequent El Niños (Rohini et al., 2016). In April 2016, as a response to the extreme El Niño, southeast Asia experienced surface air temperatures that surpassed national records, increased energy consumption, disrupted agriculture and resulted in severe human discomfort (Thirumalai et al., 2017).

ENSO events affect tropical cyclone activity through variations in the low-level wind anomalies, vertical wind shear, mid-level relative humidity, steering flow, the monsoon trough and the western Pacific subtropical high in Asia (Yonekura and Hall, 2014; Zhang and Guan, 2014). The subsurface heat discharge due to El Niño can intensify tropical cyclones in the eastern Pacific (Jin et al., 2014; Moon et al., 2015b).

Tropical Cyclones are projected to become more frequent (~20–40%) during future-climate El Niño events compared with present-climate El Niño events—and less frequent during future-climate La Niña events—around a group of small island nations (for example, Fiji, Vanuatu, Marshall Islands and Hawaii) in the Pacific (Chand et al., 2017). The Indian Ocean basin-wide warming has led to an increase in tropical cyclone heat potential in the Indian Ocean over the last 30 years, however the link to the changes in the frequency of tropical cyclones is not robust (Rajeevan et al., 2013).

During the early stages of an extreme El Niño event (2015/16 El Niño), there is an initial decrease in atmospheric CO_2 concentrations over the tropical Pacific Ocean, due to suppression of equatorial upwelling, reducing the supply of CO_2 to the surface (Chatterjee et al., 2017) —followed by a rise in atmospheric CO_2 concentrations due reduced terrestrial CO_2 uptake and increased fire emissions (Bastos et al., 2018). It is not clear how a future increase in the frequency extreme events would modulate the carbon cycle on longer decadal time scales.

Studies on projections of changes in ENSO impacts or teleconnections are rather limited. Nevertheless, Power and Delage (2018) provide a multi-model assessment of CMIP5 models and their simulated changes in the precipitation response to El Niño in the future (Figure 6.6). They identify different combinations of changes that might further impact natural and human systems. El Niño causes either positive or negative precipitation anomalies in diverse regions of the globe. Dry El Niño teleconnection anomalies may be further strengthened by, either mean climate drying in the region (Amazon, Central America and Australia in JJA), or a strengthening of the El Niño dry teleconnection, or both. Conversely, wet El Niño teleconections can be further strengthened by either increases in mean precipitation (East Africa and Southeastern South America in DJF) or a strengthening of the El Niño wet teleconnection (Southeastern South America in JJA), or both (Tibetan Plateau, DJF). However, a present day dry El Niño response may be dampened by a wet mean response (South, East and Southeast Asia in JJA) or a wet present day El Niño response may be weakened by a dry mean change (Southern Europe/Mediterranean and West Coast South America in JJA). Finally, changes in the mean and El Niño response may be opposite in sign (Southeast Asia, JJA and Central North America, DJF). Such changes could have an impact on phenomena such as wildfires (Fasullo et al., 2018). However, in many other regions that are currently impacted by El Niño, e.g., regions of South America, studies have found no significant changes in the ENSO-precipitation relationship (Tedeschi and Collins, 2017) and agreement between models for many regions suggests *low confidence* in projections of teleconnection changes (Yeh et al., 2018).

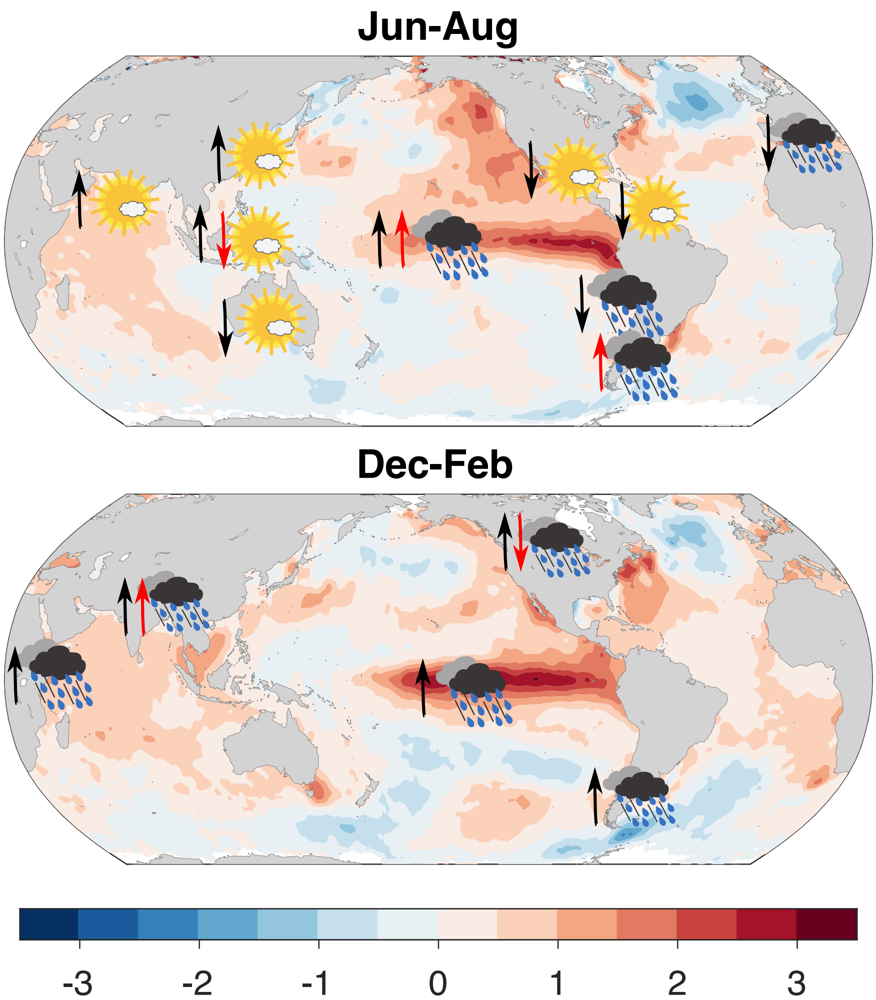


Figure 6.6: Schematic figure indicating future changes in El Niño teleconnections based on the study of Power and Delage (2018). The background pattern of sea surface temperature anomalies (°C) are averaged from June 2015 to August 2015 (panel a) and December 2015 to February 2016 (panel b), during the most recent extreme El Niño event (anomalies computed w.r.t. 1986–2005). Symbols indicate present-day teleconnections for El Niño events. Black arrows indicate if there is a significant change in mean rainfall in the region. Red arrows indicate if there is a significant change in the rainfall anomaly under a future El Niño event. Direction of the arrow indicates whether the response in precipitation is increasing (up) or decreasing (down). Significance is determined when two-thirds or more of the models agree on the sign.

6.5.3 Risk Management and Adaptation

Risk management of ENSO events has focussed on two main aspects: better prediction and early warning systems, and better mechanisms for reducing risks to agriculture, fisheries and aquaculture, wildfire and flood management, and so on. The seventh target of the Sendai Framework for disaster risk reduction 2015–2030 focuses on the substantial increase of the availability of early warning system and risk information, highlighting the importance of improved forecasting for disaster risk management to empower people to act. Extreme ENSO events are, however, rare with three such events since 1950 and they are difficult to predict due to the different drivers influencing them (Puy et al., 2017). The impacts of ENSO events also vary between events and between the different regions affected (Murphy et al., 2014; Fasullo et al., 2018; Power and Delage, 2018) however, there is limited literature on the change in the impacts of extreme ENSO compared to other ENSO events. Because of this, there are no specific risk management and adaptation strategies for human and natural systems for these extreme events other than what is in place for ENSO events (see also Chapter 4, section 4.4 for the response to sea level change, an observed impact of ENSO). A first step in risk management and adaptation is thus to better understand the impacts these events have and to identify conditions that herald such extreme events that could be used to better predict extreme ENSO events.

Monitoring and forecasting are the most developed ways to manage extreme ENSOs. Several systems are already in place for monitoring and predicting seasonal climate variability and ENSO occurrence. However, the sustainability of the observing system is challenging and currently the Tropical Pacific Observing System 2020 (TPOS 2020) has the task of redesigning such a system, with ENSO prediction as one of its main objectives. These systems could be further elaborated to include extreme ENSO events. There are potentially several indicators that could be included. There is evidence that westerly wind events (WWEs) in the Western Tropical Pacific affect the genesis of El Niño events (Lengaigne et al., 2004; Chen et al., 2015a; Fedorov et al., 2015). However, strong easterly wind events (EWEs) in the tropical Pacific have been observed to stall El Niño events (Hu and Fedorov, 2016), and the respective role of the EWEs and the absence of WWEs are still debated (Puy et al., 2017). Triggering of atmospheric deep convection leading to an enhancement of the feedbacks, and air-sea fluxes that are a source on non-linearity, also helps extreme El Niño development (Bellenger et al., 2014; Takahashi and Dewitte, 2016). Advection of mean temperature by anomalous eastward zonal currents that play an important role in producing extreme El Niño events, but not La Niña events, especially when it occurs during the early part of the developing period (Kim and Cai, 2014).

Despite the specificity of each extreme El Niño event, their forecasting is expected to improve through monitoring of recently identified precursory signals that peak in a window of two years before the event (Varotsos et al., 2016). Early warning system for coral bleaching associated, among other stressors, with extreme ENSO heat stress is provided by the NOAA Coral Reef Watch service with a 5 km resolution (Liu et al., 2018). The impacts of ENSO-associated extreme heat stress are heterogeneous, indicating the influence of other factors either biotic such as coral species composition, local adaptation by coral taxa reef depth or abiotic such as local upwelling or thermal anomalies (Claar et al., 2018). When identified and quantified, these factors can be used for risk analysis and risk management for these ecosystems.

In principle, it is easier to transfer the financial risk associated with extreme ENSO events through, for example, insurance products or other risk transfer instruments such as Catastrophe Bonds, than for more moderate events. An accurate prediction system is not required, but the measurement of these events, and quantification of likely impacts is required. As in other types of insurance systems, this can be done through, for example, calculations of Average Annual Losses (AAL) associated with extreme ENSO, and the design of appropriate financial instruments. Examples of research that can enable the design of risk transfer instruments include Anderson et al. (2018) and Gelcer et al. (2018) on specific crop yields in specific locations, Aguilera et al. (2018) and Broad et al. (2002) on specific fisheries. More broadly, other forms of risk management and governance can be designed with better information about the likely impacts of extreme ENSO events (e.g., Vignola et al., 2018).

6.6 Inter-Ocean Exchanges and Global Change

As highlighted in the previous section, interannual to decadal climate variability may be generated within ocean basins and this may be impacted by climate change or may regulate change at the global level. Exchanges of heat and fresh water between ocean basins are similarly important at the global scale and here we highlight one example that has received considerable attention in the literature since the publication of the IPCC AR5 report. That report included a box on ‘Climate Models and the Hiatus in Global-Mean Surface Warming of the Past 15 Years’ (Flato et al., 2013). Among the number of potential causes of this decadal variability in surface global temperature, a prolonged negative phase of the Pacific Decadal Oscillation/Interdecadal Pacific Oscillation (PDO/IPO) was suggested as a contributor. Because of the magnitude and duration of this Pacific-centred variability (Figure 6.7), it is identified as an extreme decadal climate event.

6.6.1 Key Processes and Feedbacks, Observations, Detection and Attribution, Projections: Strengthening of the Pacific Trade Winds

The period from around 2001–2014 saw a marked strengthening of both the easterly trade winds in the central equatorial Pacific (Figure 6.7) and the Walker circulation (L'Heureux et al., 2013; England et al., 2014). Both the magnitude and duration of this trend are large when compared with past variability reconstructed using atmosphere re-analyses. (The 1900–1920 ‘extreme event’ is poorly constrained by observations and we note the disparity between re-analysis products going back in time.) Moreover, it is very unusual when model simulations are used as an estimate of internal climate variability (Figure 6.7; England et al., 2014; Kociuba and Power, 2015). The slowdown in global surface warming is dominated by the cooling in the Pacific SSTs, which is associated with a strengthening of the Pacific trade winds (Kosaka and Xie, 2013). This pattern leads to cooling over land and possibly to additional heat uptake by the ocean, although recent studies suggest that ocean heat uptake may even slow down during surface warming slowdown periods (Xie et al., 2016; von Känel et al., 2017). The intensification of the Pacific trade winds has been related to inter-ocean basin SST trends, with rapid warming in the Indian (see section 6.5.1.2) and Atlantic Oceans both hypothesised as drivers (Kucharski et al., 2011; Luo et al., 2012; McGregor et al., 2014; Zhang and Karnauskas, 2017). While the extreme event of strengthening trade winds are potentially a result of natural internal variability, a role of anthropogenic contribution has not been ruled out. Nevertheless, the CMIP5 models indicate no general change in trends unto the future (Figure 6.7), giving more weight to natural internal variability as an explanation.

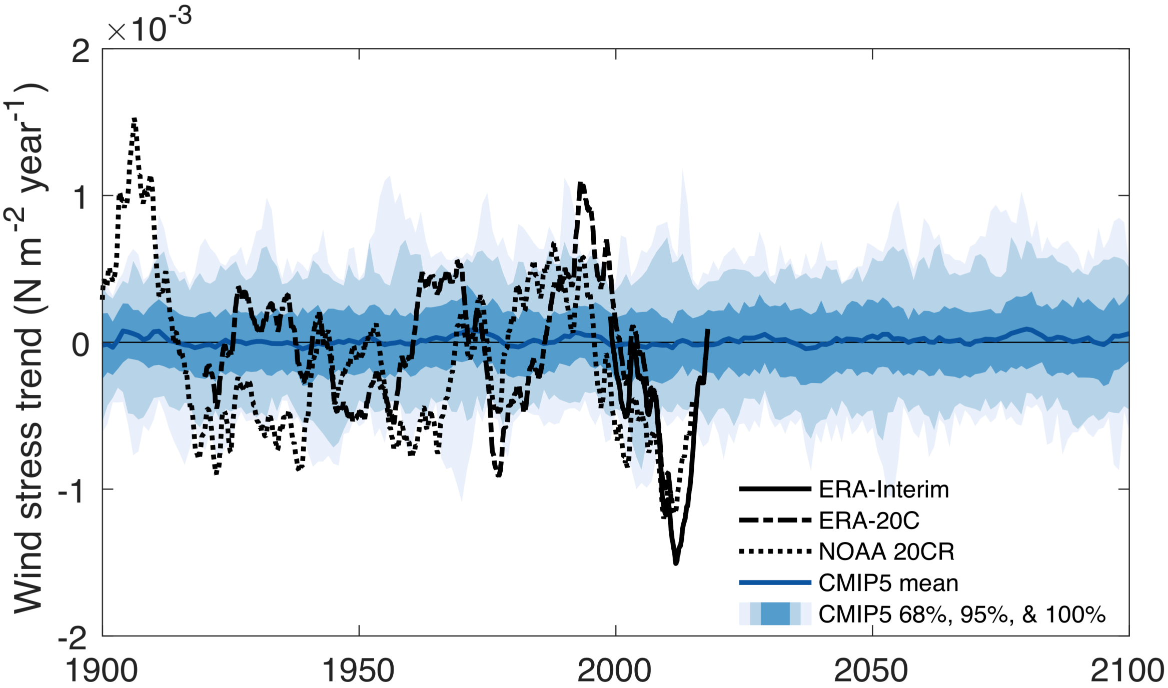


Figure 6.7: Running twenty-year trends of zonal wind stress over the central Pacific (area-averaged over 8°S–8°N and 160°E–150°W) in CMIP5 models and three re-analyses: European Centre for Medium-Range Weather Forecasts (ECMWF) Interim re-analysis, ERA-Interim (Dee et al., 2011), ECMWF 20th century reanalysis, ERA-20C (Poli et al., 2016), and the National Oceanic and Atmospheric Administration's 20th century reanalysis, NOAA 20CR v2c (Compo et al., 2011). The 68%, 95%, and 100% ranges of all-available CMIP5 historical simulations with RCP8.5 extension are shown.

One line of research has explored the role of the warm tropical Atlantic decadal variability in forcing the trade wind trends and associated cooling Pacific SST trends (Kucharski et al., 2011; McGregor et al., 2014; Li et al., 2016). It appears that climate models may misrepresent this link due to tropical Atlantic biases (Kajtar et al., 2018) and thus potentially underestimate global mean temperature decadal variability. Nevertheless, there is no indication that such an underestimation is evident in the models (Flato et al., 2013; Marotzke and Forster, 2015). The impact of modes of natural variability on global mean temperature decadal variability remains an active area of research.

The Pacific to Indian Ocean exchange or the Indonesian Throughflow (ITF) enables the transfer of mass, heat, salt and biogeochemical fluxes from the tropical Pacific Ocean to the eastern Indian Ocean through the complex topography and narrow passages of the Indonesian seas. The ITF annual average is 15 x 10^6 m^3 s^{-1} (Susanto, et al., 2012). However, during the extreme El Niño of 1997/1998, the ITF transport was reduced to 9.2 x 10^6 m^3 s^{-1} (Gordon et al., 1999). On seasonal time scale, the South China Sea Throughflow modulates the ITF and controls freshwater flux: enhances the ITF and freshwater flux during the boreal winter monsoon and reduces during the winter monsoon (Fang et al., 2010; Susanto et al., 2013). Due to lack of long-term sustained ITF observations, their impacts on Indo-Pacific climate varibility, biogeochemisty, ecosystem as well as society are not fully understood. Based on observations and proxy records from satellite altimetry and gravimetry, in the last two decades 1992–2012, ITF has been stronger (Sprintall and Revelard, 2014; Liu et al., 2015a; Susanto and Song, 2015), which translates to an increase in ocean heat-flux into the Indian Ocean (Lee et al., 2015b). ITF may have played a key role in the slowdown of the Pacific SST warming during 1998–2013, and the rapid warming in the surface and subsurface Indian Ocean during this period (section 6.5.1.2), by transferring warm water from western Pacific into the Indian Ocean (Lee et al., 2015b; Dong and McPhaden, 2018). Under 1.5°C warming both El Niño and La Niña frequencies may increase (see Section 6.5) and hence ITF variability may also increase. ITF is also influenced by the IOD events, with an increase in transport during a positive IOD and vice-versa during a negative IOD event (Potemra and Schneider, 2007; Pujiana et al., 2018). A negative IOD during the northern summer of 2016 resulted in an unprecedented 25–40% reduction in transport in the upper layer of ITF in the Makassar Strait, while the 2016 La Niña event played only a secondary role (Pujiana et al., 2018). Positive IODs are projected to increase by threefold in the 21st century as a response to changes in the mean state rather than changes in the El Niño frequency (Section 6.5.1.2; Cai et al., 2014b) and this may have an impact on the ITF, additional to the changes due to increasing extreme ENSO events. In response to greenhouse warming, climate models predict that on interannual and decadal time scales, the mean ITF may decrease (Sen Gupta et al., 2016). On long timescales (centennial to millennial variability) relatively little is known about Pacific – Indian Ocean Exchange.

In the Indian Ocean, an average 15 x 10^6 m^3 s^{-1} of water exits the Indonesian Seas, with most of it flowing westward along with the South Equatorial Current, and some supplying to the Leeuwin Current. The South Equatorial Current feeds the heat and biogeochemical signatures from the Indian Ocean into the Agulhas Current, which transports it further into the Atlantic Ocean. Observations of Mozambique Channel inflow from 2003 to 2012, measured a mean transport of 16.7 x 10^6 m^3 s^{-1} with a maximum in austral winter, and Indian Ocean Dipole-related interannual variability of 8.9 x 10^6 m^3 s^{-1} (Ridderinkhof et al., 2010). A multidecadal proxy, from three years of mooring data and satellite altimetry, suggests that the Agulhas Current has been broadening since the early 1990s due to an increase in eddy kinetic energy (Beal and Elipot, 2016). Numerical model experiments suggest an intensification of the Agulhas leakage since the 1960s, which has contributed to the warming in the upper 300 m of the tropical Atlantic Ocean (Lübbecke et al., 2015). Agulhas leakage is found to covary with the AMOC on decadal and multi-decadal timescales and has likely contributed to the AMOC slowdown (Biastoch et al., 2015; Kelly et al., 2016). Meanwhile, climate projections indicate that Agulhas leakage is likely to strengthen and may partially compensate the AMOC slowdown projected by coarse-resolution climate models (Loveday et al., 2015).

6.6.2 Impacts on Natural and Human Systems

The Pacific cooling pattern is often synonymous with predominance of La Niña events in the 2000s that had significant impacts on terrestrial carbon uptake via teleconnections. The reduced ecosystem respiration due to the smaller warming over land has significantly accelerated the net biome productivity and therefore increased the terrestrial carbon sink (Ballantyne et al., 2017) and paused the growth rate of atmospheric CO_2 despite increasing anthropogenic carbon emissions (Keenan et al., 2016). Also during the 2000s, the global ocean carbon sink has strengthened again (Fay and McKinley, 2013; Landschützer et al., 2014; Majkut et al., 2014; Landschützer et al., 2015; Munro et al., 2015), reversing a trend of stagnant or declining carbon uptake during the 1990s. It has been suggested that the upper ocean overturning circulation has weakened during the 2000s thereby decreased the outgassing of natural CO_2, especially in the Southern Ocean (Landschützer et al., 2015), and enhanced the global ocean CO_2 sink (DeVries et al., 2017). How this is connected to the global warming slowdown is currently unclear.

A dominant fraction of decadal variability in the North Pacific nutrient, chlorophyll and zooplankton taxa can be explained by the North Pacific Gyre Oscillation (NPGO) and/or Pacific Decadal Oscillation (PDO) (Di Lorenzo et al., 2013). Therefore, the hiatus may have had significant impacts on marine organisms and ecosystems, but literature is scarce.

6.7 Risks of Abrupt Change in Ocean Circulation and Potential Consequences

6.7.1 Key Processes and Feedbacks, Observations, Detection and Attribution, Projections

6.7.1.1 Observational and Model Understanding of AMOC Weakening

Paleo reconstructions indicate that the North Atlantic is a region where rapid climatic variations can occur (IPCC, 2013). Sinking of waters associated with deep convection induces a large-scale Meridional Overturning Circulation in the Atlantic (AMOC) which transports large amounts of heat northward across the hemispheres, explaining part of the difference in temperature between the two hemispheres, as well as the northward location of the Intertropical Convergence Zone (e.g., Buckley and Marshall, 2016). This circulation system is believed to be a key tipping point of the climate system (IPCC, 2013).

Considerable effort has been dedicated in the last decades to improve the observation system of the large-scale ocean circulation (e.g., Argo and its array of 3,800 free-drifting profiling floats), including the AMOC through dedicated large-scale observing arrays (at 16°N and 26°N, (McCarthy et al., 2015b), in the subpolar gyre, (Lozier et al., 2017), between Portugal and the tip of Greenland, (Mercier et al., 2015), around 30°S, (Meinen et al., 2013)). The strength of the AMOC at 26°N has been continuously estimated since 2004 with an annual mean estimate of $17 \pm 1.9 \times 10^6$ m^3 s^{-1} over the 2004–2017 period (Smeed et al., 2018), superimposed by large intra and interannual variability. The AMOC at 26°N has been 2.7×10^6 m^3 s^{-1} weaker since 2008 than in the first 4 years of measurement (Smeed et al., 2018). However, the record is not yet long enough to determine if there is a long-term decline of the AMOC. McCarthy et al. (2012) reported a 30% reduction in the AMOC in 2009–2010, followed by a weaker minimum a year later. Analysis of forced ocean models suggests such events may occur once every two or three decades (Blaker et al., 2015). At 34.5°S, the mean AMOC is estimated as 14.7×10^6 m^3 s^{-1} over the period 2009–2017 (Meinen et al., 2017) also with large interannual variability, while no trend has been identified at this latitude.

Estimates based on ocean reanalyses show considerable diversity in their AMOC mean state, and its evolution over the last 50 years (Karspeck et al., 2017; Menary and Hermanson, 2018), because only very few deep ocean observations before the Argo era, starting around 2004, are available. During the Argo era, the reanalyses agree better (Jackson et al., 2016).

Based on AMOC reconstruction using SST fingerprints, it has been suggested that the AMOC may have experienced around 3×10^6 m^3 s^{-1} of weakening (15% decrease) since the mid-20th century (Caesar et al., 2018). Paleo proxies also highlight that the historical era may exhibit an unprecedented low AMOC over the last 1600 years (Thornalley et al., 2018). Nevertheless, these proxy records have not been verified against instrumental AMOC observations so that considerable uncertainty remain concerning these results. Moreover, mechanisms for such a long term weakening are not known. Thus, *confidence* in a weakening AMOC over the historical is *low*.

Examination of 14 models from the CMIP5 archive, which do not take into account the melting (either from runoff, basal melting or icebergs) from Greenland ice sheet (cf. Section 6.7.1.2), led to the assessment that the AMOC is *very unlikely* to collapse in the 21st century in response to increasing greenhouse gas concentrations (IPCC, 2013). Nonetheless, the CMIP5 models agree that a weakening of the AMOC into the 21st century will lead to localised cooling (relative to the global mean) in the northern North Atlantic, although the precise location is uncertain (Menary and Wood, 2018).

Abrupt variations in sea surface temperature or sea ice have been found in 19 out of the 40 models of the CMIP5 archive (Drijfhout et al., 2015). Large cooling trends, which can occur in a decade, are found in the subpolar North Atlantic in 9 out of 40 models. It is found that the heat transport in the AMOC plays a role in explaining such a rapid cooling, but other processes are key for setting the rapid (decadal-scale) timeframe of subpolar gyre (SPG) cooling, notably vertical heat export in the ocean and interactions with sea ice and the atmosphere (Sgubin et al., 2017). Using the representation of stratification as an emergent constraint, rapid changes in subpolar convection and associated cooling are occurring in the 21st century in 5 of the 11 best models (Sgubin et al., 2017). The poor representation of ocean deep convection in most CMIP5 models has been confirmed in Heuze (2017), highlighting a *low confidence* in the projections of its fate.

The SPG system has been identified as a tipping point (Born et al., 2013), meaning that this circulation can change very abruptly between different stable steady states, due to positive feedback between convective activity and salinity transport within the gyre (Born et al., 2016). It has been argued that a transition between two SPG stable states can explain the onset of the Little Ice Age that may have occurred around the 14–15th century (Lehner et al., 2013; Moreno-Chamarro et al., 2017), while a few CMIP5 climate models showed a rapid cooling in the SPG within the 1970s cooling events, as a non-linear response to aerosols (Bellucci et al., 2017). The SPG therefore appears as a tipping element in the climate system, with a faster (decade) response than the AMOC (century), but with lower induced SST cooling.

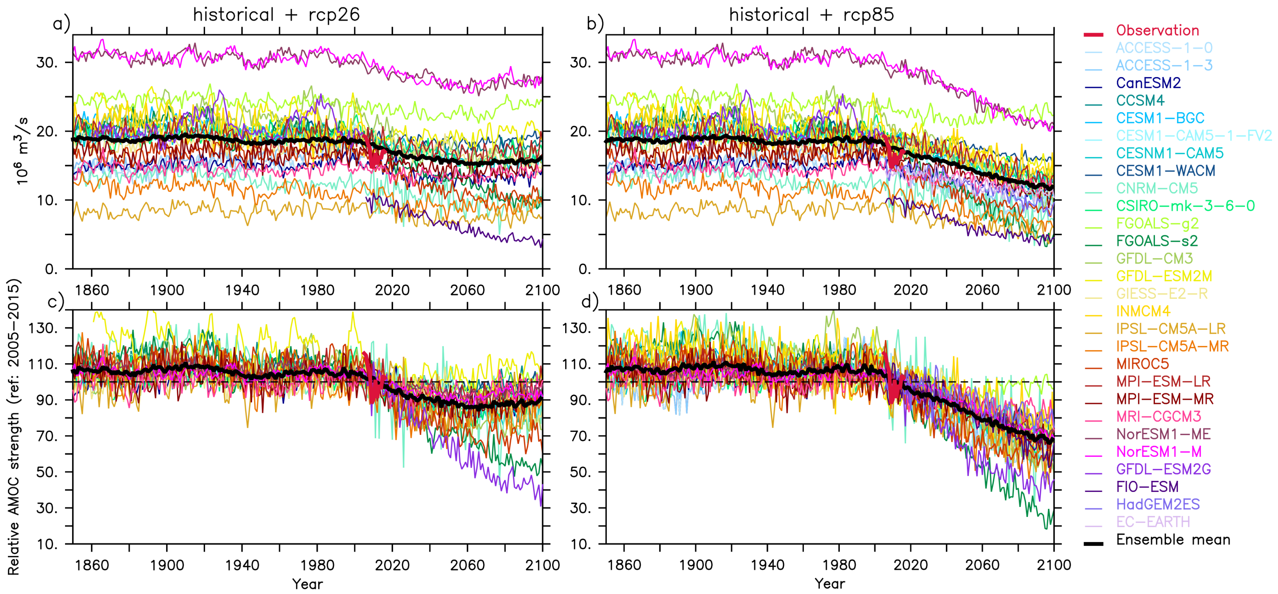


Figure 6.8: Atlantic Meridional Overturning Circulation (AMOC) changes at 26°N as simulated by 27 models (only 14 were shown in AR5; IPCC, 2013). The thick red line shows the observation-based estimate at 26°N (McCarthy et al., 2015b) and the thick black line the multi-model ensemble mean. Values of AMOC maximum at 26°N (in units 10^6 m^3 s^{-1}) are shown in historical simulations (most of the time 1850–2005) followed for 2006–2100 by a) RCP2.6 simulations and b) RCP8.5 simulations. In c) and d), the time series show the percentage of changes with reference period taken as 2005–2015, a period over which observations are available. c) shows historical followed by RCP2.6 simulations and d) shows historical followed by RCP8.5 simulations.

Evaluation of AMOC variations in CMIP5 database has been further analysed in this report (Figure 6.8) using almost twice as many models as in the AR5 assessment (IPCC, 2013). The AR5 assessment of a *very unlikely* AMOC collapse has been confirmed, although one model does show such a collapse (e.g., decrease larger than 80%) before the end of the century (Figure 6.8). Now based on up to 27 model simulations, the decrease of the AMOC is assessed to be of –1.8 ± 2.3 x 10^6 m^3 s^{-1} (–10 ± 13%) in 2090–2100 as compared 2005–2015 for RCP2.6 scenario and –5.5 ± 3.1 x 10^6 m^3 s^{-1} (–32 ± 18%) for RCP8.5 scenario. Furthermore, the uncertainty in AMOC changes has been shown to be mainly related to the spread in model responses rather than scenarios (RCP4.5 and RCP8.5) or internal variability uncertainty (Reintges et al., 2017). This behaviour is very different from the uncertainty in global sea surface temperature changes, which is mainly driven by emission scenario after a few decades (Frölicher et al., 2016). To explain the AMOC decline, a new mechanism has been proposed on top of the classical changes in heat and freshwater forcing (Gregory et al., 2016). A potential role for sea ice decrease has been highlighted (Sevellec et al., 2017), due to large heat uptake increase in the Arctic leading to a strong warming of the North Atlantic, increasing the vertical stability of the upper ocean.

6.7.1.2 Role of Greenland Ice Sheet Melting

The recent observed reduction in deep convection in the Labrador Sea has been associated with increased freshwater fluxes to the subpolar North Atlantic (Yang et al., 2016b). Satellite data indicate accelerated mass loss from Greenland ice sheet (GrIS) beginning around 1996, and freshwater contributions to the subpolar North Atlantic from Greenland, Canadian Arctic Archipelago glaciers and sea-ice melt totalling around 60,000 m^3 s^{-1} in 2013, a 50% increase since the mid-1990s (Yang et al., 2016b) in line with more recent estimates (Bamber et al., 2018). Over the same time period, there has been about a 50% decrease in Labrador Sea Water thickness, suggesting a possible relationship between enhanced freshwater fluxes and suppressed formation of North Atlantic Deep Water (Yang et al., 2016b). This hypothesis has been further supported by high-resolution ocean-only simulation showing that GrIS melting (Boning et al., 2016) may have affected the Labrador Sea convection since 2010, which may imply an emerging short-term impact of this melting on the AMOC. Thus, this melting may have affected the evolution of the AMOC over the 20th century, in line with Rahmstorf et al. (2015) and Yang et al. (2016b). Nevertheless, considerable variability and limitation in ocean models restrain the full validation of this hypothesis.

The impact of GrIS melting is neglected in AR5 projections (Swingedouw et al., 2013) but has been considered in a recent multi-model study (Bakker et al., 2016; Figure 6.9). GrIS melting estimates added in those simulations were based on the Lenaerts et al. (2015) approach, using a regional atmosphere model to estimate GrIS mass balance. Results from eight climate models and an extrapolation by an emulator calibrated on these models showed that GrIS melting has an impact on the AMOC, potentially adding up to around 5–10% more AMOC weakening in 2100 under RCP8.5. Concerning the question of the reversibility of the AMOC, a few ramp-up/ramp-down simulations have been performed to evaluate it for transient time scales (a few centuries, while millennia will be necessary for a full steady state). Results usually show a reversibility of the AMOC (Jackson et al., 2014; Sgubin et al., 2015) although the timing and amplitude is highly model dependent (Palter et al., 2018). An hysteresis behaviour of the AMOC in response to freshwater release has been found in a few climate models (Hawkins et al., 2011; Jackson et al., 2017) even at the eddy resolving resolution of ¼° (Mecking et al., 2016). The biases of present-day models in representing the transport at 30°S has been highlighted (Deshayes et al., 2013; Liu et al., 2017; Mecking et al., 2017) and may considerably affect the sensitivity of the models to freshwater release, but more on the multi-centennial time scale.

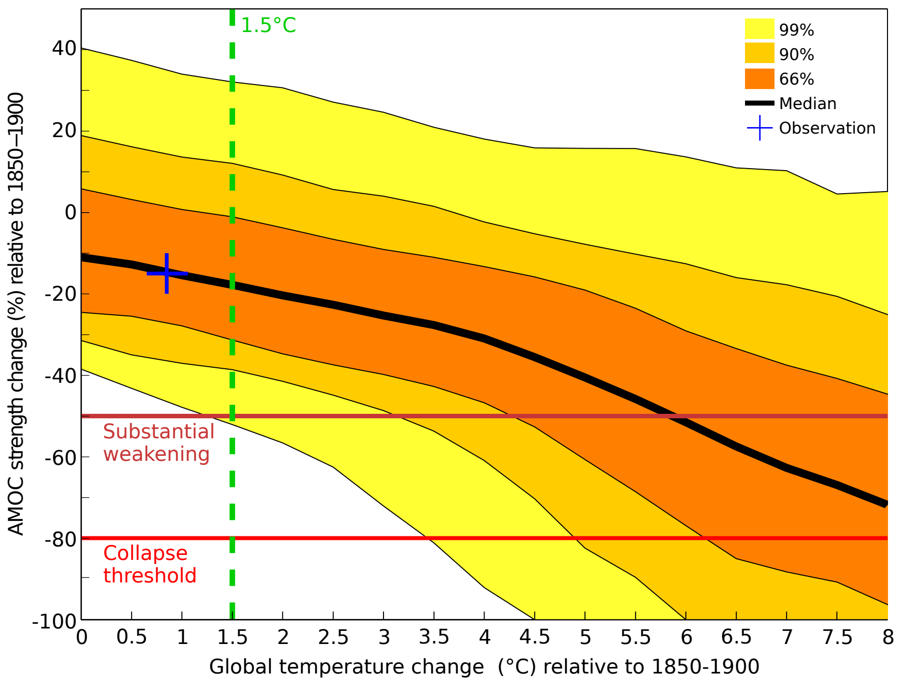


Figure 6.9: The changes in the Atlantic Meridional Overturning Circulation (AMOC) strength as a function of transient changes in global mean temperature. This probabilistic assessment of annual mean AMOC strength changes (%) at 26°N (below 500 m and relative to 1850–1900) as a function of global temperature change (Celcius; relative to 1850–1900) results from 10,000 RCP4.5 and 10,000 RCP8.5 experiments over the period 2006–2300, which are derived from an AMOC emulator calibrated with simulations from 8 climate models including Greenland Ice Sheet (GrIS) melting (Bakker et al., 2016). The annual mean AMOC strength changes are taken from transient simulations and are therefore not equilibrium values *per se*. Moreover, it should be stressed that the results stem from future runs, not past or historical runs. The ranges 66%, 90% and 99% correspond to the amount of simulations that are within each envelope. The thick black line corresponds to the ensemble mean, while the different colors stand for different probability quantiles. The horizontal red thick line corresponds to the value of 80% of AMOC decrease, which can be seen as an almost total collapse of the AMOC. The horizontal dark red thick line corresponds to a reduction of 50% of the AMOC, which can be considered as a substantial weakening. The horizontal dashed green line stands for the 1.5°C of global

warming threshold (relative to 1850–1900). The blue cross stands for the reduction estimate based on an AMOC reconstruction from Caesar et al. (2018). The size of the cross represents the uncertainty in this estimate.

Concerning the near-term changes of the AMOC, decadal prediction systems are now in place. They indicate a clear impact of the AMOC on the climate predictability horizon (Robson et al., 2012; Persechino et al., 2013; Robson et al., 2013; Wouters et al., 2013; Msadek et al., 2014; Robson et al., 2018), and indicate a possible weakening of the AMOC in the coming decade (Smith et al., 2013) but without accounting for melting of GrIS.

6.7.2 Impacts on Climate, Natural and Human Systems

Even though the AMOC remains *very unlikely* to collapse over the 21st century, its weakening may be substantial, which may therefore induce strong and large-scale climatic impacts with potential far-reaching impacts on natural and human systems (e.g., Good et al., 2018). Furthermore, the SPG subsystem has been shown to potentially shift, in the future, into a cold state over a decadal time scale, with lower amplitude but still very significant climatic implications.

The AR5 report concludes that based on paleo-climate data, large changes in the Atlantic Ocean circulation can cause worldwide climatic impacts (Masson-Delmotte et al., 2013), with notably, for an AMOC weakening, a cooling of the North Atlantic, a warming of the South Atlantic, less evaporation and therefore precipitation over the North Atlantic, and a shift of the ITCZ. Impacts of AMOC or SPG changes and their teleconnections in the atmosphere and ocean are supported by a large amount of paleo evidence (Lynch-Stieglitz, 2017). Such impacts and teleconnections have been further evaluated over the last few years both using new paleodata and higher resolution models. Furthermore, multi-decadal variations in sea surface temperature observed over the last century, the so-called Atlantic Multidecadal Variability (AMV) also provides observational evidence of potential impacts of changes in ocean circulation. Nevertheless, due to a lack of long-term direct measurements of the Atlantic Ocean circulation, the exact link between SST and circulation remains controversial (Clement et al., 2015; Zhang, 2017).

The different potential impacts of large changes in the Atlantic Ocean circulation are summarized in Figure 6.10. Based on variability analysis, it has been shown that a decrease in the AMOC strength has impacts on storm track position and intensity in the North Atlantic (Gastineau et al., 2016), with a potential increase in the number of winter storms hitting Europe (Woollings et al., 2012; Jackson et al., 2015). The influence on the Arctic sea ice cover has also been evidenced at the decadal scale, with a lower AMOC limiting the retreat of Arctic sea ice (Yeager et al., 2015; Delworth and Zeng, 2016). The climatic impacts could be substantial over Europe (Jackson et al., 2015), where an AMOC weakening can lead to high pressure over the British Isles in summer (Haarsma et al., 2015), reminiscent of a negative summer North Atlantic Oscillation (NAO), inducing an increase in precipitation in Northern Europe and a decrease in Southern Europe. In winter, the response of atmospheric circulation may help to reduce the cooling signature over Europe (Yamamoto and Palter, 2016), notably through an enhancement of warming maritime effect due to a stronger storm track (Jackson et al., 2015). The observed extreme low AMOC in 2009–2010, which was also seen in ocean heat content (Cunningham et al., 2013), has been suggested to be implicated in cold European weather events in winter 2009–2010 and December 2010 (Buchan et al., 2014) although a robust attribution is missing. In summer, cold anomalies in the SPG, like the one occurring during the so-called cold blob (Josey et al., 2018), have been suspected to potentially enhance the probability of heatwaves over Europe in summer (Duchez et al., 2016). Nevertheless, considerable uncertainties remain on this aspect due to lack of historical observations before 2004 and due to poor model resolution of small-scale processes related to frontal dynamics around the Gulf Stream region (Vanniere et al., 2017). In addition, oceanic changes in the Gulf Stream region may occur in line with AMOC weakening (Saba et al., 2016) with potential rapid warming due to a northward shift of the Gulf Stream. However, these changes are largely underestimated in coarse resolution models (Caesar et al., 2018).

Changes in ocean circulation can also strongly impact sea level in the regions bordering the North Atlantic (McCarthy et al., 2015a; Palter et al., 2018). A collapse of the AMOC or of the SPG could induce substantial increase of sea-level rise up to a few tens of centimetres along the western boundary of the North Atlantic (Ezer et al., 2013; Little et al., 2017; cf. Chapter 5). For instance, such a link may explain 30% of the extreme observed sea level rise event (a short-lived increase of 12 mm during 2 years) in northeast America in 2009–2010 (Ezer, 2015; Goddard et al., 2015). This illustrates that monitoring changes in AMOC may have practical implications for coastal protection.

The AMOC teleconnections are widespread and notably strongly affect the tropical area, as evidenced in paleodata for the Sahel region (Collins et al., 2017; Mulitza et al., 2017) and in model simulations (Jackson et al., 2015; Delworth and Zeng, 2016). These teleconnections may affect vulnerable populations. For instance, Defrance et al. (2017) found that a substantial decrease in the AMOC, at the very upper end of potential changes, may strongly diminish precipitation in the Sahelian region, decreasing the millet and sorghum emblematic crops production, which may impact subsistence of tens of millions of people, increasing their potential for migration. Smaller amplitude variations in Sahelian rainfall, driven by North Atlantic SST, has been found to be predictable up to a decade ahead (Gaetani and Mohino, 2013; Mohino et al., 2016; Sheen et al., 2017), potentially providing mitigation and adaptation opportunities. The number of tropical storms in the North Atlantic has been found to be very sensitive to the AMOC (Delworth and Zeng, 2016; Yan et al., 2017) as well as to the SPG (Hermanson et al., 2014) variations, so that a large weakening of the AMOC or cooling of the SPG may decrease the number of Atlantic tropical storms. The Asian monsoon may also potentially weaken in the case of large changes in the AMOC (Marzin et al., 2013; Jackson et al., 2015; Zhou et al., 2016) implying once again large impacts on population. The interactions of the Atlantic basin with the Pacific has also been largely discussed over the last few years, with a supposed influence of a cool North Atlantic inducing a warm Pacific (McGregor et al., 2014; Chafik et al., 2016; Li et al., 2016), although not found in all models (Swingedouw et al., 2017), which may induce stronger amplitudes of El Niño (Dekker et al., 2018).

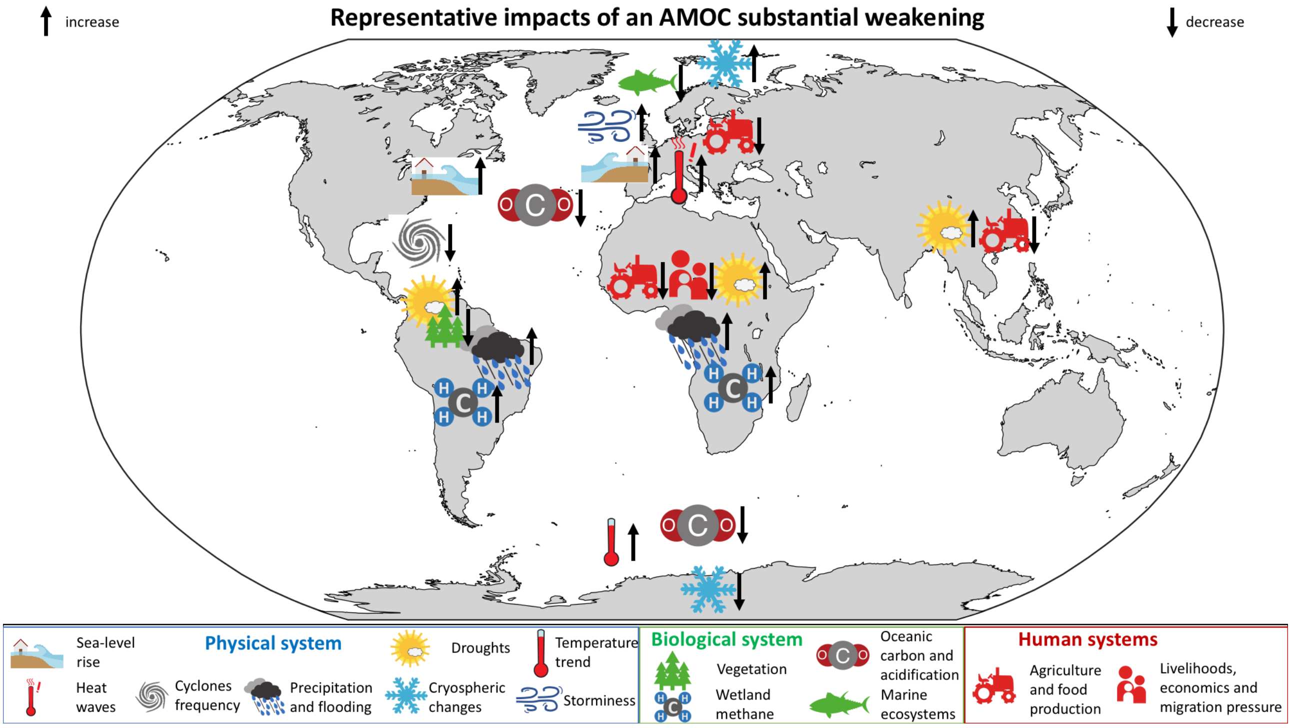


Figure 6.10: Infographic on teleconnections and impacts due to Atlantic Meridional Overturning Circulation (AMOC) or subpolar gyre (SPG) collapse or substantial weakening.

The AMOC is a key player for transporting excess heat and anthropogenic carbon from the surface to the deep ocean (Kostov et al., 2014; Romanou et al., 2017), and therefore in setting the pace of global warming (Marshall et al., 2014). A large potential decline in the AMOC strength reduces global surface warming not only due albedo changes, but also due to changes in the location of ocean heat uptake (Rugenstein et al., 2013; Winton et al., 2013), cloud cover variations and modifications in water vapour content (Trossman et al., 2016). As the uptake of excess heat occurs preferentially in regions with delayed warming (Winton et al., 2013; Frölicher et al., 2015; Armour et al., 2016), a potential large reduction of the AMOC may shift the uptake of excess heat from the low to the high latitudes (Rugenstein et al., 2013; Winton et al., 2013), where the atmosphere is more sensitive to external forcing (Winton et al., 2010; Rose et al., 2014; Rose and Rayborn, 2016; Rugenstein et al., 2016). A decrease in AMOC may also decrease the subduction of anthropogenic carbon to deeper waters (Zickfeld et al., 2008; Winton et al., 2013; Randerson et al., 2015; Rhein et al., 2017). A potential impact of methane emissions has also been highlighted for past Heinrich events related with large AMOC disruptions. Large increases (>100 parts per billion) in methane production have been associated with these events (Rhodes et al., 2015) potentially due to increased wetland production in the Southern Hemisphere, related with teleconnections of the North Atlantic with tropical area (Ringeval et al., 2013; Zurcher et al., 2013). All these different effects indicate a potentially positive feedback of the AMOC on the carbon cycle (Parsons et al., 2014), although other elements from the terrestrial biosphere may limit its strength or even reverse its sign (Bozbiyik et al., 2011). Changes in the ocean circulation can also strongly impact net primary productivity and marine life. For instance, it has been shown that the recent weakening of the SPG has strongly limited the nutrient concentration in the northeast Atlantic and marine life that depend on these nutrients (Johnson et al., 2013; Hatun et al., 2016). Large changes in ocean circulation may also affect migratory species in the Atlantic sector like tuna and billfish (Muhling et al., 2015) with potential large impacts on fisheries. A model study investigated the impact of mitigation by reversing the forcing from a RCP8.5 scenario from 2100 and found that global marine net productivity may recover very rapidly and even overshoot contemporary values at the end of the reversal, highlighting the potential benefit of mitigation (John et al., 2015).

Following all these potential impacts, it has been suggested that a collapse of the AMOC may have the potential to induce a cascade of abrupt events, related to the crossing of thresholds from different tipping points, itself potentially driven by GrIS rapid melting. For example, a collapse of the AMOC may induce changes in ENSO characteristics, dieback of the Amazon forest and shrinking of the West Antarctic Ice Sheet (WAIS) due to a seesaw effect and large warming of the Southern Ocean (Cai et al., 2016). However, such a worst-case scenario remains very poorly constrained quantitatively due to the large uncertainty in GrIS and AMOC response to global warming.

The potential impacts of such rapid changes in ocean circulation on agriculture, economy and human health remain poorly evaluated up to now with very few studies on the topic (Kopits et al., 2014). The available impact literature on AMOC weakening has focussed on impacts from temperature change only (reduced warming), largely leading to economic benefits (e.g., Anthoff et al., 2016).

6.7.3 Risk Management and Adaptation

The numerous potential impacts of AMOC weakening (see Section 6.7.2) require adaptation responses. A specific adaptation action is a monitoring and early warning system using observation and prediction systems, which can help to respond in time to effects of an AMOC decline. Although theoretical investigations have shown that it remains difficult to warn very early for large changes in AMOC to come, notably due to large natural decadal variability of the AMOC (Boulton et al., 2014), the observation array that is in place may allow the development of such an early warning system. Nevertheless, the prospects for its operational use for early warnings have not yet been fully developed.

The use of decadal predictions can be also very useful in that sense. The grand challenge of the World Climate Research Programme (WCRP) proposing to launch decadal predictions every year would be useful for anticipating rapid changes in the near term. For example, a few studies have already shown that small variations anticipated by decadal predictions (e.g., Sheen et al., 2017) can be useful for the development of climate services, notably for agriculture in south and east Africa (Nyamwanza et al., 2017).

6.8 Compound Risk and Cascading Impacts

6.8.1 Concepts

Compound risk (also referred to as multiple risks or 'multi-risk' by Gallina et al., 2016) refers to environments that are characterised by multiple failures that can amplify overall risk and/or cause cascading impacts (Helbing, 2013; Gallina et al., 2016; Figure 6.1). These impacts may be triggered by multiple hazards that occur coincidently or sequentially and can lead to substantial disruption of natural or human systems (Leonard et al., 2014; Oppenheimer et al., 2014; Gallina et al., 2016; Zscheischler et al., 2018). These concepts are illustrated in a series of recent case studies that show how compound events interact with multiple elements of the ecosystem and society to create compound risk and cascading impacts (Box 6.1).

Risks in the context of compound events and cascading impacts are an example of deep uncertainty because lack of data often prevents the assessment of probabilities and consequences of these risks. Furthermore, climate drivers that contribute to compound events could cross tipping points in the future (e.g., Cai et al., 2016; Cross-Chapter Box 4 in Chapter 1). Concepts and methods for addressing compound risk have a solid foundation in Disaster Risk Reduction (DRR) frameworks (Scolobig, 2017) where compound risk may be assessed with scenarios, risk mapping, and participatory governance (Marzocchi et al., 2012; Komendantova et al., 2014). However, these approaches have tended not to consider the effects of climate change, rather considering hazards and vulnerability as stationary entities (Gallina et al., 2016). Trends in geophysical and meteorological disasters and their interaction with more complex social, economic and environmental vulnerabilities are stretching existing governance and institutional capacities (Shimizu and Clark, 2015) because of the aggregated cascading impacts.

6.8.2 Cascading Impacts or Cumulative Effects on Ecosystems

Damage and loss of ecosystems (mangrove, coral reefs, polar deserts); or regime shifts in ecosystem communities lead to reduced resilience of the ecosystems and possible flow-on effects to human systems. For example, recent studies showed that living corals and reef structures have experienced significant losses from human-related drivers such as coastal development; sand and coral mining; overfishing, acidification, and climate-related storms and bleaching events (Smith, 2011; Nielsen et al., 2012; Hilmi et al., 2013; Graham et al., 2015; Lenoir and Svenning, 2015; Hughes et al., 2017b). As a consequence, reef flattening is taking place globally due the loss of corals and from the bio-erosion and dissolution of the underlying reef carbonate structures (Alvarez-Filip et al., 2009). Reef mortality and flattening due to non-climate and climate-related drivers trigger cascading impacts and risks due to the loss of the protection services provided to coastal areas. High emission scenarios are expected to lead to almost the complete loss of coral cover by 2100, although policies aiming to lower the combined aerosol-radiation interaction and aerosol-cloud interaction (e.g., IPCC RCP 6.0) may partially limit the impacts on coral reefs and the associated habitat loss, thereby preserving an estimated USD 14 to 20 billion in consumer surplus 2100 (2014 $ USD, 3% discount; Speers et al., 2016). Moreover, projected sea level rise will increase flooding risks, and these risks will be even greater if reefs that now help protect coasts from waves are lost due to bleaching-induced mortality.

6.8.3 Cascading Impacts and Cumulative Risks on Social Systems

Impacts of compound risk events also have significant accumulated effects in the societal system. Cascading impacts are particularly driven by the loss or (temporary) disruption of critical infrastructure (Pescaroli and Alexander, 2018), such as communications, transport, and power supply; on housing, dams and flood protection; as well as health provision. Repeated extreme and compound events are leading to critical transitions in social systems (Kopp et al., 2016) which may cause the disruption of (local) communities, creating cascading impacts consisting of short-term impacts as well as long-lasting economic effects, and in some cases migration. A combination of long term-climate scenario and responses of the economic sector to short term weather variations indicated that risks associated with climate change on different sectors is projected to be an average of 1.2% of decrease of the US Gross Domestic Product per degree Celcius of warming. Furthermore, broad geographical discrepancies generate a large transfer of value northwards and westwards with the expected consequence of increased economic inequality (Hsiang et al., 2017).

Impacts from the natural system can descend into a cascade of societal disasters; e.g., hurricane Katrina in 2005 led to heavy flooding in the coastal area, dike breaches, emergency response failures, chaos in evacuation (traffic jams) and social disruption. Female-owned establishments are more challenged with failures than businesses owned by men (Haynes et al., 2011; Marshall et al., 2015). The impact of compound events on ecosystems can also, in the long run, have devastating impacts on societal systems, e.g., cascading impacts from tropical storms can lead to coral degradation, which leads to increased wave impact and subsequent accelerated coastal erosion and impacts on fishing resources. This subsequently can have an impact on local economies, potentially leading to social disruption and migration. Impacts on marine ecosystems and habitats will also affect subsistence and commercial fisheries and, as a result, food security (Barrow et al., 2018). Climate-induced community relocations in Alaska stem from repeated extreme weather events coupled with climate change-induced coastal erosion and these impact the habitability of the whole community (Bronen, 2011; Durrer and Adams, 2011; Marino, 2011; Marino, 2012; Bronen and Chapin, 2013; see also Cross-Chapter Box 2 in Chapter 1).

The severity and intensity of impacts of compound events and compound risk depend on the affected societies' vulnerability and resilience. For example, the intensity and influence of compound events are dependent on the size and scale of the affected society and the percentage of economy or Gross Domestic Product impacted (Handmer et al., 2012 in IPCC SREX). Smaller countries face the challenge of being unable to 'hedge' the risk through geographical redistribution. Another way to cope with these changes is indigenous knowledge and local knowledge (IKLK; see Cross-Chapter Box 3 in Chapter 1). In several instances, Inuit IKLK in Alaska underpins competency in subsistence and adaptations to changing conditions, which includes flexibility with regard to seasonal cycles of hunting and resource use, hazard avoidance through detailed knowledge of the environment and understanding of ecosystem processes, and emergency preparedness, e.g., knowing what supplies to take when traveling and how to respond in emergency situations (Pearce et al., 2015).

6.8.4 Risk Management and Adaptation, Sustainable and Resilient Pathways

The management of compound risk in the context of governance poses challenges, partly because it is place dependent and heavily influenced by local parameters such as hazard experience and cultural values. Moreover, in some cases, people perceive that their community or country is less affected than others, leading to a 'spatial optimism bias' that delays or reduces the scope of actions (Nunn et al., 2016). In other cases it is unclear who will take responsibility when compound events and cascading impact occur (Scolobig, 2017). Considerable variations exist among and inside countries. The level of compound risk engagement depends on countries' capacity to develop integrated risk and disaster frameworks and regulations, viable public-private partnership in the case of multiple technological and natural hazards, the initiatives of local governments to exercise compound risk operations, and experience in interagency cooperation (Scolobig, 2017). The importance of local knowledge and traditional practices in disaster risk prevention and reduction are widely recognized (Hiwasaki et al., 2014; Hilhorst et al., 2015; Audefroy and Sánchez, 2017) (*high confidence).* The need to strengthen disaster risk management (DRM) is evident and can be improved and communicated effectively by integrating local knowledge since it is easier for communities to accept than pure science-based DRM (Ikeda et al., 2016).

Ignoring these indirect effects could lead to an under-investment in prevention. For instance, flooding in Thailand in 2011 led to the closure of many factories which not only impacted on the country's economy but impaired the global automobile and electronic industry (Kreibich et al., 2014). On the other hand, changes in the UK government coastal and flooding policies during the past 25 years have been translated into important changes of coastal defence policy with a focus on a strategic analysis to ensure that all actions provide the greatest net benefit (Famuditi et al., 2018). There is *medium evidence* that investing in disaster risk reduction has economic benefits, although the range of the estimated benefits varies from a global estimate of two to four dollars saved for each dollar invested (Kull et al., 2013; Mechler, 2016) to about 400 Euros per invested Euro in flood early warning system in Europe (Pappenberger et al., 2015). The US Federal Emergency Management Agency indicated that a 1% increase in annual investment in flood management decreases flood damage by 2.1% (Davlasheridze et al., 2017). Conserving ecosystems that provide services for risk reduction also has monetary benefits. Wetlands have been observed to reduce damages during storms. Wetlands and floodplains in Otter Creek (Vermont, US) reduced damages caused by storms by 54–78% and by 84–95% for Tropical Storm Irene (Watson et al., 2016). For the whole of the US, wetlands provide USD 23.2 billion/year in storm protection services and the loss of 1 hectare of wetland is estimated to correspond to an average USD 33,000 increase in storm damage from specific storms (Costanza et al., 2008). Engineered structures are also expected to reduce risks. In Europe, to maintain the coastal flood loss constant relative to the size of the economy, flood defence structures need to be able to protect coastal areas for a projected increase of sea level between 0.5 and 2.5 m. Without these risk reduction actions, the expected damages from coastal flood could increase by two or three degrees of magnitude compared to the present (Vousdoukas et al., 2018). Although risk reduction actions are generally considered an effective way to reduce the damages by shifting the loss-exceedance curve, cost-benefit analysis of disaster risk reduction actions faces several challenges, including its limited role in informing decisions, spatial and temporal uncertainty scales, and discounting and choice of discount rate that affect cost-benefit analysis results heavily (Mechler, 2016).

Despite difficulties of governance and decision-making, many researchers and policymakers have recognised the need to study combined climatic and other hazards and their impacts. Several methods are now being employed to assess climatic hazards simultaneously, and also in combination (Klerk et al., 2015; van den Hurk et al., 2015; Wahl et al., 2015; Zscheischler and Seneviratne, 2017; Wu et al., 2018; Zscheischler et al., 2018). Given these analyses, policy can also begin to plan for disaster risk reduction and adaptation, to the combined effects. Addressing limitations in understanding the compound hazards, as well as precise mechanisms of the cascading impacts is needed. Finally, there are limits to resources to study these complex interactions in sufficient detail, as well as limits to data and information on past events that would allow the simulation of these effects, including economic impacts.

6.8.5 Global Impact of Tipping Points

A small number of studies (Lontzek et al., 2015; Cai et al., 2016; Lemoine and Traeger, 2016) use different versions of the dynamic integrated climate-economy (DICE) assessment model (Nordhaus, 1992; Nordhaus, 2017) to assess the impact of diverse sets of tipping points and causal interactions between them on the socially optimal reduction of gas emissions and the present social cost of carbon, representing the economic cost caused by an additional ton of CO_2 emissions or its equivalent.

Cai et al. (2016) consider five interacting, stochastic, potential climate tipping points: reorganization of the meridional overturning circulation (AMOC); disintegration of the Greenland Ice Sheet; collapse of the West Antarctic Ice Sheet (WAIS); dieback of the Amazon Rain Forest and shift to a more persistent El Niño regime. The deep uncertainties associated with the likelihood of each of these tipping points and the dependence of them on the state of the others is addressed through expert elicitation. There is limited evidence, but high agreement that present costs of carbon are clearly underestimated. Double (Lemoine and Traeger, 2016), triple (Ceronsky et al., 2011), to eightfold (Cai et al., 2016) increase of the carbon price are suggested, depending on the working hypothesis. Cai et al. (2016) indicates that with the prospect of multiple interacting tipping points, the present social cost of carbon increases from USD 15 to 116 per tonne of CO_2, concluding that stringent efforts are needed to reduce CO_2 emission if these impacts are to be avoided.

[START BOX 6.1 HERE]

Box 6.1: Compound Events and Cascading Risks

The following case studies illustrate that anthropogenic climate change is increasingly having a discernible influence on elements of the climate system to exacerbate extreme events and cause multiple hazards, often with compound or sequential characteristics. In turn these elements are interacting with vulnerability and exposure to trigger compound risk and cascading impacts.

Case Study 1: Tasmania's Summer of 2015/2016

Tasmania in southeast Australia experienced compound extreme climate events in 2015–2016, driven by the combined effects of natural modes of climate variability and anthropogenic climate change, with impacts on the energy sector, fisheries and emergency services. The driest warm season on record (October to April), together with the warmest summer on record, brought agricultural and hydrological droughts to Tasmania and preconditioned the sensitive highland environment for major fires during the summer. Thousands of lightning strikes during the first two months of the year led to more than 165 separate vegetation fires, which burned more than 120,000 hectares including highland zones and the World Heritage Area and incurred costs to the state of more than AUD 50 million (Press, 2016).

The dry period was followed by an intense cutoff low-pressure system, which brought heavy rainfall and floods in late January, so that emergency services were simultaneously dealing with highland fires and floods in the east and north. The floods were followed by an extended wet period for Tasmania, with the wettest wet season (April-November) on record in 2016. Meanwhile, an intense marine heatwave off the east coast persisted for 251 days from spring, 2015 through to autumn, 2016 (Oliver et al., 2017).

The extreme 2015/16 El Niño and positive Indian Ocean Dipole event partly contributed to the climate extremes, but some of the stressors were also partly linked to anthropogenic climate change. The driest October on record was influenced by both the El Niño and anthropogenic forcing (Karoly et al., 2016). Warmer sea surface temperatures due to anthropogenic warming may have increased the intensity of rainfall during the floods in January (e.g., Pepler et al., 2016a). The intensity and most notably the duration of the marine heatwave was unprecedented and both aspects had a clear human signature (Oliver et al., 2017). Several of the extremes experienced in 2015–2016 in Tasmania are projected to become more frequent or more intense due to climate change, including dry springs and summers (Bureau of Meteorology and Australian CSIRO, 2007), intense lows bringing extreme rains and floods in summer (Grose et al., 2012), and marine heatwaves on the east coast associated with convergence of heat linked to the East Australia Current (Oliver et al., 2017).

Tasmania primarily relies on hydro-electric power generation and the trading of power over an undersea cable to mainland Australia, 'Basslink', for its energy needs. Lake levels in hydro-electric dams were at relatively low levels in early spring 2015, and the extended dry period led to further reductions and significantly reduced capacity to generate power. An unanticipated failure of the Basslink cable subsequently necessitated the use of emergency diesel generators (Hydro Tasmania, 2016).

The compound extremes caused many impacts on natural systems, agriculture, infrastructure and communities. Additional emergency services from outside the state were needed to deal with the fires. The marine heatwave caused disease outbreaks in farmed shellfish, mortality in wild shellfish and species found further south than previously recorded. The energy sector experienced a severe cascade of impacts due to climate stressors together with inter-dependencies within the system. The combination of drought, fires, floods and marine heatwave led to the State of Tasmania experiencing only a 1.3% growth in its gross state product (GSP), well below the anticipated growth of 2.5% due to the declines in output from the agriculture, forestry, fishing and energy sectors. To address the energy shortages, Tasmania's four largest industrial energy users, normally responsible for 60% of Tasmania's electricity usage, agreed to a series of voluntary load reductions of up to 100 MW on a sustained basis and this contributed to a 1.7% reduction in the output of the manufacturing sector, which represents about 7% of Tasmania's GSP (Eslake, 2016). The total cost of the fires and floods to the state government was assessed at USD 300 million. In response there has been funding increases to relevant government agencies responsible for managing floods and bushfires, as well as multiple independent reviews recommending major policy reforms that are now under consideration (Blake, 2017; Tasmanian Climate Change Office, 2017).

This case illustrates the concepts presented in Figure 6.1. For several extreme hazards associated with the climate system (i.e., droughts, extreme rainfall, and marine heatwaves), anthropogenic climate change *likely* contributed to their severity. Together these hazards illustrate elements of compound events (e.g., warmer coastal currents producing a marine heatwave and triggering more extreme rainfall during an east coast low event), sequential events (droughts and bushfires, followed by extreme rainfall and floods) and multiple simultaneous independent events (e.g., low dam levels for hydropower generation coinciding with the failure of the Basslink connection). Multiple risks arose from the set of events, including risks for the safety of residents affected by floods and fires, risks to the natural environment affected by marine heatwaves and fires and risks to the economy in the food and energy sectors initially with cascading impacts on the industrial sector more broadly as it responded to the shortfall in energy supply.

Case Study 2: The Coral Triangle

The Coral Triangle is under the combined threats of mean warming, ocean acidification, temperature and sea-level variability (often associated with both El Niño and La Niña), coastal development and overfishing, leading to reduced ecosystem services and loss of biodiversity. The Coral Triangle covers 4 million square miles of ocean and coastal waters in Southeast Asia and the Pacific, in the area surrounding Indonesia, Malaysia, Papua New Guinea, the Philippines, Timor Leste, and the Solomon Islands. The Coral Triangle is the centre of the highest coastal marine biodiversity in the world, being home to 605 species of zooxanthellate corals including 15 regional endemics (Veron et al., 2011), corresponding to 76% of the world's total species complement. Biodiversity hotspots in the Coral triangle are found in the Bird's Head Peninsula of Indonesian Papua, which hosts 574 species, with individual reefs supporting up to 280 species/ha. The Coral Triangle's exceptional biodiversity is due to its geological setting, physical environment, and an array of ecological and evolutionary processes and makes it a conservation priority.

The Coral triangle is inhabited by over 100 million people from diverse and rich cultures. Marine and coastal ecosystems including coral reefs, mangroves and seagrass beds are essential for the local people's livelihoods by providing food, building materials, coastal protection and many other ecosystem services and benefits, and by supporting economic sectors such as fishing and tourism.

The riches of the ecosystems in the Coral Triangle led to expanding human activities, such as coastal development to accommodate a booming tourism sector and overfishing and there is agreement that these activities generate important pressures on the ecosystem (Pomeroy et al., 2015; Ferrigno et al., 2016; Huang and Coelho, 2017), including coastal deforestation, coastal reclamation, declining water quality, pollution, sewage, destructive fishing and over-exploitation of marine life . As a result, the coastal ecosystems of Coral Triangle have already lost 40% of their coral reefs and mangroves over the past 40 years (Hoegh-Guldberg et al., 2009).

In the case of the Coral Triangle, one of these stressors is the increasing trend in sea surface temperatures (SST) which was estimated to be 0.1°C per decade between 1960 and 2007 (Kleypas et al., 2015) but increased to 0.2°C per decade from 1985 to 2006 (Penaflor et al., 2009), an estimation comparable with that in the South China Sea (Zuo et al., 2015). However, warming within the region has not been uniform; waters in the northern and eastern parts are warming faster and this variability is increased by local parameters linked to the complex bathymetry and oceanography of the region (Kleypas et al., 2015). Areas in the eastern part have experienced more thermal stress events and these appear to be more likely during La Niña events, which generate heat pulses in the region, leading to bleaching events, some of them triggered by El Niño Southern Oscillation (ENSO) events. In the Coral Triangle, El Niño events have a relative cooling effect, while La Niña events are accompanied by warming (Penaflor et al., 2009). The 1997–1998 El Niño was followed by a strong La Niña so that degree heating weeks (DHW) values in many parts of the region were greater than 4, which caused widespread coral bleaching (DHW values greater than zero indicate there is thermal stress, while DHW values of 4 and greater indicate the existence of sufficient thermal stress to produce significant levels of coral bleaching). The 2015–2016 El Niño event had impacted Indonesia's shallow-water reefs well before high sea surface temperatures could trigger any coral bleaching (Ampou et al., 2017). Sea level in Indonesia was at its lowest in the past 12 years following this El Niño event and this affected coral living within bathymetric range. Substantial mortality was likely caused by higher daily aerial exposure during low tides and warmer SST associated with shallow waters. With extreme El Niño events projected to increase in frequency this century (Cai et al., 2014a; Wang et al., 2017), it is imperative that a clear understanding is gained of how these thermal stress anomalies impact different coral species and coral reef regions so these new risks can be managed. Another impact of climate change in the Coral Triangle is ocean acidification. Although less exposed than other reefs at higher latitudes (van Hooidonk et al., 2013), changes in pH are expected to affect coral calcification (DeCarlo et al., 2017), with an impact on coral reef fisheries (Speers et al., 2016).

At present, different approaches are used to manage the different risks to coral ecosystems in the Coral Triangle such as fisheries management (White et al., 2014) and different conservation initiatives (Beger et al., 2015), including coral larval replenishment (dela Cruz and Harrison, 2017) and marine protected areas (e.g., Christie et al., 2016). There is a *high confidence* that reefs with high species diversity are more resilient to stress, including bleaching (e.g., Ferrigno et al., 2016; Mellin et al., 2016; Mori, 2016). Sustainable Management of coastal resources, such as marine protected areas is thus a commonly used management approach (White et al., 2014; Christie et al., 2016), supported in some cases by ecosystem modelling projections (Weijerman et al., 2015; Weijerman et al., 2016). Evaluations of these management approaches led to the development of guiding frameworks and supporting tools for coastal area managers (Anthony et al., 2015); however biological and ecological factors are expected to limit the adaptive capacity of these ecosystems to changes (Mora et al., 2016).

Case Study 3: Hurricanes of 2017

The 2017 hurricane season was notable for the above-average hurricane activity during which time Hurricanes Harvey, Irma and Maria wreaked havoc on the Caribbean and southern US coasts (Klotzbach and Bell, 2017) collectively causing USD 265 billion damage and making 2017 the costliest hurricane season on record (Blake et al., 2011; Blake and Zelinsky, 2018).

The role of climate change in contributing to the severity of these recent hurricanes has been much discussed in the public and media. It has not been possible to identify robust long-term trends in either hurricane frequency or strength given the large natural variability, which makes trend detection challenging especially given the opposing influences of greenhouse gases and aerosols on past changes. However, observational data shows a warming of the surface waters of the Gulf of Mexico, and indeed most of the world's oceans, over the past century as human activities have had an increasing impact on our climate (Sobel et al., 2016).

Harvey brought unprecedented rainfall to Texas and produced a storm surge that exceeded 2 m in some regions (Shuckburgh et al., 2017). It has been estimated that climate change increased the rainfall intensity of Harvey by 15% (8%–19%; van Oldenborgh et al., 2017), 20% (13%–37%; Wang et al., 2018), at least 18% with a best estimate of 38% (Risser and Wehner, 2017). Emanuel (2017) estimated that the annual probability of 500 mm of area-integrated rainfall had increased from 1% in the period 1981–2000 to 6% in 2017. Furthermore, if society were to follow RCP8.5, the probability would increase to 18% over the period 2081–2100.

Applying the method described in Emanuel (2017) to tropical cyclone (TC) Irma that penetrated Caribbean islands such as Barbuda and Cuba, indicates that the annual probability of encountering Irma's peak wind of 160 knots within 300 km of Barbuda had increased from 0.13% in the period 1981–2000 to 0.43% by 2017 and will increase to 1.3% by 2081–2100 assuming a greenhouse gas concentration pathway of RCP8.5. TC Maria, followed Irma, and made landfalls on the island of Dominica, Puerto Rico, and Turks and Caicos Islands. The annual probability of encountering Maria's peak wind of 150 knots within 150 km of 17N, 64W has increased from 0.5% during 1981–2000 to 1.7% in 2017 and will increase to 5% by 2081–2100 assuming a greenhouse gas concentration pathway of RCP8.5.

The combination of storm surge with riverine flooding heightened the cascading impact of compound events. At least 68 people died from the direct effects of Harvey in Houston (Blake and Zelinsky, 2018). The Houston metropolitan area was devastated with the release of about 4.6 million pounds of pollutants from petrochemical plants and refineries. Irma caused 44 direct deaths (Cangialosi et al., 2018) and wiped out housing, schools, fisheries, and livestock in Barbuda, Antigua, St. Martin, and the British Virgin Island (ACAPS et al., 2017). Maria caused 31 direct deaths in Dominica and two in Guadeloupe and around 65 in Puerto Rico (Pasch et al., 2018) Maria destroyed almost all power lines, buildings, and 80% of crops in Puerto Rico (Rexach et al., 2017; Rosselló, 2017) and is expected to increase the poverty rate by 14% because of unemployment in tourism and agriculture sectors for more than a year in Dominica (The Government of the Commonwealth of Dominica, 2017). These hurricanes hit the Caribbean severely, and resulted in outmigration to the neighbouring country or the US (ACAPS et al., 2017; Rosselló, 2017). The post-disaster reconstruction plan is to renovate telecommunications, develop climate resilient building plans, and emergency coordination (Rosselló, 2017; The Government of the Commonwealth of Dominica, 2017).

[END BOX 6.1 HERE]

6.9 Governance and Policy Options, Risk Management, Including Disaster Risk Reduction and Enhancing Resilience

6.9.1 Decision Making for Abrupt Change and Extreme Events

As outlined earlier in this report, several approaches exist for adaptive responses towards climate change impacts, in addition to preventing impacts through mitigation. Other sections that deal with adaptation responses to extremes include Section 1.5.2, Section 4.4 (sea-level rise and coastal flooding), as well as Cross Chapter Box 4 in Chapter 1. Here, we address adaptation responses especially to abrupt and extreme changes.

Successful adaptation to abrupt change and extreme events takes into account spatial and the temporal dimensions at which interventions are made and can be distinguished in three categories: institutional adaptation, livelihoods adaptation and risk reduction and management for resilience (Barange et al., 2018). Temporal scales encompass interventions before and after abrupt changes and extreme events (prevention and post-event response), long- and short-term adaptation measures, and the lag time between forecast, warning, and event (IPCC SREX; Field et al., 2012). Spatial dimensions of adaptation include local risk management and adaptation as well as regional and international coordination to prepare for unexpected extremes (Devine-Wright, 2013; Barnett et al., 2014; Lyth et al., 2016; Barange et al., 2018). Decision-making about abrupt change or extreme events is not autonomous: it is constrained by institutional processes such as regulatory structures, property rights, culture and traditions, and social norms associated with rules in use (see also IPCC SREX; Field et al., 2012). Efforts in various countries and large cities are rapidly increasing to improve resilience and adaptation, and they link to a global network of research, information and best practices (e.g., Aerts et al., 2014). The question is whether extreme events and abrupt change require specific adaptation responses that differ from the management of 'normal' weather disaster risk. While there are several impact studies on extreme events and abrupt change, very few focus on the necessity of dedicated human adaptive responses (Tol et al., 2006; Anthoff et al., 2010; Anthoff et al., 2016).

Making appropriate decisions to manage abrupt change and extreme events given deep uncertainty is challenging (Weaver et al., 2013; see Cross-Chapter Box 4 in Chapter 1). This requires the construction of an analytical cost-benefit model integrating different uncertainties under extreme or abrupt scenarios and evaluation of value for money (Weaver et al., 2013). Examples include the inclusion of extremely rapid sea-level rise for assessing coastal impacts and adaptation options (Ranger et al., 2013; Haasnoot et al., 2018; see Sections 6.4 and 6.7). Robust frameworks such as Robust Decision Making (RDM)', 'Decision Scaling (DS)', 'Assess Risk of Policy', 'Info-gap', 'Dynamic Adaptation Policy Pathways' and 'Context-First', accommodate a wide range of uncertainties with subsequent social-ecological impact (Weaver et al., 2013). The central question remains, however, how one can overcome current path dependencies which may cause technical lock-ins in the current system. Also, suggestions are made for monitoring systems of climatic and derived variables, in order to predict necessary shifts in adaptation policies (Haasnoot et al., 2015). However, these frameworks have so far been mostly applied to more gradual shifts of climate change, rather than extreme events and abrupt changes.

Request for 'actionable' information based on climate science and modelling will increase (McNie, 2007; Moser and Boykoff, 2013). Such information can only be effective when it is perceived as 'credible, salient, and legitimate' (Paton, 2007; Paton, 2008; Dilling et al., 2015). Since SREX (IPCC, 2012), there is *medium confidence* that credibility based on trust in the information provided as well as trust in the institution (Hardin, 2002; Townley and Garfield, 2013) that governs extreme events and abrupt change (Malka et al., 2009; Birkmann et al., 2011; Schoenefeld and McCauley, 2016). Trust in expert and scientific knowledge help people make sense of climate change impact and engage with adaptation measures (Moser and Boykoff, 2013; Yeh, 2016). Without such knowledge, people have little recourse to believe and evaluate relevant information (Bråten et al., 2011). Individuals who trust their institution can be complacent and do not prepare for disasters themselves (Simpson, 2012; Edmondson and Levy, 2019) . Familiarity with and information about hazards, community characteristics, as well as the relationship between people and government agencies influence the level of trust (Paton, 2007).

Under the United Nations Framework Convention on Climate Change (UNFCCC), the Warsaw International Mechanism on Loss and Damage (L&D) aims to address impacts beyond adaptation and irreversible changes and impacts (see also Cross-Chapter Box 1 in Chapter 1 and Section 1.5). Within the SROCC report, several of the documented and projected impacts would potentially fall under this category (e.g., Warner and van der Geest, 2013; Huggel et al., 2018; Mechler et al., 2019), including impacts on small island states, changes in the high mountains and cryosphere changes, as well as changes in ocean organic species and resources. Apart from the climate hazards, risks for L&D are also determined by increasing exposure and vulnerability (Birkmann and Welle, 2015). Debate on the precise scope of impacts remains, including those from anthropogenic climate change impacts as well as natural climate variability and extremes (e.g., James et al., 2014). Still, the L&D framework can become an important instrument at the international level to address residual risks as well as identifying needs for transformation and alternative livelihoods in case of irreversible change.

Under the same L&D mechanism, insurance has also been suggested as a specific adaptation policy option. Several forms for 'climate change' insurance have been proposed recently, but their potential for adaptation has met with criticism, importantly because of the costs of formal insurance and other risk transfer options, as well as issues with sustainability given the general lack of prevention of risks and adaptation (Surminski et al., 2016; Linnerooth-Bayer et al., 2019). Insurance (see also Section 4.4.4) can help absorb extreme shocks, but eventually, also needs to become coupled to adaptation and risk reduction efforts in order to keep risk under control (Botzen, 2013).

6.9.2 Transformative Governance and Integrating Disaster Risk Reduction and Climate Change Adaptation

Governance for effective adaptation - defined as changes in practices, processes and structures (Smit et al., 2001) - in the areas of equity, legitimacy and co-benefits (Patterson et al., 2018) is critical. Countries, sectors, and localities place different values and perspectives on these areas, and they can change over time (Plummer et al., 2017). Transformative governance embraces the wider application of climate change-induced mitigation and adaptation to generate fundamental change that is society-wide and goes beyond the goals of climate change policies and measures (IPCC, 2013; Patterson et al., 2018). It is distinguished from conventional strategies and solutions, inclusive of both natural and human systems and intertwined with sustainable development goals (Fleurbaey et al., 2014; Tàbara et al., 2018). Planned retreat from sea-level rise and climate refugees illustrate the need for transformative governance as the current coastal and risk management regimes do not have the capacity to handle adequately. Inclusion of bilateral and regional agreements related to climate-induce migration (McAdam, 2011), land use planning framework to respond to policy, institutional and cultural implications of migration (Matthews and Potts, 2018), and identification of beneficiaries of managed retreat (Hino et al., 2017) along with positive opportunities for migrants to diversify income and avoid being in harm's way (Gemenne, 2015) are steps towards transformative governance. Retreat and migration entail local responses that include indigenous and local knowledge and perspectives that can be applied to solve these issues (Farbotko and Lazrus, 2012; Hilhorst et al., 2015; Tharakan, 2015; Iloka, 2016; Nunn et al., 2016; see also Cross-Chapter Box 2 in Chapter 1 and Cross-Chapter Box 7). Accountability for transformations and transitions has been identified as crucial factor to support responsible action and strengthen climate governance (Edmondson and Levy, 2019).

Though discourse abounds related to transformative governance, it falls short of its ideal in climate change action plans as it is unclear whether communities have the capacity to engage in substantive change to build low-carbon and resilient communities (Burch et al., 2014). The results of a study on the US by Tang and Dessai (2012) also indicate that climate adaptation and mitigation plans' treatment of extreme climate conditions and disaster preparedness is limited. Moreover, risk communication with the public is part of an integrated disaster warning system, but behavioural response to disaster warnings are often governed by personal beliefs about the nature of the hazard; and ultimately swaying individual decisions to comply with or ignore the warning message (Mayhorn and McLaughlin, 2014).

Coupling disaster management and climate change adaptation has shown progress since SREX and AR5. Substantial literature exists on the topic, but there is little assessment of practices on the ground in the implementation of integrated disaster management and climate change adaptation (Nalau et al., 2016) including health (Banwell et al., 2018). Though mainstreaming and integrating disaster risk reduction within and across sectors is considered essential to ensure administrative coordination and coherence across sectoral plans and policies (Shimizu and Clark, 2015), no assessment is available of the efficiency and effectiveness of mainstreaming especially related to the integration of climate change adaptation and disaster risk reduction, let alone for abrupt and extreme impacts.

Case studies of integration note major problems with coordination: weak coordination among government agencies (Seidler et al., 2018); lack of data and information to guide decision-making at the local level and the need for the central governmental support for data availability (Putra et al., 2018); fragmentation due to differing local goals between climate change adaptation and the built environment (Forino et al., 2017); dependence on regional and international frameworks in the absence of a national framework (Rivera and Wamsler, 2014); limited availability of formal training in the integration (Hemstock et al., 2017); and turf wars between responsible government agencies (Nemakonde and Van Niekerk, 2017). The case of Pacific islands such as Vanuatu illustrates this problem of coordination. Though they have coupled disaster risk reduction with climate change adaptation, the problem is not necessarily about the implementation of the coupled management (Nalau et al., 2017). Rather, systemic and contextual issues occur, such as on relationships, responsibilities, capacity and expectations between government agencies and other actors (e.g. international donors and non-governmental organizations), as analysed by Vanuatu's response to the category 5 tropical cyclone Pam (Nalau et al., 2017). Some solutions are proposed such as getting all the actors on the same page and focusing on reducing vulnerability to environmental hazards in the longer-term that disaster management practices often overlook (Schipper et al., 2016); getting more specific with goals, objectives and strategies (Organization of American States, 2014); and assigning a single department to handle integration (APEC, 2016). Locally place-based responses also entail the inclusion and the acknowledgement of IKLK for an enhanced resilience pathway (Hilhorst et al., 2015; Tharakan, 2015; Iloka, 2016; Nunn et al., 2016).

Coordinating solely within the field of disaster management also poses challenges. In post-disaster situations, e.g., military, commercial and voluntary organizations that manage disasters have found it challenging to coordinate between them, as key capabilities remain outside preparedness planning partly due to the lack of a common threat profile as well as unclear and inconsistent regulations (Kaneberg et al., 2016). Successful coordination can occur when different organizations face a common and shared problem, are in the same location, build trust while responding to the disaster, and create a shared identity (Beck and Plowman, 2013). Contingent coordination that activate existing organizations to respond to crises under a unified framework of disaster response such as the US's Incident Command System also exists (McNamara et al., 2014). Though hierarchical in appearance, such a unified system is considered network governance as organizations share the standard operating framework to work together (Moynihan, 2009). The difficulties stem from emergent organizations that were not previously exposed to the framework and the ambiguity of shared authority in responding to disasters.

The Sendai Framework for Disaster Risk Reduction 2015–2030 outlines seven targets and four priorities for disaster risk reduction by improved coordination and collaboration (UNISDR, 2015). They foster participation beyond information sharing, and include partnerships and collaborations within society (UNISDR, 2015). A recent study on disaster risk reduction in the European Wadden Sea coastal area, for example, highlights cooperation as crucial, including (i) responsibility-sharing among authorities, sectors and stakeholders, (ii) an all-of-society engagement and partnership with empowerment and inclusive participation, and (iii) the development of international, regional, subregional and transboundary cooperation schemes (González-Riancho et al., 2017). Pal et al. (2017) demonstrated a successful case that reduced fatalities from over 10,000 in 1999 from Cyclone Orissa to 45 from Cyclone Phallin in India. The changed coordination structure with the formation of Disaster Management Act of 2005 established a comprehensive policy, and invited a command and control system that empowers the most suitable government officials responding to disasters regardless of their rank. This system provides authority to and holds accountability for those in charge of the ground operation. Though the rigid command and control system may be counter intuitive, the lack of maturity and capacity of personnel and the disaster management system necessitates the unified command in order to enhance future resilience (Pal et al., 2017).

[START FAQ 6.1 HERE]

FAQ 6.1: How can risks of extreme events and abrupt changes in the ocean and cryosphere related to climate change be addressed?

Climate change is projected to influence extreme events and to cause abrupt changes in the ocean and the cryosphere. While extreme events only last for a certain period of time, abrupt changes occurring over a short time may be permanent. Both these phenomena can add to other, slow-onset impacts of climate change, such as a more gradual warming or sea level rise.

In the ocean, a growing number of periods of extreme ocean temperature, known scientifically as marine heatwaves, can lead to irreversible impacts on marine organisms. Extreme sea level events causing coastal flooding and associated with tropical and mid-latitude storms can occur more often as well. In addition, "El

Niño” events, in which the waters of the eastern tropical Pacific warm, may become more frequent and trigger extreme rainfall. In the cryosphere, the frozen parts of the Earth, ice melt can cause glacial lakes overflow and flash floods, as well as landslides and avalanches in valleys below the lakes. In the Arctic region, episodes of extreme high temperatures during winter have already been recorded recently, with consequences for the local ecosystems and the formation of sea ice.

A possible abrupt change in the ocean is associated with an interruption of the Atlantic Meridional Overturning Circulation (AMOC), an important component of global ocean circulation. A slowdown of the AMOC could have consequences around the world: Rainfall in the Sahel region could reduce, hampering crop production. The summer monsoon in Asia could weaken, too. Regional sea level rise could increase around the Atlantic, and there might be more winter storms in Europe. The collapse of the West Antarctic ice sheet is considered be the highest risk of abrupt change. Such an event can be triggered when ice shelves break and ice flows towards the ocean. While, in general, it is difficult to assess the probability of occurrence of abrupt climate events they are physically plausible events that could cause large impacts on ecosystems and societies, and may be irreversible.

Reducing greenhouse gas emissions helps to limit the occurrence of extreme events and abrupt changes. In addition, a variety of measures and risk management strategies supports adaptation to future risks. They depend on local conditions and different characteristics of the events themselves: One major factor for adaptation is whether the extreme events will simply amplify the known impacts or whether they will cause completely new conditions, which may be related with a tipping point. Another essential factor is whether an extreme event or abrupt change will happen in isolation or in conjunction with other events, in a chain of cascading risks or as a part of a compound event where several events happen at the same time so that impacts can multiply each other. Also, impacts are heavily aggravated by increasing exposure and changes in vulnerability, for example reducing the availability of food and water supply, and not just the occurrence of extremes themselves.

A successful management of extreme events and abrupt changes in the ocean and cryosphere involves all available governance resources, including land-use planning, indigenous knowledge, local knowledge and ecosystem services. There are three general approaches that can enable communities to adapt to these events: retreat from the area, accommodation to new conditions and protection. But only transformative governance that integrates a variety of strategies and benefits institutional change helps to address larger risks posed by compound extremes. Integrating risk-reduction approaches into institutional practices and inclusive decision-making that builds on the respective competences of different government agencies can support management of these extremes. A change of lifestyles and livelihoods might further support the adaptation to new conditions.

[END FAQ 6.1 HERE]

6.10 Summary and Knowledge Gaps

6.10.1 Summary

Figure 6.11 provides a visual summary of the assessment provided in this chapter.

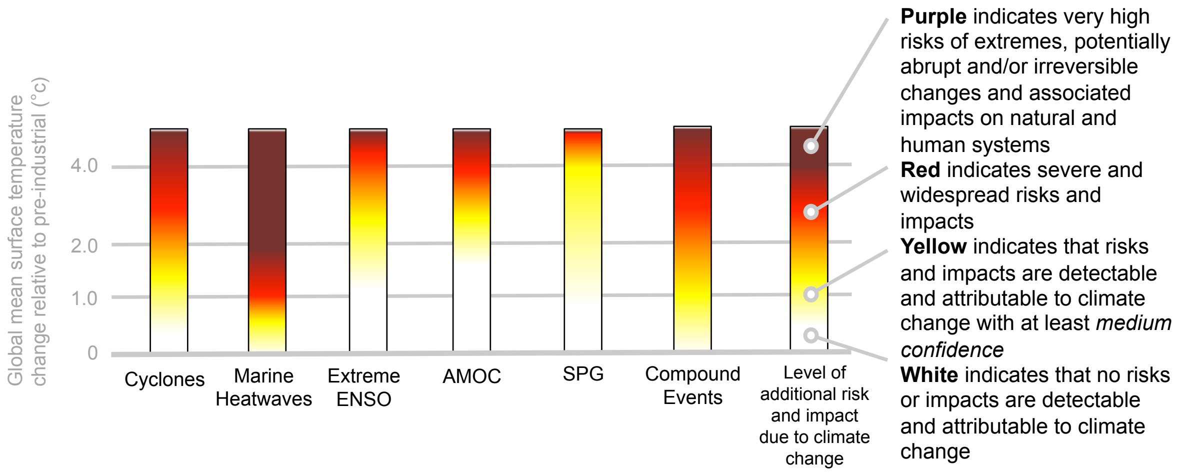


Figure 6.11: 'Burning Embers' diagram summarising changes in extreme events and abrupt and potentially irreversible phenomena assess in this chapter. Colours fading from white, through yellow, red and purple indicate both an increase in risk in the physical phenomena (i.e., the hazard) and also the potential for increasing impacts on human and natural systems. (See explanation in the figure.)

6.10.2 Knowledge Gaps

A comprehensive, detailed list of all the knowledge gaps that have been identified during the assessment performed in this chapter is not possible, hence we focus here on gaps that are relevant for multiple phenomena.

Detection, attribution and projection of physical aspects of climate change at regional and local scales are generally limited by uncertainties in the response of climate models to changes in greenhouse gases and other forcing agents. Additionally, regionally-based attribution studies for extreme events may be lacking in some areas, possibly reflecting the lack of capacity or imperative by regional and national technical institutions to undertake such studies. Thermodynamic aspects of change may be more robust than those involving changes in dynamics e.g., the tracks of tropical cyclones or ocean dynamical components of marine heatwave formation. Increasing resolution and improvements in climate models may help reduce uncertainty. However, because extreme events and highly non-linear changes (e.g., Atlantic Meridional Overturning Circulation collapse) are, by definition, found in the 'tails' of distributions, ensembles or long climate model runs are required.

While it may not be possible to quantify the likelihood of very rare events or irreversible phenomena, it may be possible to quantify their impacts on natural and human systems. Such information may be more useful to policy makers (Sutton, 2018). Impacts on natural systems (e.g., marine ecosystems) are in general better quantified than impacts on human systems, but there are still many gaps in the literature for the phenomena assessed here (e.g., future impacts of extreme El Niño and La Niña events). The body of literature on compound risks and cascading impacts is growing but is still rather small. One area where there seems to be a serious lack of literature is in the assessment of the economic impacts of extreme and abrupt/irreversible events.

Literature on managing risks and adaptation strategies for abrupt and irreversible events is sparse, as is the literature on the combined impacts of climate-driven events and societal development or mal-adaptation. The same is true for compound risks and cascading impacts. Theory on transformative governance is emerging but practical demonstrations are few.

Finally, research is still often 'siloed' in physical modelling, ecosystem modelling, social sciences etc. Researchers who can cross boundaries between these disciplines are required in order to accelerate research in the areas covered by this chapter.

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