Chapter 6: Extremes, Abrupt Changes and Managing Risks

Coordinating Lead Authors: Matthew Collins (UK), Michael Sutherland (Trinidad and Tobago)

Lead Authors: Laurens Bouwer (Netherlands), So-Min Cheong (Republic of Korea), Thomas Frölicher (Switzerland), Hélène Jacot Des Combes (Fiji), Roxy Mathew Koll (India), Iñigo Losada (Spain), Kathleen McInnes (Australia), Beate Ratter (Germany), Evelia Rivera-Arriga (Mexico), Raden Dwi Susanto (Indonesia), Didier Swingedouw (France), Lourdes Tibig (Philippines)

Contributing Authors: Pepijn Bakker (Netherlands), C. Mark Eakin (USA), Kerry Emanuel (USA), Michael Grose (Australia), Stéphane Hallegatte (France), Mark Hemer (Australia), Andreas Kääb (Norway), Jules Kajtar (UK), Thomas Knutson (USA), Charlotte Laufkötter (Switzerland), Roshanka Ranasinghe (Netherlands), Giovanni Sgubin (Italy), Mary-Louise Timmermans (USA)

Review Editors: Amjad Abdulla (Maldives), Marcelino Hernádez González (Cuba), Carol Turley (UK)

Chapter Scientist: Jules Kajtar (UK)

Date of Draft: 20 April 2018

Notes: TSU Compiled Version

Table of Contents

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.

Changes in Tracks, Intensity, and Frequency of Tropical and Extra-tropical Cyclones

An anthropogenic influence on tropical and extra-tropical cyclones is *likely*[1]. Trends in mean sea surface temperature (SST) and sea level have contributed to increased precipitation, winds and extreme sea level events associated with a number of observed tropical and extra-tropical cyclones. Sustainable and resilient plans exist to prepare for these storms although the implementation of the plans is sometimes lacking. In the future, stronger tropical cyclones are *likely* although they may be fewer in number. The AR5 assessment of changes in both tropical and extratropical cyclones thus remains valid. The unexpected nature of future storms that change track, intensity, or frequency leave governments and people ill-prepared. Warnings and evacuations are not well heeded. Coordination among disaster response organizations has the potential to become more chaotic. Social media as a new tool for information transfer provide emotional support and real-time responses, but also generate second hand and wrong information. Reductions in vulnerability from storm surges have been documented, and can continue to mitigate some future impacts. {6.3, Table 6.2, Figure 6.2}

Marine Heat Waves and their Implications

Marine heat waves have *very likely* become more frequent in recent decades and human-induced global warming has increased their probability of occurrence (*high confidence*[2]). Marine heat waves are projected to become commonplace and will *likely* push marine organisms and ecosystems to the limits of their resilience. Marine heat waves, defined as coherent areas of extreme warm sea surface temperature that persist for days-months, have *very likely* become more frequent since the beginning of satellite sea surface temperature observations in 1982. There is *high confidence* that human-induced global warming has increased the probability of marine heat waves over the past few decades. Marine heat waves have occurred in all ocean basins with detrimental impacts on coral reefs and other marine ecosystems, and cascading impacts on economies and societies. Marine heat waves are projected to become commonplace and very extreme under future global warming. The probability of marine heat waves will be 41% (36–45) larger under 3.5°C global warming relative to preindustrial times (*high confidence*). The largest changes are projected to occur in the tropical Ocean and the Arctic Ocean. The probability of occurrence of marine heat waves is only 40% of that at 3.5°C if global warming relative to preindustrial is kept below 2°C. An increase in marine heat waves will *likely* push marine organisms and ecosystems to the limits of their resilience and even beyond, especially those with reduced mobility and those living at low latitudes, potentially causing dramatic and irreversible changes. {6.4, Figures 6.3-6.4}

Interannual to Decadal Climate Variability and Change

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 and risk management strategies exist, and can be adapted and improved to ameliorate the impacts of extreme El Niño events. There have been three occurrences of extreme El Niño events during the modern observational period (1982/1983, 1997/1998, 2015/2016), all characterised by pronounced rainfall in the

---

[1] 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 1.8.3 and Table 1.2 for more details).

[2] 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 1.8.3 and Table 1.2 for more details).

equatorial east Pacific. Paleoclimate evidence suggests that El Niño-Southern Oscillation (ENSO) has been unusually active in the past century. Because of large natural variability, and because of model inadequacies, it has not been possible to determine if there has been an anthropogenic influence on observed ENSO events and impacts. These factors also limit confidence in future projections. Literature on projections of the combined impacts of modes of climate variability and mean climate change is sparse. {6.5, Figures 6.5-6.6}

Inter-Ocean Exchanges and Global Change

The equatorial Pacific trade wind system has experienced extreme variability in the last two decades, influencing global-scale climate (*high confidence*). In the last two-decades total exchange transports from Pacific to Indian Ocean (Indonesian Throughflow), and Indian Ocean to Atlantic Ocean has increased *(high confidence*). Increased Indonesian throughflow (ITF) has been attributed to Pacific cooling and basinwide warming in the Indian Ocean. Pacific trends have been linked to an anomalously warming tropical Atlantic. Models fail to simulate the magnitude of trade wind 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}

Abrupt Changes in Ocean Circulation

The AMOC will *very likely* weaken over the 21st century under all RCP scenarios but an abrupt transition or collapse of the AMOC during the 21st century is *unlikely*. Observations and model analysis since the publication of AR5 have confirmed that (i) there is no significant trend in the Atlantic Meridional Overturning Circulation (AMOC) over the years 2005–2016 based on direct observations, although AMOC reconstructions based on SST fingerprints and proxies suggest an unprecedented weakening over the historical era, (ii) the AMOC will *very likely* weaken over the 21st century under all RCP scenarios and (iii) an abrupt transition or collapse of the AMOC during the 21st century is *unlikely*, although there are more models available since the AR5 assessment that simulate a very rapid weakening. A substantial weakening of the AMOC would lead to wide-spread impacts on surface climate and natural and human systems such as: 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 storms 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. 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 quantified. {6.7, Figures 6.8-6.10}

The likelihood of encountering an abrupt Subpolar Gyre cooling in the 21st century is *about as likely as not.* A new tipping element, the Subpolar Gyre (SPG) System, has been identified. It involves an abrupt cooling of the SPG on a shorter time scale (decade) than the AMOC decline and with smaller potential climate impacts, which mainly opposes the general warming trend in the North Atlantic bordering region, but could also increase the frequency of extreme summer heat waves in Europe (*low confidence*). {6.7}

Compound Events and Cascading Risks

Climate change is increasingly exacerbating extreme events and causing multiple hazards, often with compound or sequential characteristics. In turn, these elements are interacting with vulnerability and exposure to trigger multi-risk and cascading impacts *(high confidence).* Three examples of recent compound events and cascading risks; (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; indicate how extreme climate events are being influenced by anthropogenic climate change and are contributing to multi-risk and cascading impacts *(high confidence).* {6.8}

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

Emergent and sustained cooperation among organizations and institutions for adaptation proves necessary, as climate change can accelerate and deepen extremes and abrupt changes. New modes of governance, linking to a global network, integrating natural and social systems at varying spatial scales are being developed that are fundamentally different than existing governance systems for disaster management and climate change adaptation. These can promote adaptation to unexpected consequences of future hazards, and promote ways to concretely operationalize adaptation strategies and actions for extreme and abrupt changes. Valuation and demonstration of rewards that encourage behaviour towards such transformation would be paramount to successful resilient pathways to catastrophic and cascading effects of climate extremes. {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; 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. Confounding factors;
- Monitoring and early warning systems;
- Risk management and adaptation, sustainable and resilient pathways.

The chapter is approximately 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).

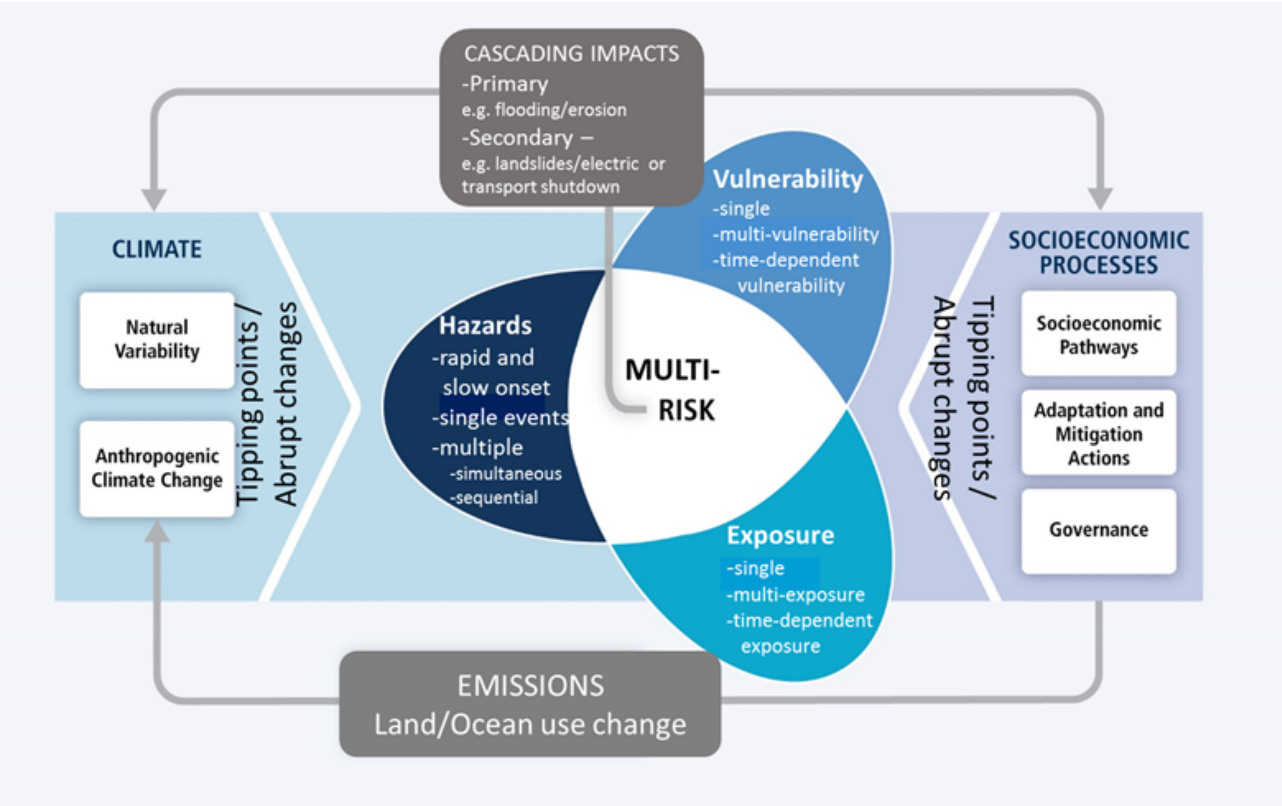

Figure 6.1: Framework used in this chapter for assessing the role of extremes, abrupt changes, tipping points, cascading or multi-risks and impacts.

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 and the atmosphere, including tropical and extra-tropical cyclones in section 6.3.

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.

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 time scale of interest is centennial to millennial.

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. Tipping points are also used when referring to adaptation: it can imply that adaptation actions need to be taken as a climate (impact) tipping point is (about to be) reached; or an adaptation tipping point can refer to the point at which an adaptation option is expected to be no longer effective.

These terms generally reference 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 and irreversible changes in an ecosystem. There may be a tipping point within a governance structure.

We also introduce the following new terms, **multi-risk** (also referred to as **compound risk**) and **cascading impacts** that arise from the interaction of hazards, which may be characterised by single extreme events or multiple coincident (e.g., flooding due to storm surge combined with slower onset sea-level rise) or sequential events (e.g., successive high wave/storm surge events that progressively erode a coastline) that interact with exposed systems or sectors (Figure 6.1). The systems or sectors may be vulnerable at the outset of an extreme event due to the nature and severity of the hazard or may be rendered increasingly vulnerable as sequentially-occurring hazards erode the resilience of the system on time scales that preclude adequate time for recovery. The increased coastal exposure to erosion events may be linked to increased intensity or frequency of storms (section 6.3) and/or regional factors such as sequential marine heat waves in coral reef-fronted locations, that lead to coral bleaching and mortality, which in turn reduces the reefs efficacy in providing coastal protection (section 6.4 and box 6.1), or in the high latitudes, the melting of sea ice that leads to exposed coastlines (see Chapter 4). 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 (e.g., road infrastructure becomes damaged preventing evacuation of people or provision of supplies). In this way multi-risk can lead to cascading impacts. Assessment of multi-risk therefore requires not only information on climate-induced hazards but also dynamic exposure and vulnerability (Gallina et al., 2016). The crossing of tipping points and abrupt changes can occur in human and natural systems as a result of dynamic changes, just as changes in the climate system can affect extreme hazards (Figure 6.1).

6.2 Summary of Abrupt Changes, Irreversibility and Tipping Points

Some potentially abrupt or irreversible events are assessed in other chapters hence the following 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.

Change in climate or ecosystem system component	Potentially abrupt	Irreversibility if forcing reversed (time scales indicated)	Impacts on natural and human systems; global *vs.* regional *vs.* local	Projected likelihood and/or confidence level in 21st century under scenarios considered
Climate				
Atlantic MOC collapse {6.7}	Yes	Unknown	Widespread; increased winter storms in Europe, reduced Sahelian rainfall and agricultural capacity, variations in tropical storms and regional sea level on Atlantic coasts	*Unlikely*
Sub-polar gyre cooling {6.7}	Yes	Irreversible within decades	Considerably smaller than AMOC impacts.	*About as likely as not*
Rapid sea-ice retreat {3.2}	Yes	Reversible within years to decades	Coastal erosion in Arctic, impact on mid-latitude storms (*low confidence*); rise in Arctic winter temperatures (*high confidence*)	*Likely* (*medium confidence*)
Methane release from permafrost {3.4}	No	Irreversible for millennia	Positive feedback on global change	*Low confidence*
Methane release from ocean subsurface hydrates {5.2}	No	Irreversible for millennia	Positive feedback on global change	*Low confidence*
Partial West-Antarctic Ice sheet collapse {3.2, 4.2}	No	Irreversible for millennia	Significant contribution to sea-level rise and ocean salinity	*Low confidence*
Greenland Ice sheet decay {3.2, 4.2}	No	Irreversible for millennia	Significant contribution to sea-level rise, shipping (icebergs)	*Low confidence*
Ice-shelf collapses {3.2, 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 {2.4}	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 {2.2}	Yes	Reversible within decades to centuries	Regional impact on water resources and tourism	*Very likely (high confidence)*
Landslides related to glaciers and permafrost, glacier lake outbursts {2.4}	Yes	Irreversible for rock slopes; reversible within decades to centuries for glaciers, debris and lakes	Local direct impact on humans, land use, infrastructure (hazard), and ecosystems	*Likely (medium confidence) for increase in frequency*
Rapid permafrost thermokarst {2.2}	Yes	Unknown	Local and regional impacts on infrastructure, mobility and hydrology	*Very likely (high confidence)*
Marine heat waves increase {6.5}	Yes	Yes	Coral reef bleaching, loss of biodiversity and ecosystem services	*Very Likely*
Sandy shore changes {5.2}				
Permafrost ground water changes {2.4}	Yes	Unknown	Local impacts on groundwater flows	*Likely (medium confidence)*
Ecosystem				
Hypoxic events and de-oxygenation {5.2}				
Switch to different state in river communities and related loss of endemic species {2.4}	Yes	In many cases non-reversible	Local impacts on ecosystems and ecosystem services	*Likely (medium confidence)*

Higher trophic level production and ecosystem structure {3.3}				
Loss of endemic species and invasion of new species {3.3, 5.2}				
Change in biodiversity {2.4}	Yes	In many cases non-reversible	Local impacts on ecosystems and ecosystem services	*Very likely (high confidence)*

6.3 Changes in Tracks, Intensity, and Frequency of Tropical and Extra-Tropical Storms and Associated Wave Height

6.3.1 Introduction

Severe tropical and extra-tropical storms pose a major threat to society, infrastructure and marine activities due to damaging winds and rainfall, and associated ocean hazards such as storm surges and severe waves. Several attributes of severe storms are important in the context of the physical impacts. The storm intensity relates to the central pressure of the storm and the maximum wind strength and rainfall. The size of the storm determines the footprint of the storm on the underlying land or ocean region. The frequency with which storm events occur in a given location may affect the ability for communities and the natural environment to recover and rebuild before subsequent storm occurrence. To this end, understanding the sequencing of extreme weather and climate events and the influence of modes of variability such as ENSO is important. Changes in large-scale circulation patterns may alter the regions where storms form or travel thereby exposing regions to new or more frequent hazards.

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). There is also 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 over this period (Rhein et al., 2013).

In terms of future climate projections, 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 the attributes of waves in adjacent ocean basins such as wave heights, periods and directions. The projected reduction in sea-ice extent in the Arctic Ocean will increase wave heights and the length of the wave season (Church et al., 2013).

6.3.2 Recent Anomalous Extreme Climate Events and their Causes

The important role of the ocean in influencing atmospheric and oceanic extreme events has become increasingly apparent. Events include marine heat waves and associated coral bleaching (e.g., Lewis and Mallela, 2018b), tropical and extra-tropical 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).

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 indicate how the link to climate change is building through time as is attribution for ocean and cryospheric events. Three studies in the most recent edition 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 have also emerged that undertake 'impacts attribution' to determine whether the climate change influence on the extreme event can be tied to a change in risk of the socio-economic or environmental impacts (Herring et al., 2018).

Table 6.2: Record-breaking extreme events relevant to this report and their impacts attributable to climate change. (Adapted and updated from Coumou and Rahmstorf, 2012)

Year	Region	Meteorological record-breaking event	Impact, costs	Attribution to climate change?
2004 	South Atlantic	First hurricane in the South Atlantic since 1970.	Three deaths, USD425 million damage (McTaggart-Cowan et al., 2006).	Increasing trend to positive 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 (Hurricane Katrina).	Trend in SSTs due to global warming contributed to half to total SST anomaly. AMO and ENSO 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, salt water flooding of food and water supplies in FSM, 1408 houses damaged and 63,000 people affected across 8 province of PNG	Event shown to have been made more extreme compared to other historical events due to La Nina and sea level rise. (Hoeke et al., 2013)
2010 	Eastern Australia	Highest December rainfall recorded since 1900 (ref. 45).	Brisbane flooding in January 2011, costing 23 lives and an estimated USD2.55 billion (van den Honert and McAneney, 2011)	Based on La Nina SSTs during satellite era, La Nina 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 (TS SENDONG) was world's deadliest storm in 2011	Fatalities: >1,250, injured: 2,002, missing: 1,049 (Rasquinho et al., 2013) total socio-economic costs: USD63.3 million (Espinueva et al., 2012)	No attribution done; disaster was the outcome of interplay of climatic, environmental and social factors (Espinueva et al., 2012)
	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 IPO and

				anthropogenic global warming (Feng et al., 2015)
	Golden Bay, New Zealand	two-day extreme rainfall in	In town of Takaka 453 mm was recorded in just 24 hours and 674 mm in 48 hours.	Total moisture available for precipitation in Golden Bay, New Zealand extreme rainfall was 15–5% higher due to anthropogenic emissions (Dean et al., 2013)
2012	Arctic	Arctic sea-ice minimum		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 (Zhang and Knutson, 2013)
	US East coast	Hurricane Sandy	Repair & mitigation expenditures funded at USD60.2 billion	Relative SLR shown to have increased probabilities of exceeding peak impact elevations since the mid-20th century (Sweet 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)	Occurred in a season with remarkably warm SSTs (David et al., 2013; Takagi and Esteban, 2016)
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		Human influence has increased the probability of regional high SST extremes over the western tropical and northeast Pacific Ocean during the 2014 calendar year and summer, with a likely role of natural internal variability. (Weller et al., 2015)
	Hawaiian hurricane season	Third largest hurricane season since 1949		Anthropogenic forcing contributed to the unusually large number of hurricanes in Hawaii in 2015, in combination with the moderately favorable condition of the El Nino event. (Murakami et al., 2015)
	Northland New Zealand	Extreme 5-day rainfall in Northland	NZD18.8 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	Third largest hurricane season since 1949	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)
	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)

	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 in a sunny day.	The probability of a 0.57 m flood has increased by 500%. (Sweet et al., 2016)
2015/2016	Northern Australia	1000 km of mangrove tidal wetland dieback	Potential flow-on consequences to Gulf of Carpentaria fishing industry worth AUD USD30M/ann 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 heat wave 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	global	warmth	thermal stress, coral bleaching, and melting of sea and land ice	Only possible with anthropogenic forcing (Knutson et al., 2018)
2016	central Equatorial Pacific, California Current	Record warm SSTs	Impacted the 2015–2016 El Nino event/impacted on marine resources	Appear to partly reflect an anthropogenic influence (Jacox et al., 2018a; Newman et al., 2018a)
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 heat waves	Impacts on marine ecosystems	Data suggest human-induced climate change (Oliver et al., 2018b; Walsh et al., 2018)
2016	Asia, Thailand	Record heat	In India, at least 580 were killed by the heat waves from March to May, 2016 In Thailand, devastating effects on major crops, and USD0.5 billion total loss in the agricultural production of about half a billion U.S.	Would not have been possible without anthropogenic climate change (Christidis et al., 2018; Imada et al., 2018)
2016	California, United States Yangtze-Huai and Wuhan,	Extreme rains		Both anthropogenic and the 2015–2016 increased the risk of extreme rains tenfold (Hope et al., 2018;

	China, southeastern Australia			Sun and Miao, 2018; Zhou et al., 2018)
2016	Great Barrier Reef, Australia	Extended period of heat stress	Extensive coral bleaching	Anthropogenic GHG emission increased the risk of coral bleaching through anomalously high SSTs and accumulation of heat stress (Lewis and Mallela, 2018b)
2017	Caribbean	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)

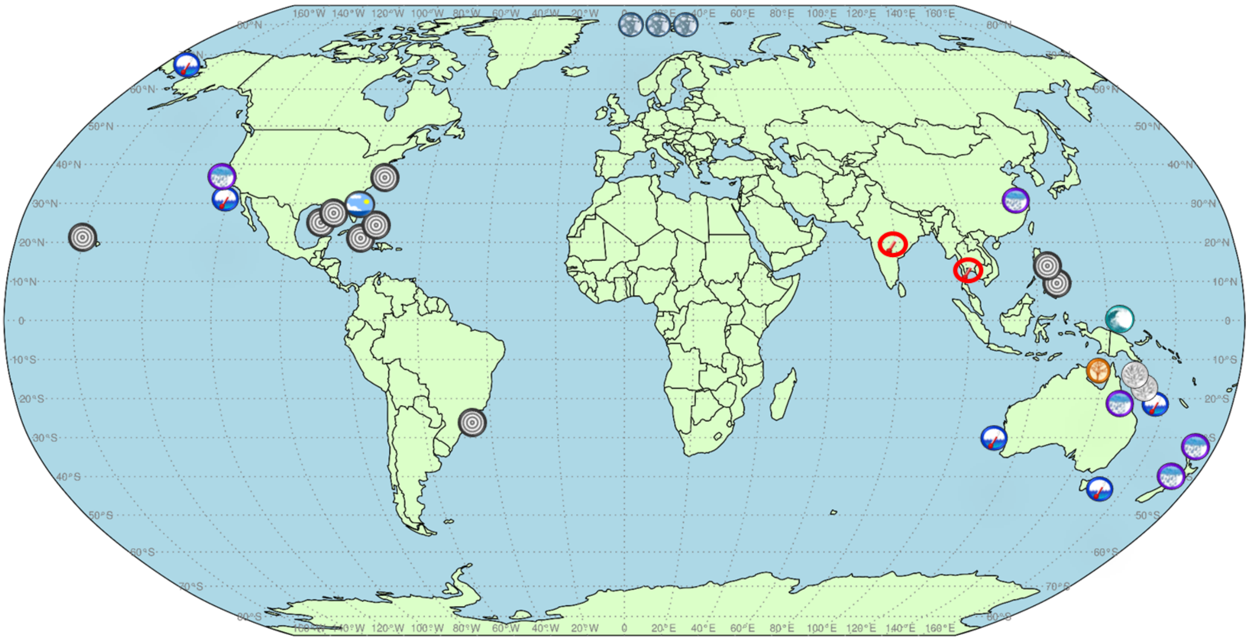

Figure 6.2: Locations where various attribution studies of extreme events have found a link to climate change. See Table 6.2 for details.

6.3.3 Projections of Cyclones and Wave Heights

6.3.3.1 Tropical Cyclones

Tropical cyclones are a source of coastal storm surges and extreme wave heights. While sea level rise will increase surge heights from storms, all other factors equal, a more difficult question is to determine how the tropical cyclone climate will change. IPCC AR5 concluded: "Globally, there is low confidence in any long-term increases in tropical cyclone activity (Hartmann et al., 2013) and we assess that there is *low confidence* in attributing global changes to any particular cause. In the North Atlantic region there is *medium confidence* that a reduction in aerosol forcing over the North Atlantic has contributed at least in part to the observed increase in tropical cyclone activity since the 1970s. There remains substantial disagreement on the relative importance of internal variability, GHG forcing and aerosols for this observed trend. It remains uncertain whether past changes in tropical cyclone activity are outside the range of natural internal variability." For tropical cyclone projections, IPCC AR5 concluded: "Based on process understanding and agreement in 21st century projections, it is likely that the global frequency of occurrence of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and precipitation rates. The future influence of climate change on tropical cyclones is likely to vary by region, but the specific characteristics of the changes are not yet well quantified and there is low confidence in region-specific projections of frequency and intensity. However, better process understanding and model agreement in specific regions provide medium confidence that precipitation will be more extreme near the centres of tropical cyclones making landfall in North and Central America; East Africa; West, East, South and Southeast Asia as well as in Australia and many Pacific islands. Improvements in model resolution and downscaling techniques increase confidence in projections of intense storms, and the frequency of the most intense storms will more likely than not increase substantially in some basins."

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 the Atlantic basin (Dunstone et al., 2013); identification of a poleward expansion of the latitudes of maximum tropical cyclone intensity in recent decades (Kossin et al., 2014) and comparison of such features to climate model historical runs and projections (Kossin et al., 2016). There have been a number of tropical cyclone dynamical or statistical/dynamical downscaling studies and higher resolution global climate model experiments that support previous projections of future tropical cyclone 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); and 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. One study (Emanuel, 2013) was notable for a marked projected increase in global tropical cyclone frequency, at variance with most other tropical cyclone frequency projections and with previous assessments.

Previous extensive studies had indicated the important role of warming oceans on TC activity (Emanuel, 2005; Mann and Emanuel, 2006; Trenberth and Fasullo, 2007; Trenberth and Fasullo, 2008; Villarini and Vecchi, 2012). Further, TCs stir the ocean and mix the subsurface cold water to the surface, leaving a cold wake after storm passage (Shay et al., 1992; Lin et al., 2009). Hence, ocean subsurface structure can affect TC intensity, but TC simulations including ocean coupling still indicated increased intensities in a warmer climate (Knutson et al., 2001). In a new study, the greater increase of thermal stratification of the upper ocean under global warming in CMIP5 models was anticipated to reduce the projected intensification of TCs (Huang et al., 2015). Subsequent follow-up studies found that 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.

Several observed historical landfalling tropical cyclone analyses have been published, including for global (Weinkle et al., 2012) and northwest Pacific basin (Lee et al., 2012) domains. The expected detectability of hurricane activity climate change signals and some proposed reasons for the lack of detection of intensity changes to date has been further explored (Sobel et al., 2016).

A relatively recent development for tropical cyclones and climate change is the event attribution approach where the attribution of certain individual tropical cyclone events or anomalous seasonal cyclone activity events to anthropogenic forcing is explored (Lackmann, 2015; Murakami et al., 2015; Takayabu et al., 2015; Zhang et al., 2016; Emanuel, 2017). In general, these are examples of model-based attribution without climate change detection. van Oldenborgh et al. (2017) and Risser and Wehner (2017) investigating the Hurricane Harvey event, conclude that 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 tropical cyclone-related precipitation.

There have been a number of studies exploring future track changes of tropical cyclones 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 across these studies, 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 generally of the order of 10% or less, and the size changes are variable even in sign between basins and studies. The initial studies represent preliminary findings on this issue, which future studies will continue to investigate.

Taking into account these developments and new findings, the following is a summary assessment of tropical cyclone 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 tropical cyclone 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) present evidence 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 including a contribution from anthropogenic forcing. They regard the poleward expansion of the latitude of maximum TC intensity as related to the expansion of the tropical circulation with climate warming (e.g., Bindoff et al., 2013). There are several other examples of observed long-term TC changes, which could represent emerging anthropogenic signals, but where there is presently only *low confidence* in a detectable anthropogenic influence. These include: i) decreasing frequency of severe landfalling tropical cyclones 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 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 tropical cyclone 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) For global tropical cyclone frequency, there is *medium confidence* that the global frequency will decrease or remain the same; confidence is *low* at the individual basin scale, except for the southwest Pacific where confidence in a decrease is *medium*. 2) For the frequency of very intense tropical cyclones (Category 4–5) there is *low-to-medium confidence* that the global frequency will increase. 3) For tropical cyclone intensity, there is *medium confidence* in an increase, and an increase is *likely* at the global scale. At the individual basin scale, the most consistent modeled increases are in the North Atlantic, Northwest Pacific, and South Indian basins. 4) For tropical cyclone precipitation rates, there is *medium-to-high confidence* in a projected global increase, and an increase is *likely* at the global scale, with *medium confidence* in an increase in each individual northern hemisphere tropical cyclone basin. 5). The most confident tropical cyclone-related projection is that sea level rise over the coming century will lead to higher storm surge levels for the tropical cyclones that do occur, assuming all other factors are unchanged.

6.3.3.2 Extra-Tropical Cyclones

Extratropical cyclones (ETCs) form in defined storm track regions characterised by large surface temperature gradients and baroclinic instability. Jet streams influence their direction and speed of movement. Future changes in storm tracks will influence extreme weather events in the mid-latitudes. Projecting future changes to midlatitude storms is challenging because different 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 the gradient (Shaw et al., 2016). Trends in poleward movement of baroclinic instability and associated storm formation over the observational period, due to external radiative forcing, are projected to continue, leading to associated declining rainfall trends in the midlatitudes and positive trends further polewards in a CMIP5 multimodel ensemble (Frederiksen et al., 2017).

Asian pollution has been found to invigorate winter cyclones over the northwest Pacific in regional and seasonal simulations of a cloud-resolving model, increasing precipitation by 7%, net cloud radiative forcing at the top of the atmosphere by 1.0 W m^2 and at the surface by 1.7 W m^2. A global climate model incorporating the diabatic heating anomalies from Asian pollution increased transient eddy meridional heat flux by 9% consistent with decadal variations in mid-latitude cyclones derived from reanalysis data (Wang et al., 2014c).

The link between the mid-latitude jet-stream and the loss of sea ice in the Arctic has also been further studied given that observations indicate the Arctic has warmed at twice the global-averaged rate and exceeds that simulated by climate models (Cohen et al., 2014). Using different blocking indices, Barnes et al. (2014) find no clear link between recent Arctic warming and sea ice loss with increased blocking over the northern hemisphere.

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 30% increase in 100-year return level wave energy flux for the majority of coastal areas in the southern temperate zone, while projected decrease in wave energy flux for most NH coastal areas. The most significant long-term trends in extreme wave energy flux are explained by the relationship to climate indices (AO, ENSO and NAO). Wang et al. (2014b) assessed the climate change signal and uncertainty in a 20-member ensemble of wave height simulations, and found model uncertainty (intermodal 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 SST in the tropical Pacific Ocean.

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 SLR on astronomical tides reveals that for SLR scenarios from 0.5 m, to 10 m MHW 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). Despite the advancements in global tide and surge modelling, using CMIP multi-model 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 global climate models being able to represent small scale weather systems such as tropical cyclones. 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 likely improve with further GCM and resolution improvements (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. For example, extreme sea levels are largely driven by swell waves that are largest in austral winter, 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 modeling 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 tropical cyclones 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 are projected along 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 ∼500 y during the preindustrial era have fallen to ∼25 y at present and are projected to fall to ∼5 y 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 potential to affect 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 influence cyclogenesis (e.g. Booth et al. (2012) for the Gulf Stream, Hirata et al. (2016) for the Kuroshio and Pepler et al. (2016a) for the East Australian Current), 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 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 together with tropical cyclone frequency and intensity changes. In a multi-model ensemble they find that relative to 1986–2005 changes in the FI by 2080–2099 are 4–75 times higher for RCP2.6 (10–90th percentile range) and 35–350 times higher for RCP8.5. In terms of ETC's in the EAC region, 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.

In summary, there have been significant developments since the AR5 to understand past and future changes in TC's and ETC's. Significant advances have been made in hydrodynamic models required to simulate storm surges and tides at global scale. Of relevance to compound hazards is several new studies that variously identify the western boundary currents 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

Impacts from weather extremes such as tropical cyclones are principally driven by hazard, exposure and vulnerability characteristics. 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 and signals from anthropogenic climate change have not been shown (Handmer et al., 2012; Arent et al., 2014). 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 local exposure characteristics. The frequency of nuisance flooding along the US east coast may accelerate in the future (Sweet and Park, 2014).

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). The relation between changes in tropical cyclones and property losses is however complex, and there are indications that wind shear changes may have larger impacts 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).

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 global circulation model (GCM) realizations. For example, projections by 2100 under an 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

Generally, lack of familiarity with the changed nature of storms prevails. Storm surge, for example, is a rare occurrence in areas prone to hurricanes, cyclones, and typhoons. Storms that changed track are often accompanied by storm surge, and surge warnings are not well understood and followed because they tend to be new or rare to the locality (Lagmay et al., 2015). A U.S. study on storm surge warnings highlights the issue of right timing to warn, as well as the difficulty in delivering accurate surge maps (Morrow et al., 2015). There is so far scant literature on the management of storms that change track. The most recent and relatively well studied ones are Superstorm Sandy in 2012 in New York and Typhoon Haiyan in 2013 in the Philippines. These two storms were unexpected and people, having underestimated the levels of impacts, ignored warnings and evacuation directives. Previous experiences with storms harmed rather than benefited disaster responses to storms changing tracks, intensities, or frequencies. 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 (Lejano et al., 2016). People's negative experiences of previous evacuations, such as traffic jams and unhealthy evacuation sites, contributed to less than half of the population being evacuated in New Jersey (Kulkarni et al., 2017), and to the higher number of casualties during Sandy (Dalisay and De Guzman, 2016).

After the storms, retreat or rebuild options exist. Buyout programs gained traction after Sandy, and the decision to retreat or rebuild depends on how communities have recovered in the past (Binder, 2014). Conflicts between local and state governments over land management responsibilities; lack of coordinated state-wide coastal adaptation plans; and clashes among individuals and communities needs have led to buyouts becoming unpopular (Boet-Whitaker, 2017). Relocation is more controversial, can incur the largest political risk (Gibbs et al., 2016), and is rarely implemented with much success. It is fraught with legal and human rights issues as seen in the case of resettlements after Haiyan (Thomas, 2015). To prepare for storms in a changing climate, discourse and planning abound (Knowlton and Rotkin-Ellman, 2014; Rosenzweig and Solecki, 2014). Despite resilient designs and sustainable urban plans integrating climate change concerns that are inclusive of vegetation barriers as coastal defenses, more hard-defense structures that are known to be less sustainable and short-term were built after Sandy.

Coordination of different organizations is typically cited as a problem in disaster response (Abramson and Redlener, 2013). The lack of coordination is seen among government agencies such as in the U.S. (between the Federal Emergency Management Agency and Housing and Urban Development) (Olshansky and Johnson, 2014); between government and nongovernmental organizations offering suspended services

(Santiago et al. 2016); and among the government and self-organized volunteers that use participatory mapping and social media tools (Wridt et al., 2016). Social media use proliferated during these storms with varied findings related to transmitting second hand information, generating scientific misinformation, understanding sentiments, and providing damage assessment (Guan and Chen, 2014; Knox et al., 2016; Takahashi and Tandoc, 2016).

6.4 Marine Heat Waves and their Implications

6.4.1 Observations and Key Processes, Detection and Attribution, Projections

Marine heat waves are important climatic extremes that can have significant, and sometimes devastating and long-lasting impacts on the physical and natural systems, with subsequent socioeconomic consequences (Pearce and Feng, 2013; Hobday et al., 2016a). Marine heat waves are characterized by ocean temperatures that are extremely warm for days to months (see SROCC Glossary; Hobday et al., 2016a), can extend hundreds of kilometres (Scannell et al., 2016) and can penetrate multiple hundreds of metres into the deep ocean (Benthuysen et al., 2018). However, unlike the effects of atmospheric heat waves 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 marine heat waves and their effects on marine organisms and ecosystems in IPCC AR5 (IPCC, 2013; IPCC, 2014) and IPCC SREX (IPCC, 2012).

6.4.1.1 Recent Marine Heat Wave Events and Key Driving Mechanisms

Several marine heat waves have been observed over the last few decades (Figure 6.3a). One of the first marine heat waves that has been documented in the literature occurred in the northern Mediterranean Sea (Garrabou et al., 2009; Galli et al., 2017) and was associated with the strong heat wave over Europe in 2003. The very warm atmosphere and weak winds caused excess heating of the sea surface and the highest ever recorded sea water temperatures in the Mediterranean Sea from June to August in 2003 (1°C-3°C above the climatological mean) (Olita et al., 2007). Record high ocean temperatures have been also observed in early 2011 off the coast of Western Australia from Ningaloo (22°S) to Cape Leeuwin (34°S) (Pearce and Feng, 2013; Wernberg et al., 2013; Benthuysen et al., 2014; Caputi et al., 2016; Perkins-Kirkpatrick et al., 2016). Predominant La Niña conditions in 2010 and 2011 strengthened and shifted the Leeuwin Current southward along the west coast of Australia leading to sea surface temperature (SST) anomalies of up to 5°C that persisted for more than 10 weeks (Pearce and Feng, 2013; Kataoka et al., 2014). In the first half of 2012, an anomalous atmospheric jet stream position induced smaller heat loss from the ocean (Chen et al., 2014; Chen et al., 2015b) leading to 1°C–3°C warmer surface coastal waters, the highest SST recorded in 150 years of measurements off the East Coast of the United States 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 experienced the largest marine heat wave 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). This marine heat wave emerged in the fall of 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 and suppressed heat loss from the ocean to the atmosphere (Bond et al., 2015; Di Lorenzo and Mantua, 2016). Low sea ice concentrations in the Arctic may have also played a role (Lee et al., 2015a). 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). This high-latitude marine heat wave was initiated by elevated SST in the North Pacific and associated shifts to southerly warm winds over Alaska (Overland et al., 2018). Reduced snow cover and associated albedo feedback may have also played a role (Walsh et al., 2017).

In 2015 and 2016, an unprecedented heat wave in the Tasmanian Sea lasted for 251 days with maximum SSTs of 2.9°C above climatology (Oliver et al., 2014b; Oliver et al., 2017). The anomalous warming was dominated 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 wind changes also having played a role (Schaeffer and Roughan, 2017). In early 2017, the fast and strong ocean warming of up to 10°C off the northern coast of Peru (Ramírez and Briones, 2017) was caused by local air-sea interactions involving northerly winds and the strengthening of the Intertropical Convergence Zone in the Southern Hemisphere (Takahashi and Martínez, 2017; Garreaud). Marine heat waves also repeatedly occurred over the western Pacific Warm Pool including the Coral Sea and the Indonesian-Australian Basin in 1998, 2010, 2015–2016 (Hughes et al., 2017b; Le Nohaïc et al., 2017; Benthuysen et al., 2018)**.** The 2015–2016 extreme warming across tropical Australia was caused by reduced cloud cover during the strong El Niño, which led to enhanced air-sea heat flux anomalies in these regions (Benthuysen et al., 2018). In the Indian Ocean, coral records for the period 1795–2010 indicate multidecadal variations in the occurrence of marine heatwaves, with the highest amplitudes between 1795 and 1850 and post 1980 — although the proxy SST reconstruction for 1795–1850 should be interpreted with caution (Zinke et al., 2015).

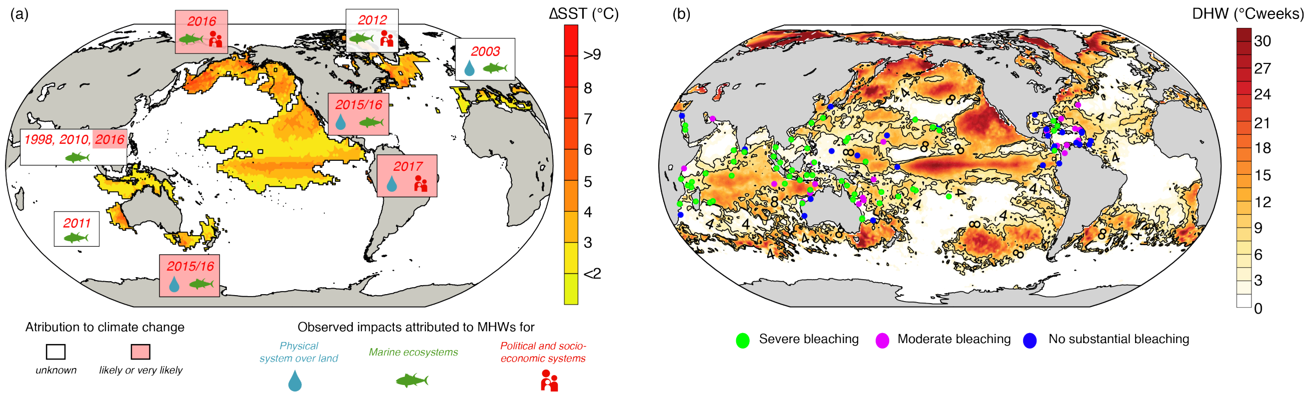

Figure 6.3: (a) Recent marine heat waves and their documented impacts. The color map shows the maximum sea surface temperature anomaly during documented marine heat waves using NOAA's daily Optimum Interpolation sea surface temperature dataset (Reynolds et al. 2007, Banzon et al. 2016). A marine heat wave is defined 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 deseasonalizing the data. The numbers indicate the year of the marine heat wave occurrence. Red shading of the boxes indicates if the likelihood of marine heat wave occurrence has increased due to climate change, and symbols denote observed impacts on physical systems over land, marine ecosystems, and political and socio-economic systems. Figure is updated from Frölicher and Laufkötter (2018). (b) The record-warming years 2015–2016 and the global extent of mass bleaching of corals during these years. The color map shows the degree heating week annual maximum over 2015 and 2016 from NOAA's Coral Reef Watch Daily Global 5km Satellite Coral Bleaching Heat Stress Monitoring Product Suite v.3.1 (Liu et al., 2014). 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 processes leading to the build-up, persistence and decay of the individual marine heat waves depend on the location and season of occurrence (Pearce and Feng, 2013). Marine heat waves may be associated with large-scale modes of climate variability, such as El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole, North Pacific Oscillation and North Atlantic Oscillation. These modes can change the strength and position 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. Extreme warm SSTs and the termination of marine heat waves 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 large marine heat wave in 2016 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 rescued the southern part of the Great Barrier Reef corals from bleaching.

6.4.1.2 Detection and Attribution of Marine Heat Wave 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). Exacerbated by one of the strongest El Niño events on record, this ocean warming has resulted in the warmest sea surface temperature in 2015 and 2016 since the beginning of the instrumental record in the 19th century (Figure 6.3b). Concomitant with the long-term ocean warming trend, satellite observations and in-situ measurements reveal that marine heat waves have *very likely* increased since 1925 (Oliver et al., 2018a). Over the satellite period between 1982 and 2016, the number of marine heat wave days exceeding the 1982–2016 99th percentile have been doubled globally (*high confidence*) (Frölicher et al., 2018; Oliver et al., 2018a), *very likely* due to anthropogenic warming (Frölicher et al., 2018). Marine heat waves 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 marine heat waves 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), and is possibly too short for a full recovery of mature assemblages of bleached corals (Hughes et al., 2018a). The trend towards more frequent and intense marine heat waves can largely be explained by the increase in mean ocean temperatures with large increases in the probability of marine heat waves during El Niño years (Frölicher et al., 2018; Oliver et al., 2018a). This suggests that a further increase in the probability of marine heat waves under ongoing global warming can be expected.

Major scientific progress in probabilistic extreme event attribution research makes it now possible to attribute the risk of individual extreme climate events to human-induced climate change. Most of the studies use a fraction of attributable risk approach (Stott et al., 2004), in which characteristics of extreme events are compared between climate model simulations including human influences and simulations without to quantitatively estimate anthropogenic influences. While many attribution studies exist for land-based extreme events, only a few attribution analyses have been conducted so far for marine heat waves. (Weller et al., 2015). These studies show that all of the individual marine heat wave events that have been analysed have a clear human-induced signal (*high confidence*) (Figure 6.3a). However, natural variability still lays the foundation for the events to occur. On a global scale, about 90% of today's occurrence of marine heat waves are attributable to 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 2016 Alaskan marine heat wave (Oliver et al., 2018b; Walsh et al., 2018) and the marine heat wave in Northern Australia in 2016 (Oliver et al., 2018b) have been nearly fully attributed to anthropogenic forcing. This means that human-caused climate change is strong enough to push these events beyond the bounds of natural variability alone. Also, there was clear anthropogenic influence on the extreme ocean temperature along in the California Current large marine ecosystem (Jacox et al., 2018b). The Northeast Pacific marine heat wave in 2014 has become about five times as likely with human-caused global warming (Wang et al., 2014a; Weller et al., 2015), and the 2015/2016 anomalously warm SST in the Niño-4 region of the central equatorial Pacific and the extensive warming over the Great Barrier Reef were likely unprecedented (Lewis and Mallela, 2018a; Newman et al., 2018b). The duration and intensity of the marine heat wave 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 heat waves will *very likely* increase in frequency and intensity under future global warming (Oliver et al., 2017; Ramírez and Briones, 2017; Frölicher et al., 2018; Frölicher and Laufkötter, 2018). Projections based on CMIP5 Earth System Models suggest that, on global scale, the probability of marine heat waves exceeding the preindustrial 99th percentile will increase by a factor of 41 (intermodel range: 36–45) (Figure 6.4a) under a global warming of about 3.5°C relative to preindustrial levels (Frölicher et al., 2018). At this level of global warming, marine heat waves have an average spatial extent that is 21-times (15–29) bigger than at preindustrial; i.e., the typical spatial extent increases from $4.2\cdot10^5$ km^2 to $94.5\cdot10^5$ km^2; last on average 112 days (92–129 days) and reach maximum intensities of 2.5°C (2.1°C–2.9°C). The probability of occurrence is halved if warming could be limited to 2°C rather than 3.5°C, and further reduced by about 30% when global warming is kept below 1.5°C.

The changes in marine heat waves will not be globally uniform. Largest changes in the probability of marine heat waves are projected to occur in the western tropical Pacific and the Arctic Ocean (Figure 6.4b). Climate model analysis also reveals that marine heat wave events in the Great Barrier Reef, such as the one associated with the bleaching in 2016, would be at least twice as frequent in a 2°C world than they are today (King et al., 2017). However, if warming is kept to 1.5°C instead of 2°C, marine heat waves would be 25% less frequent. Recent research has also indicated that anthropogenic climate change will further strengthen the southward transport in the East Australian Current Extension and therefore increase 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 changes in the probability of marine heat waves are driven by the global-scale shift in the mean ocean SST stemming from ocean warming. When contrasting the changes in the probability of marine heat waves with land-based heat waves (Fischer and Knutti, 2015), it becomes evident that marine heat waves are projected to occur much more frequently than land-based heat waves (Frölicher et al., 2018; Frölicher and Laufkötter, 2018).

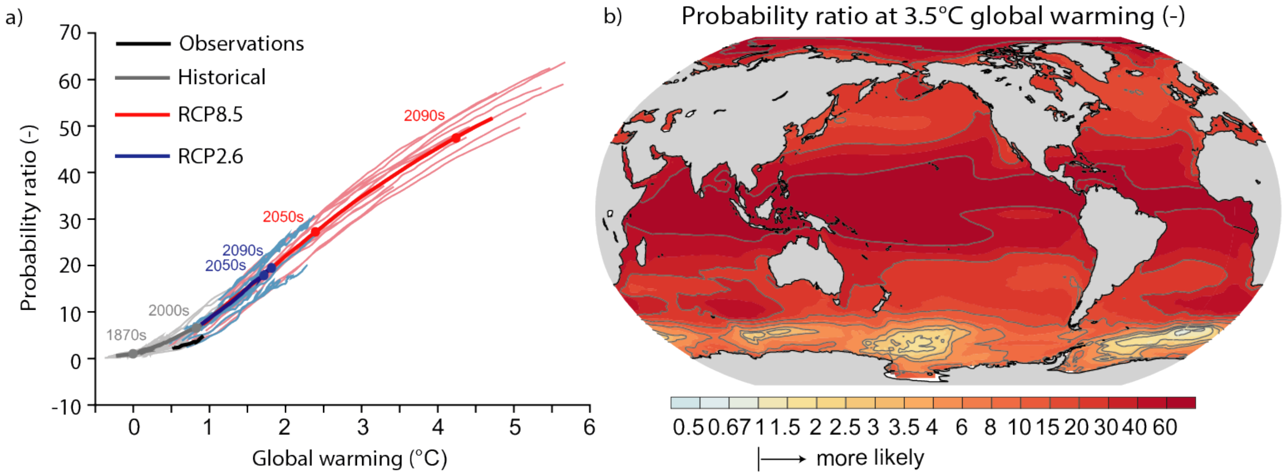

Figure 6.4: (a) Probability ratio exceeding the 99th percentile of preindustrial daily sea surface temperature at a given warming level relative to pre-industrial conditions averaged over the ocean. The thinner lines represent individual model projections, while the thicker lines represent the observations and the multi-model averages for the RCP8.5 and RCP2.6 scenario. The simulated and observation-based time series are smoothed with a 30-year and 10-year running mean, respectively (b) Changes in the multi-model mean probability of marine heat waves exceeding the preindustrial 99th percentile under 3.5°C global warming. 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

Marine heat waves can strongly impact 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), local (Wernberg et al., 2013; Wernberg et al., 2016) and potentially global (Brainard et al., 2011) extinctions. With marine heat waves predicted to increase with further climate warming, it is very likely that this will result in profound impacts on natural, physical and human systems.

A growing number of studies have reported that recent marine heat waves negatively affected corals and coral reefs through bleaching, disease, and mortality. Coral bleaching involves the disruption of the symbiotic relationship between corals and their endosymbiotic algae triggered by positive temperature anomalies (Spalding and Brown, 2015). Bleached corals are physiologically and nutritionally compromised, and prolonged bleaching over several months leads to high levels of coral mortality (Spalding and Brown, 2015) (LINK TO CHAPTER 5). Heat-stressed corals that either do not visibly bleach or may recover from bleaching can also be more susceptible to disease, either from infection or imbalances in existing microbiota (Heron et al., 2010; Burge et al., 2014). Coral bleaching events have impacts on the entire coral reef ecosystem, leading to rapid erosion of reef structure (Couch et al., 2017) and changes to fish communities (Graham et al., 2007). The recent (2014–2017) high ocean temperature 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 1997–1998 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 of mass bleaching of corals, mainly determined by the spatial pattern and magnitude of the marine heat wave. 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), resulting in a loss of 30% of the live corals on the Great Barrier Reef and significant shifts in coral community composition (Hughes et al., 2018b). However, the southernmost region of the Great Barrier reef escaped with only minor heat stress and bleaching, because protracted storminess and a large cyclone held summer temperatures there close to average (Hughes et al., 2017b). In addition, impacts to corals were severe in the central equatorial Pacific at Jarvis with concomitant decreases in total reef fish biomass and seabirds, but only moderate at nearby Howland, Baker and Kanton Islands (Brainard et al., 2018).

As climate change has increased the frequency and intensity of marine heatwaves affecting reefs (Hughes et al., 2018a) the extent of bleaching in response to heat stress on some reefs has been modified by prior events (Guest et al., 2012). Not only do corals bleach less when they are subject to non-bleaching thermal stress in prior years ('thermal acclimatization' or 'ecological memory'), but also short-term pulses of low-level heat stress may help corals prepare for higher heat stress later in the same season (Ainsworth et al., 2016). However, such modifications were not observed during the 2015–2016 mass coral bleaching event (Hughes et al., 2017b). The protective mechanism will likely be lost in the future due to a general increase in SST under climate change, which reduces the occurrence of the "protective bleaching trajectory" (in which a protective, sub-bleaching thermal stress event precedes a bleaching event), as most increases in SST will directly exceed the corals' temperature threshold and result in bleaching (Ainsworth et al., 2016). Climate models suggest the onset of annual bleaching conditions is associated with about 510 ppm CO_2 equivalent (median year of all locations is 2040 under the RCP8.5 scenario) (van Hooidonk et al., 2013), although lags in the response of the climate to CO_2 suggest annual bleaching may result from lower CO_2 levels (Hoegh-Guldberg et al., 2017). Not surprisingly, global projections of bleaching conditions are not spatially uniform. For example, 26% of reef cells (mainly in the western Indian Ocean, Thailand, the southern Great Barrier Reef and central French Polynesia) are projected to experience annual bleaching more than 5 years later than the median. Reducing emissions would only have a positive effect on the health of corals in the long-term and negative emissions may be necessary to reduce CO_2 levels to those needed for long-term reef health (Veron et al., 2009; Gattuso et al., 2015). The impact of such CO_2 policies is likely to vary regionally. While the effect of a reduction in emissions on Caribbean reefs will be modest and realized only after more than 60 years, Pacific reefs would start to show benefits within the first half of this century (Ortiz et al., 2014).

Apart from strong impacts on corals, marine heat waves can also have extensive impacts on other marine ecosystems (Ummenhofer and Meehl, 2017). Two of the best studied marine heat waves with extensive ecological implications occurred in 2010/2011 off Western Australia and in 2013–2015 in the northeast Pacific. The 2010/2011 marine heat wave off Australia resulted in an entire regime shift of the temperate reef ecosystem (Wernberg et al., 2013; Wernberg et al., 2016). Biodiversity patterns of temperate seaweeds, sessile invertebrates and demersal fish were significantly altered after the event, which led to a reduction in abundance of habitat-forming seaweeds, a subsequent shift in community structure, and a southward distribution shift in tropical fish communities. The sea grass *Amphibolis antarctica* in Shark Bay underwent defoliation after the marine heat wave (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 followed by high mortality and effects on invertebrate fisheries were observed (Depczynski et al., 2013; Caputi et al., 2016). The 2013–2015 marine heat wave in the northeast Pacific also caused large 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 in the northern California region (Di Lorenzo and Mantua, 2016), and novel species compositions (Peterson et al., 2017). In addition, a coast-wide bloom of toxigenic diatom and the largest recorded outbreak of the neurotoxin, domoic acid was observed (McCabe et al., 2016), which resulted in elevated toxins in marine mammals and closure of razor clam, rock crab and crab fisheries.

Other marine heat waves have also highlighted the vulnerability of marine organisms to elevated ocean temperatures. The 2012 marine heat wave event in the Northwest Atlantic resulted in a major impact on 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 2003 marine heat wave in the Northwestern Mediterranean lead to mass mortalities of macro-invertebrate species (Garrabou et al., 2009) and the recent 2015/16 Tasman Sea marine heat wave 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 SST (Baker-Austin et al., 2013). The 2016 Alaskan marine heat wave favoured some phytoplankton species, leading to harmful algal blooms, shellfish poisoning events and mortality events in seabirds (Walsh et al., 2018).

6.4.2.2 Impacts on the Physical System

Marine heat waves can impact the physical systems over land via teleconnections. For example, the warm North Pacific Ocean during 2013 to 2015 and the associated persistent atmospheric high-pressure ridge prevented normal winter storms from reaching the West Coast of the U.S and contributed to the drought conditions across the entire West Coast (Seager et al., 2015; Di Lorenzo and Mantua, 2016). The Tasman Sea marine heat wave of 2015/2016 may have increased the intensity of rainfall that caused flooding in northeast Tasmania in January 2016 (see Box 6.1) and that the Peruvian marine heat wave in early 2017 caused heavy rainfall and flooding on the west coast of tropical Southern American and the adjacent Andes mountains (Garreaud). Similarly, marine heat waves in the Mediterranean Sea can contribute to heat waves (García-Herrera et al., 2010) and heavy precipitation events over central Europe (Messmer et al., 2017).

6.4.2.3 Impacts on the Human System

Marine heat waves can also lead to significant political and socio-economic ramifications when affecting aquaculture or important fishery species, or when triggering heavy rain or droughts on land. The marine heat wave in the northwest Atlantic in 2012 lead to altered fishing practices and harvest patterns, with major economic impacts (Mills et al., 2013). Due to the marine heat wave, lobsters moved from the deep offshore waters into shallower coastal areas much earlier in the season than usual, and catch rates rose rapidly. The record catch outstripped market demand and contributed to a price collapse that threatened the economic viability of both US and Canadian lobstermen (Mills et al., 2013). The 2013–2015 North Pacific marine heat wave lead to closing of both commercial and recreational fisheries resulting in millions of dollars in losses among fishing industries (Cavole et al., 2016). The ecological changes associated with the 2016 Alaskan marine heat wave also impacted subsistence and commercial activities. The lack of winter sea ice in western Alaska delayed or prevented ice-based harvesting of fish, crabs, seal and whale, and caused oyster farm closures. The heavy rain associated with the Peruvian marine heat wave in 2017 triggered numerous landslides and flooding, which resulted in a death toll of several hundred, widespread damage to infrastructure and civil works (United Nations, 2017) and significant economic losses (Macroconsult, 2017).

6.4.3 Risk Management and Adaptation, Monitoring and Early Warning Systems

Marine resource management decisions on how to respond to marine heat waves will benefit greatly from a clear understanding of the background conditions and underlying processes resulting in extreme ocean conditions (Oliver et al., 2017), and from seasonal (weeks to months) and multi annual-to-decadal forecasts of marine heat waves.

Knowledge of marine heat wave history can influence the way in which managers and researchers evaluate the current condition of reefs, and how they anticipate and respond to bleaching impacts on reefs. Since 1997, NOAA's 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 2014–2016 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). As the prediction skill of seasonal SST often exceed that of persistence, even in coastal ecosystems (Stock et al., 2015), such seasonal SST predictions have been used for multiple ecosystems and fisheries, including aquaculture, lobster, sardine, and tuna fisheries (Hobday et al., 2016b; Tommasi et al., 2017b). For example, seasonal forecasts of SST help salmon aquaculture farm managers in Tasmania to prepare and respond to upcoming marine heat waves 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 forecasts 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). Fisheries managers, for example, are interested if SST over the next few years will be higher or lower relative to the past, to adjust their catch strategy. 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).

However, even with a monitoring and prediction system in place, marine heat waves have developed without warning and had catastrophic effects. For example, governmental agencies, socioeconomic sectors, public health officials and citizens were not forewarned of the 2017 Peruvian marine heat wave, 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).

In coral reefs, resilience can depend on locally manageable stressors such as fishing pressure and water quality (McClanahan et al., 2012; Scheffer et al., 2015). For example, the takeover of most Caribbean reefs by seaweeds was triggered by sea-urchin mortality, but was facilitated in many locations by high nutrient loading and overharvesting of fish functional groups that controlled the seaweeds. On the Great Barrier Reef, coral recovery rates after the 1998 bleaching event were markedly suppressed by experimental exclusion of herbivorous fishes. However, it has been shown that local protection of reefs from bad water quality and fishing pressure leads to little or no resilience against extreme heat. Water quality and fishing pressure had minimal effect on the unprecedented bleaching in 2016 in the Great Barrier Reef (Hughes et al., 2017b). On the remote northern Great Barrier Reef, hundreds of individual reefs were severely bleached in 2016 regardless of whether they were zoned as no-entry, no-fishing, or open to fishing, and irrespective of inshore-offshore differences in water quality. While these local protective measures may not convey resilience against heat stress, they can be important for the recovery of coral reef ecosystems after marine heatwaves (Scheffer et al., 2015).

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 no substantial 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), with some indication that the ENSO variance over 1979–2009 to be much larger than that over 1590–1880 (McGregor et al., 2013). 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).

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, in the United Kingdom in December 2015, the Yangtse and Huai Rivers in China resulting in severe urban inundation in huge cities (Wuhan and Nanjing) with losses approximating USD10 billion, and increasing their risk of flood events ten-fold, and also, in southeastern China as the event reached its peak (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). They define an extreme El Niño event as being 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, 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 makes the 2015/2016 El Niño the warmest in the instrumental records (Santoso et al., 2017). However, once the warming trend is removed, the 2015/2016 El Niño is comparable with the 1997/98 El Niño. 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 (Santoso et al., 2017).

A combination of strong ENSO and Indian Ocean Dipole (IOD) events lead to shifts in the 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).

Extreme El Niño frequency increases with the global mean temperatures (GMT) with a doubling in the 21st century under RCP8.5 (Cai et al., 2014a) (Figure 6.5) and the increase in frequency continues for up to a century after GMT 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 GMT has 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). Nevertheless, some studies find little impact of climate change on ENSO rainfall anomalies in, for example, South America (Tedeschi and Collins, 2017).

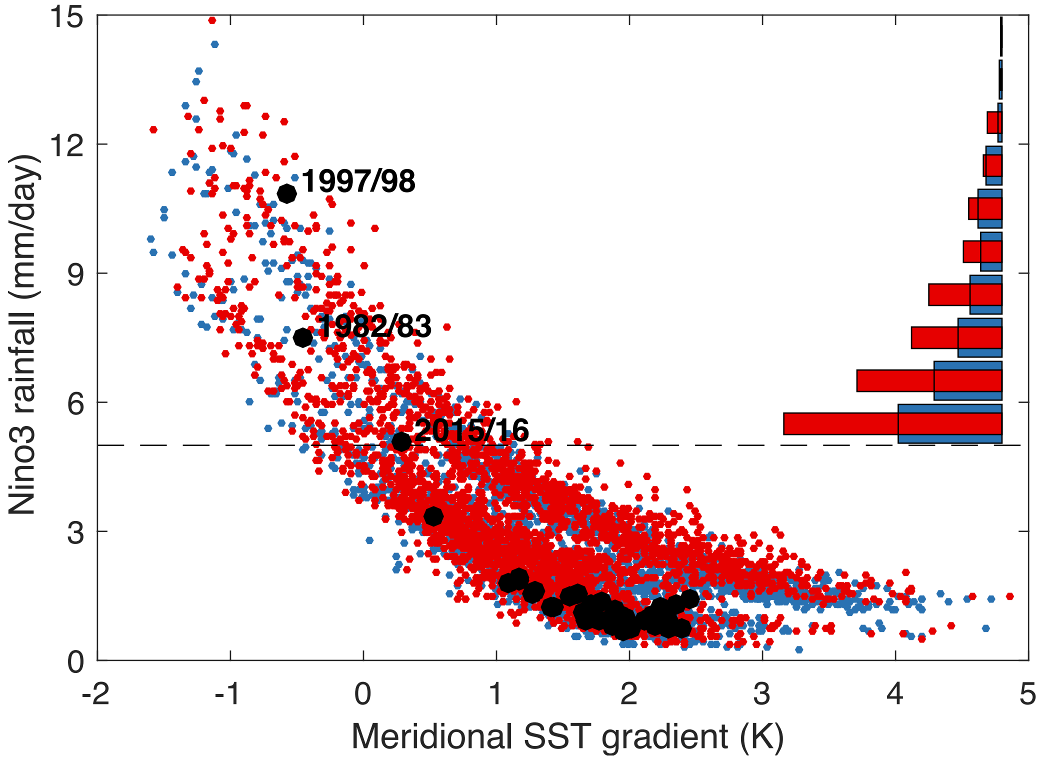

Figure 6.5: Frequency of extreme El Niño events, adapted from Cai et al. (2014a). The dots indicated Dec-Feb mean meridional SST gradient (x-axis: 5°N–10°N, 210°E–270°E minus 2.5°S–2.5°N, 210°E–270°E) and NINO3 anomalous rainfall (y-axis: 5°S–5°N, 210°E–270°E). Blue dots are from CMIP5 historical simulations and red dots from future RCP8.5 simulations, using those models than can simulate extreme El Niño events. The horizontal dashed line indicates the threshold for an extreme. Black dots are from observations. The histogram bars on the right side of the plot show the relative frequency of events in historical (blue) and RCP8.5 simulations (red) highlighting the future increase in frequency.

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

The Indian Ocean basin-mean temperature has experienced consistent warming from the surface to 2000 m during recent decades, and most of the warming has occurred 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, accounting for more than 28% of the global ocean heat gain, despite only representing ~12% of the global ocean area (Cheng et al., 2017). While the global mean SST warming is about 0.65°C and the tropical SST warming is about 0.83°C during 1950–2015, the tropical Indian Ocean SST has warmed by 1.04°C. Climate model experiments indicate that anthropogenic forcing accounts for about 90% of the surface warming in the Indian Ocean (Dong et al., 2014). Frequent warm events in the Indian Ocean in the recent decades are a response to El Niño events through the atmospheric bridge via the Walker circulation (Roxy et al., 2014) and the oceanic tunnel via the Indonesian Throughflow (Susanto et al., 2012; Sprintall and Revelard, 2014; Lee et al., 2015b; Susanto and Song, 2015).

The frequency of extreme positive IOD events is projected to increase by almost a factor of three, over the twenty-first 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 (Wang and Liu, 2014; Yonekura and Hall, 2014; Zhang and Guan, 2014; 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., 2016) and agriculture (Iizumi et al., 2014). 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 increasing extreme El Niño events, the northern hemisphere summer monsoon shows substantial intensification during 1979–2011, with a striking increase of rainfall by 9.5% per degree of global warming (Wang et al., 2013). However, the Indian summer monsoon 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) but also to increased aerosol emissions (Guo 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, aggravated 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); Risk Management Solutions, 2015). The subsurface heat discharge due to El Niño can intensify tropical cyclones in the eastern Pacific (Jin et al., 2014; Moon et al., 2015). 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., 2016). 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—followed by a rise in atmospheric CO_2 concentrations due an increase to the response from the terrestrial component of the carbon cycle (Chatterjee et al., 2017). It is not clear how a future increase in the frequency extreme events would modulate the carbon cycle on longer decadal time scales.

Figure 6.6 provides a summary of studies of the combined impacts of mean climate change and modes of variability.

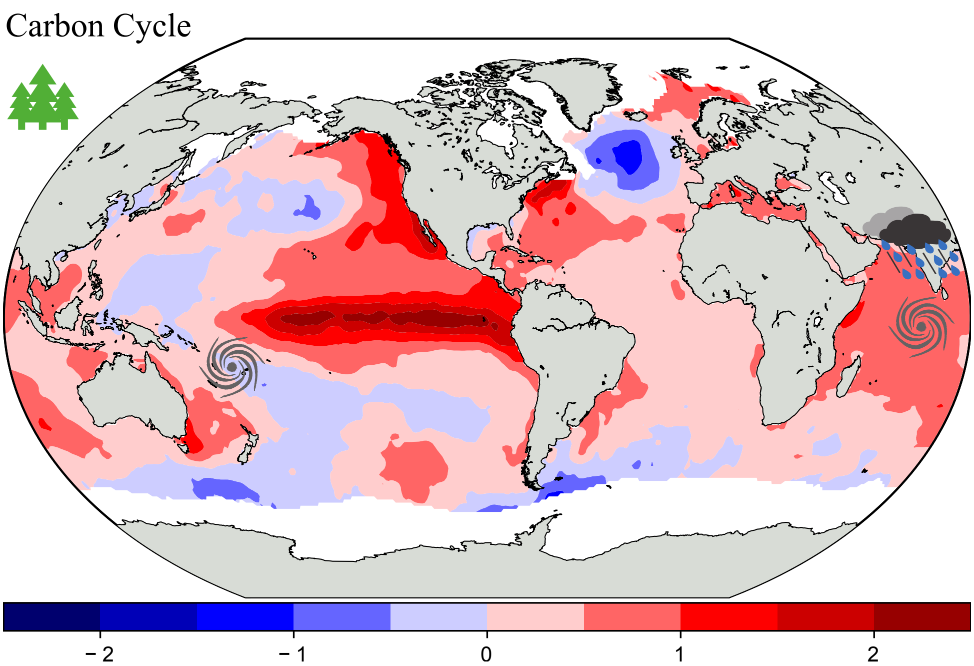

Figure 6.6: Schematic figure indicating where studies have considered the joint impacts of climate change and modes of variability. The background pattern of SST anomalies are averaged from June 2015 to July 2016 during the most recent extreme El Niño event.

6.5.3 Risk Management and Adaptation

Risk management of 'normal' ENSO events has focussed on better prediction and early warning systems, and better mechanisms for reducing risks to agriculture, wildfire and flood management, and so on. Extreme ENSO events are, however, very rare and difficult to predict. 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 'normal' ENSO events (see e.g., also Chapter 4, for coastal risks). 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 bursts in the Western Tropical Pacific affect the genesis of El Niño events (Chen et al., 2015a; Fedorov et al., 2015). On the other hand, strong easterly wind bursts in the tropical Pacific have been observed to stall El Niño events (Hu and Fedorov, 2016). Advection of mean temperature by anomalous eastward zonal current also plays an important role in producing extreme El Niño events. Another parameter is the advection of mean temperature by anomalous eastward zonal current that plays 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 individual characteristic of each El Niño extreme event, a recent study indicates a new method of forecasting given the 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 5km resolution (Liu et al., 2018). The impacts of ENSO associate extreme heat stress are heterogeneous, likely 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). These factors can be used for risk management for these ecosystems.

6.6 Inter-Ocean Exchanges and Global Change

The AR5 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 contributing. While not noted at the time, because of the magnitude and duration of this Pacific-centered variability (Figure 6.7), we may label this as an abrupt change or, at the very least, an extreme event. Hence, we discuss it in this chapter, noting a considerable new amount of literature. Whether natural or having an anthropogenic component, it is much discussed in the climate change literature.

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 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). The magnitude and duration of this trend was unprecedented in the, albeit, rather limited and uncertain observational record. Moreover, it is a very extreme event when model simulations are used as an estimate of internal climate variability (England et al., 2014; Kociuba and Power, 2015). The slowdown in global surface warming was 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 additional heat uptake by the ocean. The intensification of the Pacific trade winds is *likely* due to the inter-ocean warming contrast, with the slowdown in the Pacific surface warming and rapid warming in the Indian (see section 6.5.1.2) and Atlantic Oceans (Kucharski et al., 2011; Luo et al., 2012; McGregor et al., 2014; Zhang and Karnauskas, 2017). Although, because the strengthened Pacific trades are coupled to cooler Pacific SSTs, because of its unprecedented nature and importance in driving global-scale temperature variability, we describe the Pacific trends and associated pattern of SST anomalies (the ‘Interdecadal Pacific Oscillation’, IPO), an extreme decadal variability event. While it is potentially a result of natural internal variability, a role of anthropogenic contribution cannot be ruled out.

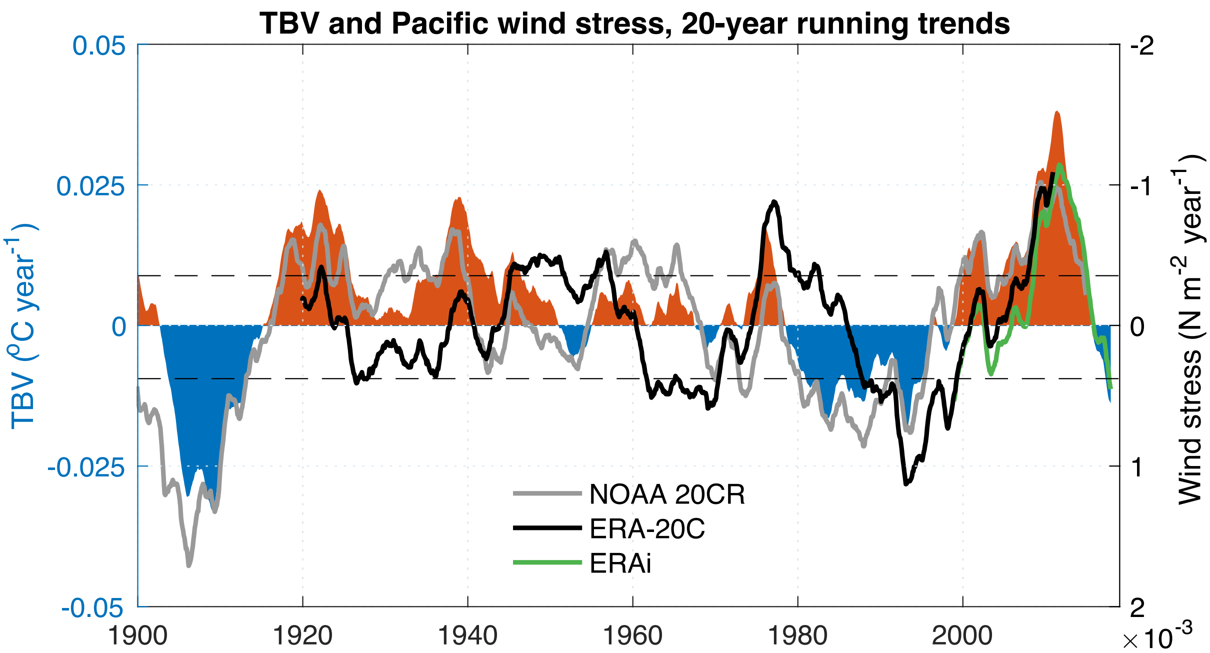

Figure 6.7: 20-year running trends in the trans-basin variability (TBV) index (degrees per year), which denotes tropical Atlantic area-average SST (20°S–20°N and 70°W–20°E) minus tropical Pacific SST (20°S–20°N and 120°E–90°W),

from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST; Rayner et al. (2003); red and blue shading). Also shown are 20-year running trends of zonal wind stress (N m^{-2} per year) over the central Pacific (area-averaged over 8°S–8°N and 160°E–150°W) from three re-analyses: NOAA 20CR v2c (Compo et al. (2011); grey line), ERA-20C (Poli et al. (2016); black line) and ERA Interim (Dee et al. (2011); green line). The dashed lines show the 5–95 percentiles of the frequency distribution of the 20-year running wind stress trends from all-available r1i1p1 CMIP5 historical simulations with RCP8.5 extension, over the period 1900 to 2014.

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., 2017) and thus potentially underestimate global mean temperature decadal variability.

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. As part of the global ocean conveyer belt, the ITF plays a significant role in global ocean circulation and climate (Sprintall et al., 2014). The ITF has tidal to interannual and possibly decadal variability, a stronger transport during La Niña and a weaker transport during El Niño (Susanto et al, 2012). The ITF annual average is 15 Sv (1 Sv = 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 Sv (Gordon et al., 1999). 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., 2015; 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 (section 6.5.1.2), by transferring warm water from western Pacific into the Indian Ocean (Lee et al., 2015b). Under 1.5°C warming both El Niño and La Niña frequencies increase (Cai et al., 2014a; Cai et al., 2015), and hence ITF variability may also increase. 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 Sv 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 Sv with a maximum in austral winter, and Indian Ocean Dipole-related interannual variability of 8.9 Sv (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 co-vary 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).

It is hence essential to capture decadal variations of the Indian Ocean's boundary currents and the ITF in order to understand their roles, as capacitors for Pacific variability and as carriers of heat and freshwater, in driving decadal climate variability and rapid warming trends in the Indian Ocean.

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.

6.6.3 Risk Management and Adaptation

There already are evidence of cases of regional abrupt changes in the ocean, (such as abrupt change in sea-ice interaction and circulation), with these events occurring for global warming less than two degrees, a threshold presented as a safe limit.

It is deemed that monitoring for tipping points are vital in order to be able to predict when and where the abrupt changes/frequency at which systems cross thresholds and abruptly shift to new state will occur. Studies have highlighted the need for policy designs that will decrease the risk of undesired tipping points or, when necessary, to facilitate transitions across tipping points to a new preferred state, use/application of the social-ecological system (SES) perspective as it explicitly accounts for social and biophysical feedbacks that can precipitate tipping points, framing of marine governance arrangements in order to anticipate increasing marine social-ecological vulnerability, design of management strategies that consider tipping points in order to have better management outcomes, development of early warning systems including signals of ecosystem instability, threshold-integrated management, and increased investment in monitoring and mitigation as the likelihood of dramatic social-ecological system change increases (Selkoe et al., 2015; Brown et al., 2016; Serrao-Neumann et al., 2016; Yletyinen et al., 2017).

There is agreement in the studies that management is most effective when it is using explicitly science to avoid thresholds or to reverse ecosystem change after a threshold has been crossed. Effective management is associated with routine monitoring of the system on a temporal and spatial scale relevant to the ecological threshold, and with local- and regional -scale management rather than decision making at larger spatial scales, increased integration of threshold-based science tools into ecosystem management and the continued investigation of thresholds as leverage points for efficiently maintaining ecosystem structure and functioning (Kelly et al., 2016). It is suggested that early action to preserve system resilience is likely more practical, affordable, and effective than late action to halt or reverse a tipping point.
The strict monitoring/ implementation of regulatory functions by the 17 Regional Fisheries Management Organizations (RFMOs) in order to regulate fisheries on the high seas are also being considered (Ewell et al., 2017).

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). This is related to large changes in the ocean circulation due to variations in convective activity. Indeed, the North Atlantic is one of the few locations in the ocean where deep convection connects the upper with the deeper ocean. The associated sinking of waters induces a large-scale Meridional Overturning Circulation in the Atlantic (AMOC) which transports large amounts of heat northward even 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).

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 large-scale oceanic section (RAPID section measuring the AMOC at 26°N, OSNAP measuring the AMOC in the subpolar gyre, and OVIDE measuring the AMOC through a repeated section between Portugal and the tip of Greenland) including in the Southern Hemisphere (SAMOC, which will measure the AMOC around 30°S in the coming years). The strength of the AMOC at 26°N has been continuously estimated since 2004 with an annual mean estimate of 16.9 ± 1.5 Sv over the 2005–2016 period superimposed by large intra and interannual variability and of 14.7 Sv at 34.5°S over the period 2009–2017 (Meinen et al., 2017).

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), because only very few deep ocean observations before the ARGO era starting around 2004 are available. No significant (95% confidence level) decreasing trend is found for the annual mean AMOC measured by the RAPID array over the period 2005–2016, but this result remains very sensitive, due to the short length of direct observational records. Based on AMOC reconstruction using its potential SST fingerprints, it has been suggested that the AMOC may have experienced around 3 Sv 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). This weakening over the historical era needs to be confirmed (*low confidence*), while its potential causes remain largely unknown.

Based on 14 models from the CMIP5 archive, the changes in the AMOC have been assessed to be *very unlikely* to collapse in the 21st century in response to increasing greenhouse gas concentrations (IPCC, 2013). Nevertheless, abrupt variations in sea surface temperature and sea ice can be found in a lot of models from the CMIP5 archive (Drijfhout et al., 2015). For instance, large cooling changes, 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 related with the AMOC is playing a role in explaining such a rapid cooling, but other processes are key for setting the rapid (decadal-scale) timeframe of 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, it has been argued that rapid changes in subpolar convection and associated cooling is *as likely as unlikely* to occur in the 21st century (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 their fate.

The subpolar gyre (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 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 cooling.

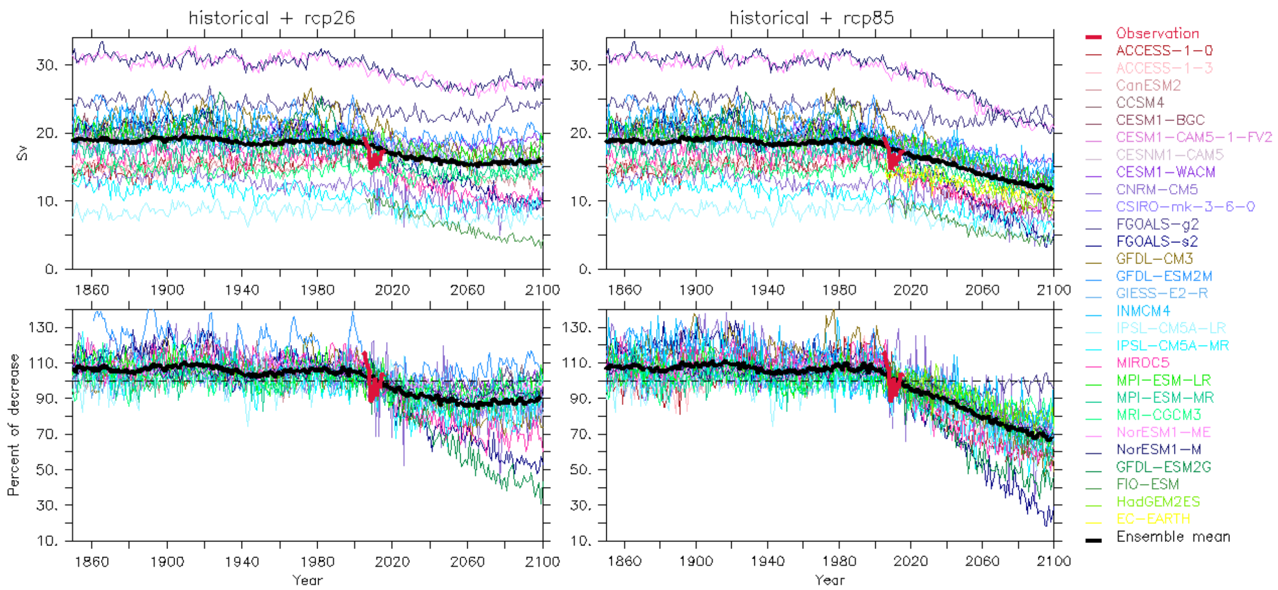

Figure 6.8: AMOC changes at 26°N from 27 models (only 14 were shown in the AR5 (IPCC, 2013)). The thick red line shows the observation-based estimate at 26°N (McCarthy et al., 2015) and the thick black line the ensemble mean of the different models. Values of AMOC maximum at 26°N (in Sv) are shown in 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 6.1) using almost twice more models than in former assessment (IPCC, 2013). The AR5 assessment of low probability of AMOC collapse has been confirmed, although one model now does show such a collapse (e.g. decrease larger than 80%) before the end of the century (Figure 6.1). Now based on up to 27 model simulations, the decrease of the AMOC is assessed to be of –1.8 ± 2.3 Sv (–10 ± 13%) in 2090–2100 as compared 2005–2015 for RCP2.6 scenario and –5.5 ± 3.1 Sv (–32 ± 18%) for RCP8.5 scenario. Furthermore, the uncertainty in AMOC changes has been shown to be mainly related with spread in model responses rather than scenario or internal variability uncertainty (Reintges et al., 2017), in opposition to 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 few new mechanisms have 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, which forms dense Labrador Sea Water (a main component of the southward Atlantic Meridional Overturning Circulation), 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 totaling around 60,000 m^3/s in 2013, a 50% increase since the mid-1990s (Yang et al., 2016b). 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 affect the Labrador Sea convection since 2010, which may imply a coming 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; Yang et al., 2016b). Nevertheless, as highlighted in 6.7.1.1, this hypothesis remains difficult to fully validate and dedicated detection-attribution analyses will be necessary to properly validate it.

The impact of GrIS melting has been neglected in CMIP5 projections (Swingedouw et al., 2013). To assess the impact of GrIS melting on the future evolution of the AMOC, an international effort under AMOCMIP has been led (Bakker et al., 2016). 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 AOGCMs and an extrapolation by an emulator calibrated on these models showed that GrIS melting can have a substantial impact on the AMOC, potentially adding up to around 5–10% more AMOC weakening in 2100 under RCP8.5. However, it remains of second order as compared to other global warming effects in line with other multi-model analysis (Swingedouw et al. 2015). The AMOC weakening from these emulators appears almost linearly related with the amount of global warming, illustrating that risk of collapse only starts to be consequent above 5°C of warming in transient state (cf. Figure 6.2). Hansen et al. (2016), using far larger rates than the one estimated in Lenaerts et al. (2015) approach, found much stronger impacts on the AMOC. Nevertheless, even though large uncertainty exists concerning GrIS fate, such high rate of GrIS melting as used in Hansen et al. (2016) is not supported by present-day knowledge of ice sheet dynamics (Ritz et al., 2015).

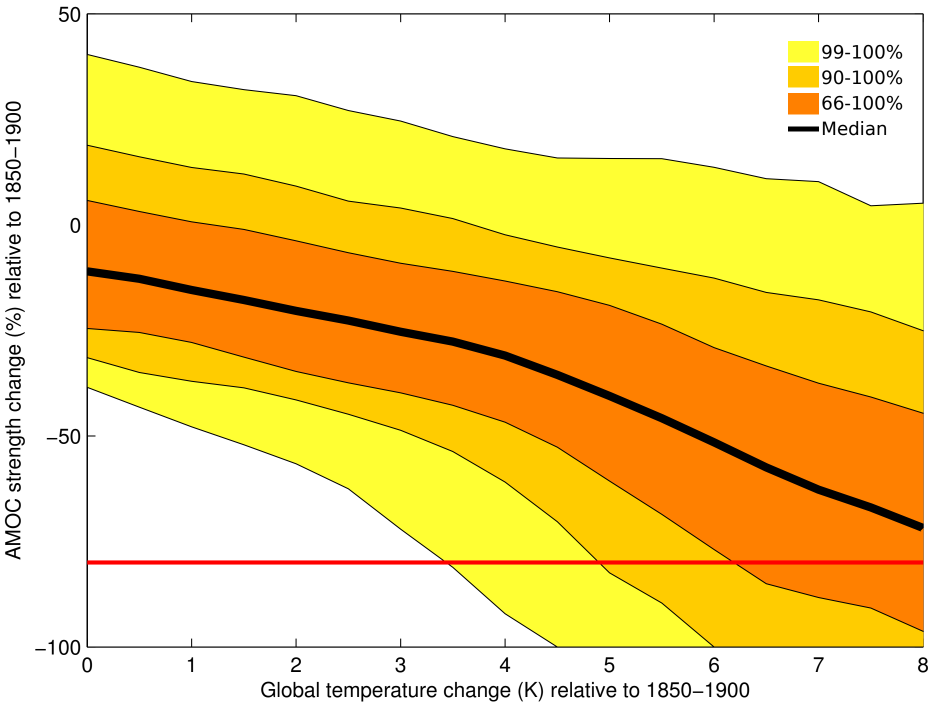

Figure 6.9: The changes in the AMOC strength as a function of transient changes in global mean temperature. This probabilistic assessment of annual mean AMOC strength changes (%) at 26°N (below 500 m and relative to 1850–1900) as a function of global temperature change (K; relative to 1850–1900) results 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 AOGCMs including 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*. 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.

On the longer term (2300), Bakker et al. (2016) found a larger impact of GrIS melting up to around 20% under the RCP8.5 scenario, where AMOC is found to be weakened by more than 70% in 2200 in this 8-model ensemble. However, the AMOC slowly recovers under the RCP4.5 scenario in the longer term, indicating that the greenhouse gases emission pathway can play a substantial role in the fate of the AMOC. 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 (Sgubin et al., 2015; Jackson et al., 2017) although the timing and amplitude is highly model dependent (Palter et al., 2017). It has been shown that the response of the AMOC was more depending on North Atlantic transient response rather than on the classical indicator of transport at 30°S (Sgubin et al., 2015). Such an indicator remains for AMOC hysteresis, implying a multi-centennial time scale. This hysteresis behaviour of the AMOC in response to freshwater release has been found in a few AOGCMs (Hawkins et al., 2011; Jackson et al., 2017) even at the eddy permitting 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 centennial time scale.

These different modelling results remains highly sensitive to the model considered, which are all still of coarse resolution and not able to correctly resolve key processes in the ocean, notably related with oceanic eddies, whose typical scale is below the size of the usual ocean grid box in the particular CMIP5 model, which is around 1°. The influence of the oceanic resolution has been evaluated by using higher resolution ocean-atmosphere coupled models or ocean-only models, concerning either the impact of global warming (Winton et al., 2014; Saba et al., 2016) or of GrIS melting (Weijer et al., 2012; Saenko et al., 2017) on ocean circulation. Generally speaking, no decisive impact of the ocean model resolution on the AMOC response has been found, which remains very dependent on the model considered. Nevertheless, very few studies have been led, up to now, to make any strong statement on this aspect. Furthermore, the processes controlling ocean circulation are clearly improved in these high-resolution models. More generally, it is suspected that existing bias in the ocean circulation may limit the sensitivity of the ocean circulation response to global warming, which could be therefore expected to be larger than the ensemble mean of models (Swingedouw et al., 2013; Liu et al., 2017; Sgubin et al., 2017).

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., 2017), and indicate a possible weakening of the AMOC in the coming decade (Smith et al., 2013). More validation in line with recent AMOC observations remains to be done to evaluate their capability of providing useful insights on the AMOC and SPG fates, whose impacts are discussed hereafter.

6.7.2 Impacts on Climate, Natural and Human Systems

Even though the AMOC remains unlikely to collapse over the 21st century, its weakening can be substantial, and therefore induce strong and large-scale climatic impacts with potential far-reaching impacts on natural and human systems. Furthermore, the SPG subsystem has been shown to potentially shift over decadal time scales, with lower amplitude but still very significant climatic implications, which are assessed in the following.

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). Impact of AMOC or SPG changes and their teleconnections are indeed still supported by a large amount of paleo evidence (Lynch-Stieglitz, 2017). These impacts are caused through teleconnections both by the atmosphere and the ocean. Such impacts and teleconnections have been further evaluated over the last few years both using new paleodata and higher resolution models. They confirmed the main climatic impacts related with AMOC weakening and the additional vulnerability of some populations it may induce. 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-enough 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 6.3. 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 (Haarsma et al., 2015). The impacts on storm tracks is largest when the AMOC collapses (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 can be substantial over Europe, especially in winter, albeit damped by atmospheric circulation (Haarsma et al., 2015; Jackson et al., 2015; Yamamoto and Palter, 2016). In summer, cold anomalies in the SPG, like the one occurring during the so-called cold blob (Josey et al., 2018), has been suspected to potentially strongly enhance the probability of heat waves in summer (Duchez et al., 2016). Nevertheless, considerable uncertainties remain on this aspect due to short period of observations and due to poor 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 a to a northward shift of the Gulf Stream. However, these changes are largely underestimated in coarse resolution models.

Changes in ocean circulation can also strongly impact sea level in the regions bordering the North Atlantic. A collapse of the AMOC or of the SPG can induce substantial increase of sea-level rise up to a few tenths of centimetres (Ezer et al., 2013; Little et al., 2017; cf. Chapter 5). For instance, such a link is suspected to explain 30% of the extreme observed sea level rise event (a short-lived increase of 128mm 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 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 Atlantic circulation (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., 2017).

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 vapor 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 ppb) in methane production have been associated with these events (Rhodes et al., 2015) potentially due to increase wetland production in the Southern Hemisphere, related with teleconnections of the North Atlantic with tropical area (Ringeval et al., 2013). All these different effects indicate a potentially positive feedback of the AMOC on the carbon cycle, 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 the 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 billfishes (Muhling et al., 2015) with potential large impacts on fisheries.

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 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. Furthermore, 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, urging for a better assessment in the future.

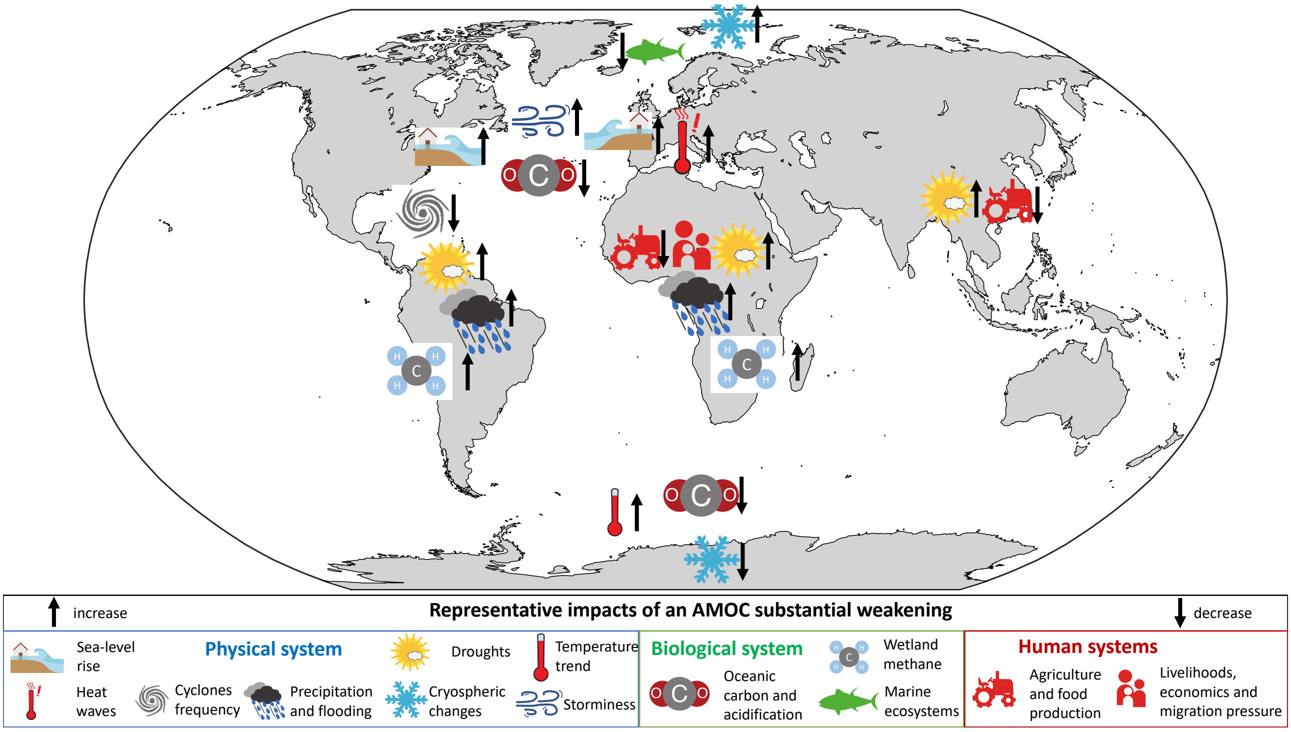

Figure 6.10: Infographic on teleconnections and impacts due to AMOC or SPG collapse.

6.7.3 Risk Management and Adaptation

The key responses to possible abrupt changes in the AMOC include avoiding weakening or rapid transition, through mitigation of greenhouse gas emissions, or adaption to the effects in order to reduce anticipated impacts in natural and human systems.

The probability of triggering transitions, such as a weakening of the AMOC, generally increases with increasing greenhouse gas emissions (Figure 6.10). However, no mitigation targets or levels of warming are specifically determined for avoiding an AMOC decline, according to the IPCC (2013). AR5 WG2 has further indicated that there can be delays between triggering and experiencing a threshold response, which may have implications for mitigation policies (Oppenheimer et al., 2014). [PLACHOLDER FOR SECOND ORDER DRAFT: inclusion of material from the SR1.5]

Literature that explicitly addresses impacts from an AMOC weakening is scarce. Overall, the AMOC is expected to lead to reduced warming over Europe, but possibly also lead to other impacts such as changes in cyclone tracks in Europe and changes in the water cycle potentially leading to droughts (Jackson et al., 2015)(see also Section 6.5.2). This potentially requires adaptation responses. A specific adaptation action is a monitoring and early warning system using an observation and prediction system, 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 RAPID and OSNAP systems that are in place are the main monitoring system that may allow the development of such an early warning system. Nevertheless, the prospects for its operational use for early warning have not been fully developed yet.

The use of decadal predictions can be also very useful in that sense. The grand challenge of WCRP proposing to launch decadal predictions every year appears as a very useful activity to anticipate any rapid changes to come in the near term. Furthermore, a few studies have shown that already small variations anticipated by decadal predictions can be useful for the development of a few climate services, notably for agriculture in south and east Africa (Nyamwanza et al., 2017).

6.8 Multi-risk, Cascading Impact (or Effects), and Compound Events

6.8.1 Concepts

Multi-risk 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). Multi-Risk is a consequence of vulnerability and exposure to one or more hazards (Figure 6.1) with each of these elements potentially exhibiting multiple compounding components that may be coincident or time dependent (Gallina et al., 2016). Multi-risk can lead to substantial disruption to natural or human systems as a result of single or multiple externally-generated climate hazards that interact with complex and evolving interactions within human societies and ecosystems (Oppenheimer et al., 2014). Key risks for human systems arise from compound climate events, occurring simultaneously or in sequence that lead to losses of biodiversity and ecosystem services, and pose challenges for the management of water, energy and land use. 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 multi-risk (Box 6.1).

Concepts and methods for addressing multi-risk have a solid foundation in Disaster Risk Reduction frameworks (Scolobig, 2017). Attempts exist to articulate multi risk assessments with scenarios, risk mapping, and participatory governance (Marzocchi et al., 2012; Komendantova et al., 2014). 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 sizeable aggregate impacts of inherent cascading impacts. Therefore defining the application is critical to establish the scope of the risk assessment application to be undertaken (Leonard et al., 2014; Gallina et al., 2016).

6.8.2 Cascading Impacts or Cumulative Effects on Ecosystems

Damage and loss of ecosystems (mangrove, coral reefs); or regime shifts in ecosystem communities lead to reduced resilience of the ecosystems and possible flow on effects to human systems. For example, living corals and reef structures have experienced significant losses from human-related drivers such as coastal development; sand and coral mining; overfishing and climate-related storms and bleaching events (Graham et al., 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. Currently, across reef coastlines (71,000 km), reefs reduce the annual expected damages from storms by more than 4 billion USD. With the loss of reefs, annual damages would more than double (118%) and the flooding of the currently protected land would increase by 69% affecting 81% more people annually. Moreover, projected sea level rise will increase flooding risks, and these risks will be even greater if reefs are lost too, due to bleaching-induced mortality. In 2100, the land flooded under a 100-year storm event increases by 64% under a business-as-usual (high) emissions scenario (RCP8.5) with no reef loss. If this relative sea level rise is coupled with a 1m loss in reefs, the land flooded increases by 116%.

6.8.3 Cascading Impacts or Cumulative Risks on Social Systems

Impacts of multi-risk events also have significant accumulated effects in the societal system. They include impacts on critical infrastructure such as communications, transport, and power supply; on housing, dams and flood protection; on health provision, which may cause disruption of (local) communities, creating long-lasting economic effects, and migration.

Cascading 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, dyke breaches, emergency response failures, chaos in evacuation (traffic jams) and social disruption. 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 erosion and impacts on fishing resources. This subsequently can have an impact on local economies, potentially leading to social disruption and migration.

The severity and intensity of impacts of compound events and multi-risk depend on the affected societies' vulnerability, resilience and adaptive capacity. For example, the intensity and influence of compound effects are dependent on the size and scale of the affected society and the percentage of economy or GDP impacted (Handmer et al., 2012 in IPCC SREX). Smaller countries face the challenge of being unable to 'hedge' the risk through geographical redistribution.

6.8.4 Risk Management and Adaptation, Sustainable and Resilient Pathways

The management of multi-risk in the context of governance poses challenges. It is unclear who will take responsibility when compound events and cascading impact occur (Scolobig, 2017). Considerable variations exist among countries. The level of multi-risk engagement depends on countries' availability of an integrated risk and disaster framework and regulations, viable public-private partnership in the case of multiple technological and natural hazards, the initiatives of local governments to exercise multi-risk operations, and experience in interagency cooperation (Scolobig, 2017).

Managing multi-risk and cascading impacts also relate significantly to the indirect damage costs that affect decision making on disaster risk reduction and adaptation. 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).

Despite difficulties of governance and decision-making, advances in managing multi-risk and cascading impacts have been made in several ways. Many researchers and policymakers have recognised the need to study combined weather and climatic hazards and their impacts. Analytically, methods are now being employed to assess several 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). Such assessments are now also expanding to risks (to include impacts). Given these analyses, policy can also begin to plan for disaster risk reduction and adaptation, to the combined effects. Further consideration is needed to solve some limitations in understanding the compound hazards, as well as precise mechanisms of the cascading risks. 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 integrated climate-economy assessment model DICE (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 (ENSO). The deep uncertainties associated to 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 high agreement that present costs of carbon are clearly underestimated. Double (Lemoine and Traeger, 2016) to eightfold (Cai et al., 2016) increase of the carbon price is proposed 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 USD15 per tCO_2 to USD116 per tCO_2, concluding that there is a need for immediate, stringent effort to reduce CO_2 emission to constrain warming below 1.5°C.

[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 multi-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 and preconditioned the sensitive highland environment for major fires in 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 AUD50 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.

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 and fishing sector and the energy sector. 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).

This case illustrates many of the concepts presented in Figure 6.1. For several extreme hazards associated with the climate system (i.e., droughts, extreme rainfall, and marine heat waves), 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 heat waves 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, 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 is an area encompassing almost 4 million square miles of ocean and coastal waters in Southeast Asia and the Pacific surrounding Indonesia, Malaysia, Papua New Guinea, the Philippines, Timor Leste, and the Solomon Islands. The Coral Triangle (CT) is the center 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). This amounts to 76% of the world's total species complement, giving this reef province the world's highest conservation priority. Within the Coral Triangle, highest richness resides in the Bird's Head Peninsula of Indonesian Papua, which hosts 574 species, with individual reefs supporting up to 280 species/ha. Reasons for the exceptional richness of the Coral Triangle include the geological setting, physical environment, and an array of ecological and evolutionary processes.

Over 100 million people from some of the most diverse and rich cultures on Earth live there. These people depend on healthy ecosystems such as coral reefs, mangroves and seagrass beds to provide food, building materials, coastal protection, support industries such as fishing and tourism, and many other ecosystem services and benefits.

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). As a result, the coastal ecosystems of Coral Triangle are deteriorating rapidly and 40% of coral reefs and mangroves have already been lost over the past 40 years. Coastal deforestation, coastal reclamation, declining water quality, pollution, sewage, destructive fishing and over-exploitation of marine life have had a severe impact on these essential ecosystems (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 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 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). On the other hand, 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). During this event, sea level in Indonesia was at its lowest in the past 12 years following the El Niño event and this affected corals 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.

At present, different approaches are used to manage the different risks to coral ecosystems in the Coral Triangle such as fisheries management (Evans, et al., 2015), 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: Caribbean 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 USD265 billion damage and making 2017 the costliest hurricane season on record (Blake et al., 2011; Blake and Zelinsky, 2018).

The question of whether climate change may have contributed to the severity of these recent hurricanes has been much discussed in the public and media. 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. An increase in some measures of hurricanes are expected as the climate warms. 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 given the opposing influences of greenhouse gases and aerosols on past changes (Sobel et al., 2016).

Two studies have examined the role of climate change on the rainfall intensity of Harvey that brought unprecedented rainfall to Texas and produced a storm surge that exceeded 2 m in some regions (Shuckburgh et al., 2017). van Oldenborgh et al. (2017) estimated the rainfall to be about 15% (8%–19%) more intense as a result of climate change and 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 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.

These hurricanes by combining storm surge with riverine flooding in the U.S. 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 U.S. (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 BOX6.1 HERE]

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

6.9.1 Decision Making for Abrupt and Extreme Changes

Successful adaption to abrupt or extreme events depends on both the spatial and the temporal scale at which interventions are made, and should not simply be assessed in terms of the stated objectives of single and isolated actors. Thus, decision-making about abrupt or extreme climate change 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 SREX: Field et al., 2012). It can be observed that the number of efforts in various countries and large cities around the world to improve resilience and adaptation planning is rapidly increasing, and these are linking to a global network of information and best practices (e.g., Aerts et al., 2014). The question is whether extreme and abrupt changes require specific adaptation responses which differ from the management of 'normal' disaster risk, and if there is a need for specific types of adaptation measures. While there are several impact studies on extreme and abrupt changes, very few focus on the necessity of dedicated adaptive responses.

A key challenge for decision-making is to incorporate the possibility of such abrupt and impactful changes for which uncertainty is both deep and poorly characterized (Weaver et al., 2013). This requires the construction of an analytical cost–benefit model that incorporates representations of different uncertainties under extreme or abrupt scenarios (Weaver et al., 2013). 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 and recognizes the potential for abrupt climate changes with important consequences for natural systems, human communities, and socioeconomic sectors (Weaver et al., 2013). 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 applied to more gradual shifts of climate change, rather than extreme and abrupt changes.

As the number of legal and political mandates for incorporating abrupt and extreme climate change information into decision making increases, the demand on climate science and modelling to deliver so-called 'actionable' information in direct support of planning will also continue to increase—as will scrutiny of their ability to do so. Meeting the scientific and technical challenges of climate prediction, including abrupt and extreme changes, would not be the only prerequisite for achieving better climate-related decision making. Scientific information can be effective in influencing decision making, but only if this information is perceived as 'credible, salient, and legitimate'.

Credibility is based on trust in the information provided as well as trust in the institution that governs extremes and abrupt changes. The levels of trust are influenced by familiarity with and information about hazards, community characteristics, as well as the relationship between people and government agencies (Paton, 2007). Trust in the institution, however, could lead to complacency and lack of disaster preparedness by the individual. Those who do not trust information or the institution can behave either way as some are more motivated to prepare while others become indifferent to disasters (González-Riancho et al., 2017). In addition, making sense of climate change impact and engaging with adaptation measures are shaped by individuals' sense of responsibility and by the (lack of) trust towards expert and scientific knowledge (Moser and Boykoff, 2013; Yeh, 2016). Those not as versed in topical knowledge are likely to trust less credible sources and fail to differentiate between relevant and irrelevant criteria when judging the trustworthiness of sources (Bråten et al., 2011).

6.9.2 Resilient Pathways and Transformative Governance

The role of governance and the wider effectiveness of adaptation are critical, and can be assessed by analysing equity, legitimacy and co-benefits. Adaptation to abrupt or extreme events of climate change, therefore, can be evaluated through generic principles of policy appraisal seeking to promote equitable, effective, efficient and legitimate action harmonious with wider sustainability. The relative importance attached to each criterion will vary between countries, between sectors within countries, within issues within localities, and over time as attitudes and expectations change. Most importantly, the relative weight placed on these values varies between actors engaged in adaptation processes, depending on their world view and perceived limits to responsibility (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 AR5). 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).

Though discourse abounds related to transformative governance, it falls short of its ideal in climate change action plans as it is still unclear whether communities have the capacity, tools, and targets in place to trigger the transformative levels of change required to build fundamentally 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 had a medium level of awareness, analysis, and action with regard to extreme climate conditions and disaster preparedness and climate action plans have a limited relevance in managing the risks of extreme climate events and natural disasters.

Coupling disaster management and climate change adaptation has shown some progress since SREX and AR5. In disaster risk management and climate change adaptation, coordination poses a major problem. Military, commercial and voluntary organizations that manage disasters have found it challenging to coordinate between them, as key capabilities remain outside preparedness planning partly because of 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 U.S.'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. The difficulties stem from emergent organizations that were not previously exposed to the framework and the ambiguity of shared authority in responding to disasters (Moynihan, 2009).

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, such as international donors and non-governmental organizations, as analysed by Vanuatu's response to the category 5 tropical cyclone Pam (Nalau et al., 2017).

The Sendai Framework calls for improved coordination and collaboration that fosters participation beyond information sharing, and inclusive of all 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).

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. One case illustrates the effectiveness of disaster management across sectors.

Pal et al. (2017) analysed the efficacy of robust national level institutional system on India in the form of Disaster Management Act 2005 along with a wide range of National Level Institutions related to early warning, meteorology, remote sensing, information and communication technology, satellite technology, disaster response management, which have substantially contributed to a high level of preparedness, in term of effective response to disaster in the light of a category 5 tropical cyclone Phailin, which struck the east coast of India in October 2013.

[START FAQ6.1 HERE]

FAQ6.1: What risks emerge from abrupt changes in the ocean and the cryosphere?

[END FAQ6.1 HERE]

[START FAQ6.2 HERE]

FAQ6.2: How can risks of extreme events in the ocean and cryosphere related to climate change be addressed?

[END FAQ6.2 HERE]

[START FAQ6.3 HERE]

FAQ6.3: What are compound events and what is a cascading risk?

[END FAQ6.3 HERE]

References

Abramson, D. M. and I. E. Redlener, 2013: Hurricane Sandy: lessons learned, again. *Disaster medicine and public health preparedness*, **6** (4), 328-329.

ACAPS, OCHA and UNDP, 2017: *Regional Overview: Impact of Hurricanes Irma and Maria*. Conference Supporting Document, 39 pp [Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/UNDP%20%20Regional%20Overview%20Impact%20of%20Hurricanes%20Irma%20and%20Maria.pdf].

Aerts, J. C. et al., 2014: Evaluating flood resilience strategies for coastal megacities. *Science*, **344** (6183), 473-475.

Ainsworth, T. D. et al., 2016: Climate change disables coral bleaching protection on the Great Barrier Reef. *Science*, **352** (6283), 338-342, doi:10.1126/science.aac7125.

Alvarez-Filip, L. et al., 2009: Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. *Proceedings of the Royal Society of London B: Biological Sciences*, **276** (1669), 3019-3025.

Ampou, E. E. et al., 2017: Coral mortality induced by the 2015-2016 El Nino in Indonesia: the effect of rapid sea level fall. *Biogeosciences*, **14**, 817-826, doi:doi:10.5794/bg-14-817-2017.

Anthony, K. R. N. et al., 2015: Operationalizing resilience for adaptive coral reef management under global environmental change. *Global Change Biology*, **21**, 48–61, doi:10.1111/gcb.12700.

Arent, D. J. et al., 2014: Key economic sectors and services. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659-708.

Arias-Ortiz, A. et al., 2018: A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. *Nature Climate Change*, **8** (4), 338-344, doi:10.1038/s41558-018-0096-y.

Armour, K. C. et al., 2016: Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nature Geoscience*, **9**, 549, doi:10.1038/ngeo2731.

Arns, A., T. Wahl, I. D. Haigh and J. Jensen, 2015: Determining return water levels at ungauged coastal sites: a case study for northern Germany. *Ocean Dynamics*, **65** (4), 539-554, doi:10.1007/s10236-015-0814-1.

Baker-Austin, C. et al., 2013: Emerging Vibrio risk at high latitudes in response to ocean warming. *Nature Clim. Change*, **3** (1), 73-77, doi:10.1038/nclimate1628.

Bakker, P. et al., 2016: Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting. *Geophysical Research Letters*, **43** (23), 12252-12260, doi:10.1002/2016gl070457.

Balaguru, K. et al., 2015: Dynamic Potential Intensity: An improved representation of the ocean's impact on tropical cyclones. *Geophysical Research Letters*, **42** (16), 6739-6746, doi:doi:10.1002/2015GL064822.

Ballantyne, A. et al., 2017: Accelerating net terrestrial carbon uptake during the warming hiatus due to reduced respiration. *Nature Climate Change*, **7**, 148, doi:10.1038/nclimate3204.

Barnes, E. A., E. Dunn-Sigouin, G. Masato and T. Woollings, 2014: Exploring recent trends in Northern Hemisphere blocking. *Geophysical Research Letters*, **41** (2), 638-644, doi:10.1002/2013GL058745.

Beal, L. M. and S. Elipot, 2016: Broadening not strengthening of the Agulhas Current since the early 1990s. *Nature*, **540** (7634), 570-+, doi:10.1038/nature19853.

Beck, T. E. and D. A. Plowman, 2013: Temporary, emergent interorganizational collaboration in unexpected circumstances: A study of the Columbia space shuttle response effort. *Organization Science*, **25** (4), 1234-1252.

Bellprat, O. et al., 2016: The Role of Arctic Sea Ice and Sea Surface Temperatures on the Cold 2015 February Over North America. *Bulletin of the American Meteorological Society*, **97** (12), S36-S41, doi:10.1175/bams-d-16-0159.1.

Bellucci, A., A. Mariotti and S. Gualdi, 2017: The Role of Forcings in the Twentieth-Century North Atlantic Multidecadal Variability: The 1940-75 North Atlantic Cooling Case Study. *Journal of Climate*, **30** (18), 7317-7337, doi:10.1175/jcli-d-16-0301.1.

Benthuysen, J., M. Feng and L. Zhong, 2014: Spatial patterns of warming off Western Australia during the 2011 Ningaloo Niño: Quantifying impacts of remote and local forcing. *Continental Shelf Research*, **91** (Supplement C), 232-246, doi:10.1016/j.csr.2014.09.014.

Benthuysen, J. A., E. C. J. Oliver, M. Feng and A. G. Marshall, 2018: Extreme Marine Warming Across Tropical Australia During Austral Summer 2015–2016. *Journal of Geophysical Research: Oceans*, **123** (2), 1301-1326, doi:doi:10.1002/2017JC013326.

Biastoch, A. et al., 2015: Atlantic multi-decadal oscillation covaries with Agulhas leakage. *Nature Communications*, **6**, 10082.

Binder, S. B., 2014: *Resilience and postdisaster relocation: A study of New York's home buyout plan in the wake of Hurricane Sandy*. University of Hawai'i at Manoa.

Bindoff, N. L. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J.

Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952.
Blake, E. S., C. W. Landsea and E. J. Gibney, 2011: *The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2010 (and other frequently requested hurricane facts)*. NOAA/National Weather Service, National Centers for Environmental Prediction, National Hurricane Center Miami.
Blake, E. S. and D. A. Zelinsky, 2018: *Hurricane Harvey*. Tropical Cyclone Report, National Hurricane Center, Miami, FL, 76 pp [Available at: https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf].
Boet-Whitaker, S. K., 2017: Buyouts as resiliency planning in New York City after Hurricane Sandy. Massachusetts Institute of Technology, Place.
Bond, N. A., M. F. Cronin, H. Freeland and N. Mantua, 2015: Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, **42** (9), 3414-3420, doi:10.1002/2015gl063306.
Boning, C. W. et al., 2016: Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geoscience*, **9** (7), 523-+, doi:10.1038/ngeo2740.
Booth, J. F., L. Thompson, J. Patoux and K. A. Kelly, 2012: Sensitivity of Midlatitude Storm Intensification to Perturbations in the Sea Surface Temperature near the Gulf Stream. *Monthly Weather Review*, **140** (4), 1241-1256, doi:10.1175/mwr-d-11-00195.1.
Borlace, S., A. Santoso, W. Cai and M. Collins, 2014: Extreme swings of the South Pacific Convergence Zone and the different types of El Nino events. *Geophysical Research Letters*, **41** (13), 4695-4703, doi:10.1002/2014GL060551.
Born, A., T. F. Stocker, C. C. Raible and A. Levermann, 2013: Is the Atlantic subpolar gyre bistable in comprehensive coupled climate models? *Climate Dynamics*, **40** (11-12), 2993-3007, doi:10.1007/s00382-012-1525-7.
Born, A., T. F. Stocker and A. B. Sando, 2016: Transport of salt and freshwater in the Atlantic Subpolar Gyre. *Ocean Dynamics*, **66** (9), 1051-1064, doi:10.1007/s10236-016-0970-y.
Boulton, C., L. Allison and T. Lenton, 2014: Early warning signals of Atlantic Meridional Overturning Circulation collapse in a fully coupled climate model. *Nature Communications*, **5**, doi:10.1038/ncomms6752.
Bouwer, L. M. and S. N. Jonkman, 2018: Global mortality from storm surges is decreasing. *Environmental Research Letters*, **13** (1), doi:ARTN 014008
10.1088/1748-9326/aa98a3.
Bozbiyik, A. et al., 2011: Fingerprints of changes in the terrestrial carbon cycle in response to large reorganizations in ocean circulation. *Clim. Past*, **7** (1), 319-338, doi:10.5194/cp-7-319-2011.
Brainard, R. E. et al., 2011: Status Review Report of 82 Candidate Coral Species Petitioned Under the U . S . Endangered Species Act. *Endangered Species Act. U.S. Dep. Commer.*
Bråten, I., H. I. Strømsø and L. Salmerón, 2011: Trust and mistrust when students read multiple information sources about climate change. *Learning and Instruction*, **21** (2), 180-192.
Brown, J. et al., 2016: Spatio-temporal Variability in the Tipping Points of a Coastal Defense. *Journal of Coastal Research*, 1042-1046, doi:10.2112/SI75-209.1.
Brunnabend, S.-E. et al., 2017: Changes in extreme regional sea level under global warming. *Ocean Science*, **13** (1), 47 - 60, doi:urn:nbn:nl:ui:31-79188fde-9b3b-4248-8e1a-96219a4473a3.
Buckley, M. W. and J. Marshall, 2016: Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: A review. *Reviews of Geophysics*, **54** (1), 5-63, doi:10.1002/2015rg000493.
Burch, S., A. Shaw, A. Dale and J. Robinson, 2014: Triggering transformative change: a development path approach to climate change response in communities. *Climate Policy*, **14** (4), 467-487.
Bureau of Meteorology and Australian CSIRO, 2007: *Climate change in Australia: technical report 2007*. CSIRO, 148 pp.
Burge, C. A. et al., 2014: Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society. *Annual Review of Marine Science*, **6** (1), 249-277, doi:10.1146/annurev-marine-010213-135029.
Caesar, L. et al., 2018: Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, **556** (7700), 191.
Cai, W. et al., 2014a: Increasing frequency of extreme El Nino events due to greenhouse warming. *Nature Climate Change*, **4** (2), 111-116, doi:10.1038/NCLIMATE2100.
Cai, W. et al., 2014b: Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming. *Nature*, **510** (7504), 254-258.
Cai, W. et al., 2015: Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, **5** (2), 132-137.
Cai, Y., T. Lenton and T. Lontzek, 2016: Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction. *Nature Climate Change*, **6** (5), 520-525, doi:10.1038/NCLIMATE2964.
Callaghan, J. and S. B. Power, 2011: Variability and decline in the number of severe tropical cyclones making land-fall over eastern Australia since the late nineteenth century. *Climate Dynamics*, **37** (3), 647-662, doi:10.1007/s00382-010-0883-2.
Caminade, C. et al., 2016: Global risk model for vector-borne transmission of Zika virus reveals the of El Nino 2015. *Proceedings of the National Academy of Sciences*, doi:doi:10.1075/pnas.1614303114.
Camus, P. et al., 2017: Statistical wave climate projections for coastal impact assessments. *Earths Future*, **5** (9), 918-933, doi:10.1002/2017EF000609.

Cangialosi, J. P., A. S. Latto and R. Berg, 2018: *Hurricane Irma*. Tropical Cyclone Report, National Hurricane Center, Center, N. H., Miami, FL, 111 pp [Available at: https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf].
Caputi, N. et al., 2016: Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot spot. *Ecology and Evolution*, **6** (11), 3583-3593, doi:10.1002/ece3.2137.
Carrigan, A. D. and M. Puotinen, 2014: Tropical cyclone cooling combats region-wide coral bleaching. *Global Change Biology*, **20** (5), 1604-1613, doi:doi:10.1111/gcb.12541.
Cavole, L. et al., 2016: Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future. *Oceanography*, **29** (2), doi:10.5670/oceanog.2016.32.
Chafik, L. et al., 2016: Global linkages originating from decadal oceanic variability in the subpolar North Atlantic. *Geophysical Research Letters*, **43** (20), 10909-10919, doi:10.1002/2016GL071134.
Chand, S. S., K. J. Tory, H. Ye and K. J. Walsh, 2016: Projected increase in El Nino-driven tropical cyclone frequency in the Pacific. *Nature Climate Change*.
Chang, L., J. Xu, X. Tie and J. Wu, 2016: Impact of the 2015 El Nino event on winter air quality in China. *Scientific Reports*, **6**, doi:10.1038/srep34275.
Chatterjee, A. et al., 2017: Influence of El Niño on atmospheric CO2 over the tropical Pacific Ocean: Findings from NASA's OCO-2 mission. *Science*, **358** (6360), eaam5776.
Chen, D. et al., 2015a: Strong influence of westerly wind bursts on El Nino diversity. *Nature Geoscience*, **8** (5), 339-345, doi:10.1038/NGEO2399.
Chen, K., G. Gawarkiewicz, Y.-O. Kwon and W. G. Zhang, 2015b: The role of atmospheric forcing versus ocean advection during the extreme warming of the Northeast U.S. continental shelf in 2012. *Journal of Geophysical Research: Oceans*, **120** (6), 4324-4339, doi:10.1002/2014JC010547.
Chen, K., G. G. Gawarkiewicz, S. J. Lentz and J. M. Bane, 2014: Diagnosing the warming of the Northeastern U.S. Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response. *Journal of Geophysical Research: Oceans*, **119** (1), 218-227, doi:10.1002/2013jc009393.
Cheng, L. et al., 2017: Improved estimates of ocean heat content from 1960 to 2015. *Science Advances*, **3** (3), e1601545.
Cheng, L., F. Zheng and J. Zhu, 2015: Distinctive ocean interior changes during the recent warming slowdown. *Scientific Reports*, **5**.
Christensen, J. H. et al., 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1217–1308.
Christidis, N., K. Manomaiphiboon, A. Ciavarella and P. A. Stott, 2018: The hot and dry April of 2016 in Thailand. *[in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **99** (1), S128-S132.
Christie, P. et al., 2016: Improving human and environmental conditions through the Coral Triangle Initiative: progress and challenges. *Current Opinion in Environmental Sustainability*, **19**, 169-181.
Chung, C. et al., 2014: Nonlinear precipitation response to El Nino and global warming in the Indo-Pacific. *Climate Dynamics*, **42** (7-8), 1837-1856, doi:10.1007/s00382-013-1892-8.
Church, J. A. et al., 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–1216.
Claar, D. et al., 2018: Global patterns and impacts of El Nino events on coral reefs: A meta-analysis. *PLoS ONE*, **13(2)**, 0190967, doi:doi.
Clement, A. et al., 2015: The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science*, **350** (6258), 320-+, doi:10.1126/science.aab3980.
Cobb, K. M. et al., 2013: Highly variable El Niño–Southern Oscillation throughout the Holocene. *Science*, **339** (6115), 67-70.
Cohen, J. et al., 2014: Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, **7**, 627, doi:10.1038/ngeo2234.
Collins, J. et al., 2017: Rapid termination of the African Humid Period triggered by northern high-latitude cooling. *Nature Communications*, **8**, doi:10.1038/s41467-017-01454-y.
Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136.
Compo, G. P. et al., 2011: The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society*, **137** (654), 1--28, doi:10.1002/qj.776.
Couch, C. S. et al., 2017: Mass coral bleaching due to unprecedented marine heatwave in Papahānaumokuākea Marine National Monument (Northwestern Hawaiian Islands). *PLoS ONE*, **12** (9), e0185121, doi:10.1371/journal.pone.0185121.

Coumou, D. and S. Rahmstorf, 2012: A decade of weather extremes. *Nature Climate Change*, **2**, 491, doi:10.1038/nclimate1452.
Dalisay, S. N. and M. T. De Guzman, 2016: Risk and culture: the case of typhoon Haiyan in the Philippines. *Disaster Prevention and Management*, **25** (5), 701-714, doi:10.1108/Dpm-05-2016-0097.
David, C. P., B. A. B. Racoma, J. Gonzales and M. V. Clutario, 2013: A Manifestation of Climate Change? A Look at Typhoon Yolanda in Relation to the Historical Tropical Cyclone Archive. *Science Diliman (July-December)*, **25** (2), 78-86.
Dean, S. M., S. Rosier, T. Carey-Smith and P. A. Stott, 2013: The role of climate change in the two-day extreme rainfall in Golden Bay, New Zealand, December 2011. *Bulletin American Meteorological Society*, **94** (9), S61-S63.
Dee, D. P. et al., 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, **137** (656), 553--597.
Defrance, D. et al., 2017: Consequences of rapid ice sheet melting on the Sahelian population vulnerability. *Proceedings of the National Academy of Sciences of the United States of America*, **114** (25), 6533-6538, doi:10.1073/pnas.1619358114.
Delworth, T. L. and F. R. Zeng, 2016: The Impact of the North Atlantic Oscillation on Climate through Its Influence on the Atlantic Meridional Overturning Circulation. *Journal of Climate*, **29** (3), 941-962, doi:10.1175/jcli-d-15-0396.1.
Depczynski, M. et al., 2013: Bleaching, coral mortality and subsequent survivorship on a West Australian fringing reef. *Coral Reefs*, **32** (1), 233-238, doi:10.1007/s00338-012-0974-0.
Deshayes, J. et al., 2013: Oceanic hindcast simulations at high resolution suggest that the Atlantic MOC is bistable. *Geophysical Research Letters*, **40** (12), 3069-3073, doi:10.1002/grl.50534.
DeVries, T., M. Holzer and F. Primeau, 2017: Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature*, **542**, 215, doi:10.1038/nature21068.
Di Lorenzo, E. et al., 2013: Synthesis of Pacific Ocean Climate and Ecosystem Dynamics. *Oceanography*, **26** (4), 68-81.
Di Lorenzo, E. and N. Mantua, 2016: Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Clim. Change*, **6** (11), 1042-1047, doi:10.1038/nclimate3082.
Dong, L., T. Zhou and B. Wu, 2014: Indian Ocean warming during 1958–2004 simulated by a climate system model and its mechanism. *Climate Dynamics*, **42** (1-2), 203-217.
Drijfhout, S. et al., 2015: Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (43), E5777-E5786, doi:10.1073/pnas.1511451112.
Duchez, A. et al., 2016: Potential for seasonal prediction of Atlantic sea surface temperatures using the RAPID array at 26N. *Climate Dynamics*, **46** (9-10), 3351-3370, doi:10.1007/s00382-015-2918-1.
Duke, N. C. et al., 2017: Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. *Marine and Freshwater Research*, **68** (10), 1816-1829, doi:10.1071/MF16322.
Dunstone, N. et al., 2013: Anthropogenic aerosol forcing of Atlantic tropical storms. *Nature Geoscience*, **6** (7), 534-539, doi:10.1038/NGEO1854.
Eakin, C. et al., 2017: Ding, Dong, The Witch is Dead (?) - Three Years of Global Coral Bleaching 2014-2017. *Reef Encounter*, **45** (32), 33-38.
Eakin, C. M. et al., 2018: Unprecedented Three Years of Global Coral Bleaching 2014-2017. *Bulletin of the American Meteorological Society*, **in press**.
Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436** (7051), 686.
Emanuel, K., 2013: Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (30), 12219-12224, doi:10.1073/pnas.1301293110.
Emanuel, K., 2015: Effect of Upper-Ocean Evolution on Projected Trends in Tropical Cyclone Activity. *Journal of Climate*, **28** (20), 8165-8170, doi:10.1175/Jcli-D-15-0401.1.
Emanuel, K., 2017: Assessing the present and future probability of Hurricane Harvey's rainfall. *Proc Natl Acad Sci U S A*, **114** (48), 12681-12684, doi:10.1073/pnas.1716222114.
England, M. et al., 2014: Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, **4** (3), 222-227, doi:10.1038/NCLIMATE2106.
Eslake, S., 2016: *Tasmania Report 2016*. Tasmania Chamber of Commerce and Industry, 92 pp.
Espinueva, S. R., E. O. Cayanan and N. C. Nievares, 2012: A retrospective on the devastating impacts of Tropical Storm Washi. *Tropical Cyclone Reseach and Review*, **1** (2), 163-176.
Evans, J. P. and I. Boyer-Souchet, 2012: Local sea surface temperatures add to extreme precipitation in northeast Australia during La Niña. *Geophysical Research Letters*, **39** (10), doi:doi:10.1029/2012GL052014.
Ewell, C. et al., 2017: Potential ecological and social benefits of a moratorium on transshipment on the high seas. *Marine Policy*, **81** (Supplement C), 293-300, doi:https://doi.org/10.1016/j.marpol.2017.04.004.

Ezer, T., 2015: Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009-2010 and estimated variations for 1935-2012. *Global and Planetary Change*, **129**, 23-36, doi:10.1016/j.gloplacha.2015.03.002.
Ezer, T., L. P. Atkinson, W. B. Corlett and J. L. Blanco, 2013: Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. *Journal of Geophysical Research-Oceans*, **118** (2), 685-697, doi:10.1002/jgrc.20091.
Fay, A. R. and G. A. McKinley, 2013: Global trends in surface ocean pCO2 from in situ data. *Global Biogeochemical Cycles*, **27** (2), 541-557, doi:10.1002/gbc.20051.
Fedorov, A., S. Hu, M. Lengaigne and E. Guilyardi, 2015: The impact of westerly wind bursts and ocean initial state on the development, and diversity of El Nino events. *Climate Dynamics*, **44** (5-6), 1381-1401, doi:10.1007/s00382-014-2126-4.
Feng, M. et al., 2015: Decadal increase in Ningaloo Niño since the late 1990s. *Geophysical Research Letters*, **42** (1), 104-112, doi:doi:10.1002/2014GL062509.
Feng, M., M. J. McPhaden, S.-P. Xie and J. Hafner, 2013: La Niña forces unprecedented Leeuwin Current warming in 2011. *Scientific Reports*, **3**, 1277, doi:10.1038/srep01277.
Ferrigno, F. et al., 2016: Corals in high diversity reefs resist human impact. *Ecological Indicators*, **70**, 106–113.
Field, C. B., V. Barros, T. F. Stocker and Q. Dahe, 2012: *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change*. Cambridge University Press.
Fischer, E. M. and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Clim. Change*, **5** (6), 560-564, doi:10.1038/nclimate2617.
Flato, G. et al., 2013: Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–866.
Fleurbaey, M. et al., 2014: Sustainable development and equity. In: Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 283–350.
Fraser, M. W. et al., 2014: Extreme climate events lower resilience of foundation seagrass at edge of biogeographical range. *Journal of Ecology*, **102** (6), 1528-1536, doi:10.1111/1365-2745.12300.
Frederiksen, C. S., J. S. Frederiksen, J. M. Sisson and S. L. Osbrough, 2017: Trends and projections of Southern Hemisphere baroclinicity: the role of external forcing and impact on Australian rainfall. *Climate Dynamics*, **48** (9), 3261-3282, doi:10.1007/s00382-016-3263-8.
Freitas, A. C. V., L. Aímola, T. Ambrizzi and C. P. de Oliveira, 2017: Extreme Intertropical Convergence Zone shifts over Southern Maritime Continent. *Atmospheric Science Letters*, **18** (1), 2-10.
Frölicher, T. L., E. M. Fischer and N. Gruber, 2018: Marine heat waves under global warming. *under review*.
Frölicher, T. L. and C. Laufkötter, 2018: Emerging risks from marine heat waves. *Nature Communications*, **9** (1), 650, doi:10.1038/s41467-018-03163-6.
Frölicher, T. L., K. B. Rodgers, C. A. Stock and W. W. L. Cheung, 2016: Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. *Global Biogeochemical Cycles*, **30** (8), 1224-1243, doi:10.1002/2015gb005338.
Frölicher, T. L. et al., 2015: Dominance of the Southern Ocean in Anthropogenic Carbon and Heat Uptake in CMIP5 Models. *Journal of Climate*, **28** (2), 862-886, doi:10.1175/jcli-d-14-00117.1.
Fuckar, N. S. et al., 2016: Record low northern hemisphere sea ice extent in March 2015. *Bulletin of the American Meteorological Society*, **97** (12), S136-S143.
Gaetani, M. and E. Mohino, 2013: Decadal Prediction of the Sahelian Precipitation in CMIP5 Simulations. *Journal of Climate*, **26** (19), 7708-7719, doi:10.1175/JCLI-D-12-00635.1.
Galli, G., C. Solidoro and T. Lovato, 2017: Marine Heat Waves Hazard 3D Maps and the Risk for Low Motility Organisms in a Warming Mediterranean Sea. *Frontiers in Marine Science*, **4** (136), doi:10.3389/fmars.2017.00136.
Gallina, V. et al., 2016: A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. *Journal of Environmental Management*, **168**, 123-132, doi:10.1016/j.jenvman.2015.11.011.
García-Herrera, R. et al., 2010: A Review of the European Summer Heat Wave of 2003. *Critical Reviews in Environmental Science and Technology*, **40** (4), 267-306, doi:10.1080/10643380802238137.
Garner, A. J. et al., 2017: Impact of climate change on New York City's coastal flood hazard: Increasing flood heights from the preindustrial to 2300 CE. *Proceedings of the National Academy of Sciences*, **114** (45), 11861-11866, doi:10.1073/pnas.1703568114.
Garrabou, J. et al., 2009: Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology*, **15** (5), 1090-1103, doi:10.1111/j.1365-2486.2008.01823.x.
Garreaud, R. D., 2018: A plausible atmospheric trigger for the 2017 coastal El Niño. *International Journal of Climatology*, **in press** (0), doi:doi:10.1002/joc.5426.

Gastineau, G., B. L'Heveder, F. Codron and C. Frankignoul, 2016: Mechanisms Determining the Winter Atmospheric Response to the Atlantic Overturning Circulation. *Journal of Climate*, **29** (10), 3767-3785, doi:10.1175/jcli-d-15-0326.1.

Gattuso, J.-P. et al., 2015: Contrasting futures for ocean and society from different anthropogenic CO₂ emissions scenarios. *Science*, **349** (6243), doi:10.1126/science.aac4722.

Gatusso, J. P., O. Hoegh-Guldberg and H. O. Pörtner, 2014: Cross-chapter box on coral reefs. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 97-100.

Gentemann, C. L., M. R. Fewings and M. García-Reyes, 2017: Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, **44** (1), 312-319, doi:10.1002/2016gl071039.

Gibbs, L., H. C. Gallagher, K. Block and E. Baker, 2016: Post-bushfire relocation decision-making and personal wellbeing: a case study from Victoria, Australia. In: Planning for Community-based Disaster Resilience Worldwide. Routledge, 355-378.

Gnanaseelan, C., M. K. Roxy and A. Deshpande, 2017: Variability and Trends of Sea Surface Temperature and Circulation in the Indian Ocean. In: Observed Climate Variability and Change over the Indian Region [Rajeevan, M. N. and S. Nayak (eds.)]. Springer Singapore, Singapore, 165-179.

Goddard, P., J. Yin, S. Griffies and S. Zhang, 2015: An extreme event of sea-level rise along the Northeast coast of North America in 2009-2010. *Nature Communications*, **6**, doi:10.1038/ncomms7346.

González-Riancho, P., B. Gerkensmeier and B. M. Ratter, 2017: Storm surge resilience and the Sendai Framework: Risk perception, intention to prepare and enhanced collaboration along the German North Sea coast. *Ocean & Coastal Management*, **141**, 118-131.

Gordon, A. L., R. D. Susanto and A. Ffield, 1999: Throughflow within makassar strait. *Geophysical Research Letters*, **26** (21), 3325-3328.

Graham, N. A. et al., 2015: Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature*, **518** (7537), 94-97.

Graham, N. A. J. et al., 2007: Lag Effects in the Impacts of Mass Coral Bleaching on Coral Reef Fish, Fisheries, and Ecosystems. *Conservation Biology*, **21** (5), 1291-1300, doi:doi:10.1111/j.1523-1739.2007.00754.x.

Gregory, J. M. et al., 2016: The Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) contribution to CMIP6: investigation of sea-level and ocean climate change in response to CO2 forcing. *Geoscientific Model Development*, **9** (11), 3993-4017, doi:10.5194/gmd-9-3993-2016.

Grinsted, A., J. C. Moore and S. Jevrejeva, 2012: Homogeneous record of Atlantic hurricane surge threat since 1923. *Proceedings of the National Academy of Sciences*, **109** (48), 19601-19605.

Grose, M. R. et al., 2012: The simulation of cutoff lows in a regional climate model: reliability and future trends. *Climate Dynamics*, **39** (1-2), 445-459, doi:10.1007/s00382-012-1368-2.

Guan, X. Y. and C. Chen, 2014: Using social media data to understand and assess disasters. *Natural Hazards*, **74** (2), 837-850.

Guemas, V. et al., 2013: September 2012 Arctic sea ice minimum: discriminating between sea ice memory, the August 2012 extreme storm, and prevailing warm conditins. *[in "Explaining Extremes of 2012 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **94** (9), S20-S22.

Guest, J. R. et al., 2012: Contrasting Patterns of Coral Bleaching Susceptibility in 2010 Suggest an Adaptive Response to Thermal Stress. *PLoS ONE*, **7** (3), e33353, doi:10.1371/journal.pone.0033353.

Guo, L., A. G. Turner and E. J. Highwood, 2016: Local and Remote Impacts of Aerosol Species on Indian Summer Monsoon Rainfall in a GCM. *Journal of Climate*, **29** (19), 6937-6955.

Haarsma, R. et al., 2013: More hurricanes to hit western Europe due to global warming. *Geophysical Research Letters*, **40** (9), 1783-1788, doi:10.1002/grl.50360.

Haarsma, R. J., F. M. Selten and S. S. Drijfhout, 2015: Decelerating Atlantic meridional overturning circulation main cause of future west European summer atmospheric circulation changes. *Environmental Research Letters*, **10** (9), doi:10.1088/1748-9326/10/9/094007.

Haasnoot, M. et al., 2015: Transient scenarios for robust climate change adaptation illustrated for water management in The Netherlands. *Environmental Research Letters*, **10** (10), doi:Artn 105008
10.1088/1748-9326/10/10/105008.

Handmer, J. et al., 2012: Changes in Impacts of Climate Extremes: Human Systems and Ecosystems. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) [Field, C. B., V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 231-290.

Hansen, J. et al., 2016: Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 A degrees C global warming could be dangerous. *Atmospheric Chemistry and Physics*, **16** (6), 3761-3812.

Hartmann, D. L. et al., 2013: Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159–254.

Hatun, H. et al., 2016: An inflated subpolar gyre blows life toward the northeastern Atlantic. *Progress in Oceanography*, **147**, 49-66, doi:10.1016/j.pocean.2016.07.009.

Hawkins, E. et al., 2011: Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport (vol 38, L10605, 2011). *Geophysical Research Letters*, **38**, doi:10.1029/2011GL048997.

Helbing, D., 2013: Globally networked risks and how to respond. *Nature*, **497** (7447), 51.

Heron, S. F., J. A. Maynard, R. van Hooidonk and C. M. Eakin, 2016: Warming Trends and Bleaching Stress of the World's Coral Reefs 1985–2012. *Scientific Reports*, **6**, 38402, doi:10.1038/srep38402.

Heron, S. F. et al., 2010: Summer Hot Snaps and Winter Conditions: Modelling White Syndrome Outbreaks on Great Barrier Reef Corals. *PLoS ONE*, **5** (8), e12210, doi:10.1371/journal.pone.0012210.

Herring, S. C. et al., 2018: Introduction to explaining extreme events of 2016 from a climate perspective. *[in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **99** (1), S54–S59, , doi:doi:10.1175/BAMS-D-17-0118.1.

Herring, S. C., M. P. Hoerling, T. C. Peterson and P. A. Stott, 2014: Explaining extreme events of 2013 from a climate perspective. *Bulletin American Meteorological Society*, **95** S1–S96.

Herring, S. C. et al., 2015: Explaining extreme events of 2014 from a climate perspective. *Bulletin American Meteorological Society*, **96**, S1–S172.

Heuze, C., 2017: North Atlantic deep water formation and AMOC in CMIP5 models. *Ocean Science*, **13** (4), 609-622, doi:10.5194/os-13-609-2017.

Hirata, H., R. Kawamura, M. Kato and T. Shinoda, 2016: Response of rapidly developing extratropical cyclones to sea surface temperature variations over the western Kuroshio–Oyashio confluence region. *Journal of Geophysical Research: Atmospheres*, **121** (8), 3843-3858, doi:doi:10.1002/2015JD024391.

Hobday, A. J. et al., 2016a: A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, **141**, 227-238, doi:10.1016/j.pocean.2015.12.014.

Hobday, A. J., C. M. Spillman, J. P. Eveson and J. R. Hartog, 2016b: Seasonal forecasting for decision support in marine fisheries and aquaculture. *Fisheries Oceanography*, **25** (S1), 45-56, doi:doi:10.1111/fog.12083.

Hoegh-Guldberg, O. et al., 2009: *The Coral Triangle and Climate Change Ecosystems, People and Societies at Risk*. WWF Australia, Brisbane, 276 pp.

Hoegh-Guldberg, O., E. S. Poloczanska, W. Skirving and S. Dove, 2017: Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science*, **4** (158), doi:10.3389/fmars.2017.00158.

Hoeke, R., K. McInnes and J. O'Grady, 2015: Wind and Wave Setup Contributions to Extreme Sea Levels at a Tropical High Island: A Stochastic Cyclone Simulation Study for Apia, Samoa. *Journal of Marine Science and Engineering*, **3** (3), 1117.

Hoeke, R. K. et al., 2013: Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change*, **108**, 128-138.

Holland, G. and C. L. Bruyère, 2014: Recent intense hurricane response to global climate change. *Climate Dynamics*, **42** (3), 617-627, doi:10.1007/s00382-013-1713-0.

Hope, P., E.-P. Lim, H. Hendon and G. Wang, 2018: The effect of increasing CO_2 on the extreme September 2016 rainfall across southeastern Australia. *[in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **99** (1), S133-S138.

Hu, S. and A. Fedorov, 2016: Exceptionally strong easterly wind burst stalling El Nino of 2014. *Proceedings of the National Academy of Sciences of the United States of America*, **113** (8), 2005-2010, doi:10.1073/pnas.1514182113.

Huang, P., I. I. Lin, C. Chou and R.-H. Huang, 2015: Change in ocean subsurface environment to suppress tropical cyclone intensification under global warming. *Nature Communications*, **6**, 7188, doi:10.1038/ncomms8188.

Huang, P. and S. Xie, 2015: Mechanisms of change in ENSO-induced tropical Pacific rainfall variability in a warming climate. *Nature Geoscience*, **8** (12), 922-U48, doi:10.1038/NGEO2571.

Huang, Y. and V. R. Coelho, 2017: Sustainability performance assessment focusing on coral reef protection by the tourism industry in the Coral Triangle region. *Tourism Management*, **59**, 510-527.

Hughes, T. P. et al., 2018a: Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, **359** (6371), 80-83, doi:10.1126/science.aan8048.

Hughes, T. P. et al., 2017a: Coral reefs in the Anthropocene. *Nature*, **546** (7656), 82-90, doi:10.1038/nature22901.

Hughes, T. P. et al., 2017b: Global warming and recurrent mass bleaching of corals. *Nature*, **543** (7645), 373-377, doi:10.1038/nature21707.

Hughes, T. P. et al., 2018b: Global warming transforms coral reef assemblages. *Nature*, doi:10.1038/s41586-018-0041-2.

Hydro Tasmania, 2016: *Annual Report*. Hydro Tasmania, 128 pp.

Iizumi, T. et al., 2014: Impacts of El Nino Southern Oscillation on the global yields of major crops. *Nature Communications*, **5**, doi:10.1038/ncomms4712.

Imada, Y. et al., 2018: Climate change increased the likelihood of the 2016 heat extremes in Asia in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S97-S101, doi:doi:10.1175/BAMS-D-17-0118.1.

IPCC, 2012: Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) [Field, C. B., V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G. K. Plattner, S. K. Allen, M. Tignor and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 3-21.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 1-32.

Jackson, L., R. Smith and R. Wood, 2017: Ocean and atmosphere feedbacks affecting AMOC hysteresis in a GCM. *Climate Dynamics*, **49** (1-2), 173-191, doi:10.1007/s00382-016-3336-8.

Jackson, L. C. et al., 2015: Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics*, **45** (11-12), 3299-3316, doi:10.1007/s00382-015-2540-2.

Jacox, M. G. et al., 2018a: Forcing of multiyear extreme ocean temperatures that impacted California Current living marine resources in 2016 in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S26-S33, doi:doi:10.1175/BAMS-D-17-0118.1.

Jacox, M. G. et al., 2018b: Forcing of Multiyear Extreme Ocean Temperatures that Impacted California Current Living Marine Resources in 2016. *Bulletin of the American Meteorological Society*, **99** (1), S27-S33, doi:10.1175/bams-d-17-0119.1.

Jacox, M. G. et al., 2016: Impacts of the 2015–2016 El Niño on the California Current System: Early assessment and comparison to past events. *Geophysical Research Letters*, **43** (13), 7072-7080, doi:10.1002/2016gl069716.

Jin, F.-F., J. Boucharel and I.-I. Lin, 2014: Eastern Pacific tropical cyclones intensified by El Niño delivery of subsurface ocean heat. *Nature*, **516** (7529), 82-85.

Johnson, C., M. Inall and S. Hakkinen, 2013: Declining nutrient concentrations in the northeast Atlantic as a result of a weakening Subpolar Gyre. *Deep-Sea Research Part I-Oceanographic Research Papers*, **82**, 95-107, doi:10.1016/j.dsr.2013.08.007.

Jones, T. et al., 2018: Massive Mortality of a Planktivorous Seabird in Response to a Marine Heatwave. *Geophysical Research Letters*, **0** (0), doi:doi:10.1002/2017GL076164.

Josey, S. A. et al., 2018: The Recent Atlantic Cold Anomaly: Causes, Consequences, and Related Phenomena. *Annual Review of Marine Science*, **10** (1), 475-501, doi:10.1146/annurev-marine-121916-063102.

Kajtar, J. B. et al., 2017: Model under-representation of decadal Pacific trade wind trends and its link to tropical Atlantic bias. *Climate Dynamics*, doi:doi:10.1007/s00382-017-3699-5.

Kam, J., T. R. Knutson, F. Zeng and A. T. Wittenberg, 2018: CMIP5 model-based assessment of anthropoegenic influence on highly anomalous Arctic Warmth during November-December 2016. *[in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **99** (1), S34-S38.

Kaneberg, E., S. Hertz and L.-M. Jensen, 2016: Emergency preparedness planning in developed countries: the Swedish case. *Journal of Humanitarian Logistics and Supply Chain Management*, **6** (2), 145-172.

Karoly, D. J., M. Black, M. R. Grose and A. D. King, 2016: The roles of climate change and El Niño in the record low rainfall in October 2015 in Tasmania, Australia. *Bulletin of the American Meteorological Society*, **97**, S 18.

Karspeck, A. R. et al., 2017: Comparison of the Atlantic meridional overturning circulation between 1960 and 2007 in six ocean reanalysis products. *Climate Dynamics*, **49** (3), 957-982, doi:10.1007/s00382-015-2787-7.

Kataoka, T., T. Tozuka, S. Behera and T. Yamagata, 2014: On the Ningaloo Niño/Niña. *Climate Dynamics*, **43** (5), 1463-1482, doi:10.1007/s00382-013-1961-z.

Keenan, T. F. et al., 2016: Recent pause in the growth rate of atmospheric CO2 due to enhanced terrestrial carbon uptake. *Nature Communications*, **7**, 13428, doi:10.1038/ncomms13428.

Kelly, K. A. et al., 2016: Impact of slowdown of Atlantic overturning circulation on heat and freshwater transports. *Geophysical Research Letters*, **43** (14), 7625-7631.

Kim, H.-S. et al., 2014: Tropical Cyclone Simulation and Response to CO2 Doubling in the GFDL CM2.5 High-Resolution Coupled Climate Model. *Journal of Climate*, **27** (21), 8034-8054, doi:10.1175/jcli-d-13-00475.1.

Kim, W. and W. Cai, 2014: The importance of the eastward zonal current for generating extreme El Niño. *Climate Dynamics*, **42** (11-12), 3005-3014, doi:10.1007/s00382-013-1792-y.

King, A. D., D. J. Karoly and B. J. Henley, 2017: Australian climate extremes at 1.5 °C and 2 °C of global warming. *Nature Climate Change*, **7**, 412, doi:10.1038/nclimate3296.

Klerk, W.-J. et al., 2015: The co-incidence of storm surges and extreme discharges within the Rhine–Meuse Delta. *Environmental Research Letters*, **10** (3), 035005.
Kleypas, J. A., F. S. Castruccio, E. N. Curchitser and E. Mcleod, 2015: The impact of ENSO on coral heat stress in the western equatorial Pacific. *Global Change Biology*, **21** (7), 2525-2539.
Klotzbach, P. J. and M. M. Bell, 2017: *Summary of 2017 Atlantic Tropical Cyclone Activity and Verification of Authors' Seasonal and Two-Week Forecasts*. Colorado State University, Department of Atmospheric Science, 37 pp [Available at: https://tropical.colostate.edu/media/sites/111/2017/11/2017-11.pdf].
Knowlton, K. and M. Rotkin-Ellman, 2014: *Preparing for Climate Change: Lessons for Coastal Cities from Hurricane Sandy*. Natural Resources Defense Council Report, 25 pp [Available at: https://www.nrdc.org/sites/default/files/hurricane-sandy-coastal-flooding-report.pdf].
Knox, J. A. et al., 2016: Analysis of the Twitter Response to Superstorm Sandy: Public Perceptions, Misconceptions, and Reconceptions of an Extreme Atmospheric Hazard. In: Atmospheric Hazards-Case Studies in Modeling, Communication, and Societal Impacts. InTech.
Knutson, T. et al., 2015: Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. *Journal of Climate*, **28** (18), 7203-7224, doi:10.1175/JCLI-D-15-0129.1.
Knutson, T. R., J. Kam, F. Zeng and A. T. W. al, 2018: CMIP5 model-based assessment of anthropogenic influence on record global warmth during 2016 in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S11-S15, doi:doi:10.1175/BAMS-D-17-0118.1.
Knutson, T. R. et al., 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3** (3), 157-163, doi:10.1038/Ngeo779.
Knutson, T. R., R. E. Tuleya, W. X. Shen and I. Ginis, 2001: Impact of CO2-induced warming on hurricane intensities as simulated in a hurricane model with ocean coupling. *Journal of Climate*, **14** (11), 2458-2468, doi:Doi 10.1175/1520-0442(2001)014<2458:Iociwo>2.0.Co;2.
Kociuba, G. and S. Power, 2015: Inability of CMIP5 Models to Simulate Recent Strengthening of the Walker Circulation: Implications for Projections. *Journal of Climate*, **28** (1), 20-35, doi:10.1175/JCLI-D-13-00752.1.
Komendantova, N. et al., 2014: Multi-hazard and multi-risk decision-support tools as a part of participatory risk governance: Feedback from civil protection stakeholders. *International Journal of Disaster Risk Reduction*, **8**, 50-67, doi:10.1016/j.ijdrr.2013.12.006.
Koplitz, S. N. et al., 2015: Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environ. Res. Lett.*, **11**, 094023, doi:doi:10.1088/1748-9326/11/9/094023.
Kosaka, Y. and S. Xie, 2013: Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, **501** (7467), 403-+, doi:10.1038/nature12534.
Kossin, J., K. Emanuel and G. Vecchi, 2014: The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509** (7500), 349-352, doi:10.1038/nature13278.
Kossin, J. P., K. A. Emanuel and S. J. Camargo, 2016: Past and Projected Changes in Western North Pacific Tropical Cyclone Exposure. *Journal of Climate*, **29** (16), 5725-5739, doi:10.1175/Jcli-D-16-0076.1.
Kostov, Y., K. C. Armour and J. Marshall, 2014: Impact of the Atlantic meridional overturning circulation on ocean heat storage and transient climate change. *Geophysical Research Letters*, **41** (6), 2108-2116, doi:10.1002/2013gl058998.
Kreibich, H. et al., 2014: Costing natural hazards. *Nature Climate Change*, **4**, 303, doi:10.1038/nclimate2182.
Kucharski, F., I. Kang, R. Farneti and L. Feudale, 2011: Tropical Pacific response to 20th century Atlantic warming. *Geophysical Research Letters*, **38**, doi:10.1029/2010GL046248.
Kulkarni, P. A. et al., 2017: Evacuations as a Result of Hurricane Sandy: Analysis of the 2014 New Jersey Behavioral Risk Factor Survey. *Disaster medicine and public health preparedness*, **11** (6), 720-728, doi:10.1017/dmp.2017.21.
L'Heureux, M., S. Lee and B. Lyon, 2013: Recent multidecadal strengthening of the Walker circulation across the tropical Pacific. *Nature Climate Change*, **3** (6), 571-576, doi:10.1038/NCLIMATE1840.
Lackmann, G. M., 2015: Hurricane Sandy before 1900 and after 2100. *Bulletin of the American Meteorological Society*, **96** (4), 547-560, doi:10.1175/Bams-D-14-00123.1.
Lagmay, A. M. F. et al., 2015: Devastating storm surges of Typhoon Haiyan. *International Journal of Disaster Risk Reduction*, **11**, 1-12.
Landschützer, P., N. Gruber, D. C. E. Bakker and U. Schuster, 2014: Recent variability of the global ocean carbon sink. *Global Biogeochemical Cycles*, **28** (9), 927-949, doi:10.1002/2014gb004853.
Landschützer, P. et al., 2015: The reinvigoration of the Southern Ocean carbon sink. *Science*, **349** (6253), 1221-1224, doi:10.1126/science.aab2620.
Le Nohaïc, M. et al., 2017: Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia. *Scientific Reports*, **7** (1), 14999, doi:10.1038/s41598-017-14794-y.
Lee, H. S., T. Yamashita and T. Mishima, 2012: Multi-decadal variations of ENSO, the Pacific Decadal Oscillation and tropical cyclones in the western North Pacific. *Progress in Oceanography*, **105**, 67-80.

Lee, M. Y., C. C. Hong and H. H. Hsu, 2015a: Compounding effects of warm sea surface temperature and reduced sea ice on the extreme circulation over the extratropical North Pacific and North America during the 2013–2014 boreal winter. *Geophysical Research Letters*, **42** (5), 1612-1618, doi:doi:10.1002/2014GL062956.
Lee, S.-K. et al., 2015b: Pacific origin of the abrupt increase in Indian Ocean heat content during the warming hiatus. *Nature Geosci*, **8** (6), 445-449, doi:10.1038/ngeo2438.
Lee, T. and M. J. McPhaden, 2010: Increasing intensity of El Niño in the central-equatorial Pacific. *Geophysical Research Letters*, **37** (14).
Lehner, F., A. Born, C. C. Raible and T. F. Stocker, 2013: Amplified Inception of European Little Ice Age by Sea Ice-Ocean-Atmosphere Feedbacks. *Journal of Climate*, **26** (19), 7586-7602, doi:10.1175/jcli-d-12-00690.1.
Lejano, R., J. Tan and A. Wilson, 2016: A Textual Processing Model of Risk Communication: Lessons from Typhoon Haiyan. *Weather Climate and Society*, **8** (4), 447-463, doi:10.1175/WCAS-D-16-0023.1.
Lemoine, D. and C. P. Traeger, 2016: Economics of tipping the climate dominoes. *Nature Climate Change*, **6** (5), 514.
Lenaerts, J. T. M. et al., 2015: Representing Greenland ice sheet freshwater fluxes in climate models. *Geophysical Research Letters*, **42** (15), 6373-6381, doi:10.1002/2015gl064738.
Leonard, M. et al., 2014: A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change*, **5** (1), 113-128, doi:10.1002/wcc.252.
Lewis, S. C. and J. Mallela, 2018a: A Multifactor Risk Analysis of the Record 2016 Great Barrier Reef Bleaching. *Bulletin of the American Meteorological Society*, **99** (1), S144-S149, doi:10.1175/bams-d-17-0074.1.
Lewis, S. C. and J. Mallela, 2018b: A multifactor risk analysis of the record 2016 Great Barrier Reef bleaching in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S144- S149, doi:doi:10.1175/BAMS-D-17-0118.1.
Li, T. et al., 2010: Global warming shifts Pacific tropical cyclone location. *Geophysical Research Letters*, **37** (21).
Li, X., S. Xie, S. Gille and C. Yoo, 2016: Atlantic-induced pan-tropical climate change over the past three decades. *Nature Climate Change*, **6** (3), 275-+, doi:10.1038/NCLIMATE2840.
Lima, F. P. and D. S. Wethey, 2012: Three decades of high-resolution coastal sea surface temperatures reveal more than warming. **3**, 704, doi:10.1038/ncomms1713.
Lin, I. I. et al., 2009: Warm ocean anomaly, air sea fluxes, and the rapid intensification of tropical cyclone Nargis (2008). *Geophysical Research Letters*, **36** (3).
Lin, N., K. Emanuel, M. Oppenheimer and E. Vanmarcke, 2012: Physically based assessment of hurricane surge threat under climate change. *Nature Climate Change*, **2**, 462, doi:10.1038/nclimate1389.
Little, C. M. et al., 2015: Joint projections of US East Coast sea level and storm surge. *Nature Clim. Change*, **5** (12), 1114-1120, doi:10.1038/nclimate2801.
Little, C. M., C. G. Piecuch and R. M. Ponte, 2017: On the relationship between the meridional overturning circulation, alongshore wind stress, and United States East Coast sea level in the Community Earth System Model Large Ensemble. *Journal of Geophysical Research: Oceans*, **122** (6), 4554-4568.
Liu, G. et al., 2018: Predicting Heat Stress to Inform Reef Management: NOAA Coral Reef Watch's 4-Month Coral Bleaching Outlook. *Frontiers in Marine Science*, **5** (57), doi:10.3389/fmars.2018.00057.
Liu, G. et al., 2014: Reef-Scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch. *Remote Sensing*, **6** (11), 11579.
Liu, Q., M. Feng, D. Wang and S. Wijffels, 2015: Interannual variability of the Indonesian Throughflow transport: A revisit based on 30 year expendable bathythermograph data. *Journal of Geophysical Research-Oceans*, **120** (12), 8270-8282, doi:10.1002/2015JC011351.
Liu, W., S. P. Xie, Z. Y. Liu and J. Zhu, 2017: Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances*, **3** (1), doi:10.1126/sciadv.1601666.
Lontzek, T. S., Y. Cai, K. L. Judd and T. M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5** (5), 441.
Loveday, B., P. Penven and C. Reason, 2015: Southern Annular Mode and westerly-wind-driven changes in Indian-Atlantic exchange mechanisms. *Geophysical Research Letters*, **42** (12), 4912-4921.
Lübbecke, J. F., J. V. Durgadoo and A. Biastoch, 2015: Contribution of increased Agulhas leakage to tropical Atlantic warming. *Journal of Climate*, **28** (24), 9697-9706.
Lumbroso, D. M., N. R. Suckall, R. J. Nicholls and K. D. White, 2017: Enhancing resilience to coastal flooding from severe storms in the USA: international lessons. *Natural Hazards and Earth System Sciences*, **17** (8), 1357.
Luo, J.-J., W. Sasaki and Y. Masumoto, 2012: Indian Ocean warming modulates Pacific climate change. *Proceedings of the National Academy of Sciences*, **109** (46), 18701-18706.
Lynch-Stieglitz, J., 2017: The Atlantic Meridional Overturning Circulation and Abrupt Climate Change. *Annual Review of Marine Sciences, Vol 9*, **9**, 83-104, doi:10.1146/annurev-marine-010816-060415.
Macroconsult. Peruvian economic losses during El Niño 2017. [Available at: http://grupomacro.pe/2017/03/24/danos-de-el-nino-us3-124-millones-hasta-ahora-macroconsult/]
Majkut, J. D., J. L. Sarmiento and K. B. Rodgers, 2014: A growing oceanic carbon uptake: Results from an inversion study of surface pCO2 data. *Global Biogeochemical Cycles*, **28** (4), 335-351, doi:10.1002/2013gb004585.
Manganello, J. et al., 2014: Future Changes in the Western North Pacific Tropical Cyclone Activity Projected by a Multidecadal Simulation with a 16-km Global Atmospheric GCM. *Journal of Climate*, **27** (20), 7622-7646, doi:10.1175/JCLI-D-13-00678.1.

Mann, M. E. and K. A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *Eos, Transactions American Geophysical Union*, **87** (24), 233-241.
Marshall, J. et al., 2014: The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **372** (2019), doi:10.1098/rsta.2013.0040.
Marzocchi, W. et al., 2012: Basic principles of multi-risk assessment: a case study in Italy. *Natural Hazards*, **62** (2), 551-573.
Masson-Delmotte, V. et al., 2013: Information from Paleoclimate Archives. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 383–464.
McCabe, R. M. et al., 2016: An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, **43** (19), 10,366-10,376, doi:10.1002/2016gl070023.
McCarthy, G. D. et al., 2015: Measuring the Atlantic Meridional Overturning Circulation at 26 degrees N. *Progress in Oceanography*, **130**, 91-111, doi:10.1016/j.pocean.2014.10.006.
McClanahan, T. R. et al., 2012: Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate. *PLoS ONE*, **7** (8), e42884, doi:10.1371/journal.pone.0042884.
McGregor, S. et al., 2013: Inferred changes in El Niño-Southern Oscillation variance over the past six centuries. *Climate of the Past*, **9** (5), 2269.
McGregor, S. et al., 2014: Recent Walker circulation strengthening and Pacific cooling amplified by Atlantic warming. *Nature Climate Change*, **4** (10), 888-892, doi:10.1038/NCLIMATE2330.
McInnes, K. L. et al., 2016: Application of a synthetic cyclone method for assessment of tropical cyclone storm tides in Samoa. *Natural Hazards*, **80** (1), 425-444, doi:10.1007/s11069-015-1975-4.
McInnes, K. L. et al., 2014: Quantifying storm tide risk in Fiji due to climate variability and change. *Global and Planetary Change*, **116**, 115–129.
McNamara, M. W., J. C. Morris and M. Mayer, 2014: Expanding the Universe of Multi-Organizational Arrangements: Contingent Coordination and the Deepwater Horizon Transportation Challenges. *Politics & Policy*, **42** (3), 346-368.
McTaggart-Cowan, R. et al., 2006: Analysis of Hurricane Catarina (2004). *Monthly Weather Review*, **134** (11), 3029-3053, doi:10.1175/mwr3330.1.
Mecking, J. V., S. S. Drijfhout, L. C. Jackson and M. B. Andrews, 2017: The effect of model bias on Atlantic freshwater transport and implications for AMOC bi-stability. *Tellus Series a-Dynamic Meteorology and Oceanography*, **69**, doi:10.1080/16000870.2017.1299910.
Mecking, J. V., S. S. Drijfhout, L. C. Jackson and T. Graham, 2016: Stable AMOC off state in an eddy-permitting coupled climate model. *Climate Dynamics*, **47** (7-8), 2455-2470, doi:10.1007/s00382-016-2975-0.
Meinen, C. S. et al., 2017: Characteristics and causes of Deep Western Boundary Current transport variability at 34.5 S during 2009-2014. *Ocean Science*, **13** (1), 175.
Melet, A., R. Almar and B. Meyssignac, 2016: What dominates sea level at the coast: a case study for the Gulf of Guinea. *Ocean Dynamics*, **66** (5), 623-636, doi:10.1007/s10236-016-0942-2.
Mellin, C. et al., 2016: Marine protected areas increase resilience among coral reef communities. *Ecology Letters*, **19** (6), 629-637.
Mentaschi, L. et al., 2017: Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophysical Research Letters*, **44** (5), 2416-2426, doi:10.1002/2016GL072488.
Messmer, M., J. J. Gómez-Navarro and C. C. Raible, 2017: Sensitivity experiments on the response of Vb cyclones to sea surface temperature and soil moisture changes. *Earth Syst. Dynam.*, **8** (3), 477-493, doi:10.5194/esd-8-477-2017.
Mills, K. et al., 2013: Fisheries Management in a Changing Climate: Lessons From the 2012 Ocean Heat Wave in the Northwest Atlantic. *Oceanography*, **26** (2), doi:10.5670/oceanog.2013.27.
Mishra, V., B. V. Smoliak, D. P. Lettenmaier and J. M. Wallace, 2012: A prominent pattern of year-to-year variability in Indian Summer Monsoon Rainfall. *Proceedings of the National Academy of Sciences*, **109** (19), 7213-7217.
Mogollon, R. and P. Calil, 2017: On the effects of ENSO on ocean biogeochemistry in the Northern Humboldt Current System (NHCS): A modeling study. *Journal of Marine Systems*, **172**, 137-159, doi:10.1016/j.jmarsys.2017.03.011.
Mohino, E., N. Keenlyside and H. Pohlmann, 2016: Decadal prediction of Sahel rainfall: where does the skill (or lack thereof) come from? *Climate Dynamics*, **47** (11), 3593-3612, doi:10.1007/s00382-016-3416-9.
Moon, I.-J., S.-H. Kim and C. Wang, 2015: El Niño and intense tropical cyclones. *Nature*, **526** (7575), E4-E5.
Mora, C., N. A. J. Graham and N. Nyström, 2016: Ecological limitations to the resilience of coral reefs. *Coral Reefs*, **35**, 1271–1280.
Moreno-Chamarro, E. et al., 2017: Winter amplification of the European Little Ice Age cooling by the subpolar gyre. *Scientific Reports*, **7**, doi:10.1038/s41598-017-07969-0.
Mori, A. S., 2016: Resilience in the Studies of Biodiversity–Ecosystem Functioning. *Trends in Ecology and Evolution*, **35** (2), 87-90.

Morrow, B. H., J. K. Lazo, J. Rhome and J. Feyen, 2015: Improving storm surge risk communication: Stakeholder perspectives. *Bulletin of the American Meteorological Society*, **96** (1), 35-48.
Moser, S. C. and M. T. Boykoff, 2013: *Successful adaptation to climate change: Linking science and policy in a rapidly changing world*. Routledge.
Moynihan, D. P., 2009: The network governance of crisis response: Case studies of incident command systems. *Journal of Public Administration Research and Theory*, **19** (4), 895-915.
Msadek, R. et al., 2014: Predicting a Decadal Shift in North Atlantic Climate Variability Using the GFDL Forecast System. *Journal of Climate*, **27** (17), 6472-6496, doi:10.1175/jcli-d-13-00476.1.
Muhling, B. A. et al., 2015: Potential impact of climate change on the Intra-Americas Sea: Part 2. Implications for Atlantic bluefin tuna and skipjack tuna adult and larval habitats. *Journal of Marine Systems*, **148**, 1-13.
Muis, S. et al., 2016: A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, **7**.
Mulitza, S. et al., 2017: Synchronous and proportional deglacial changes in Atlantic meridional overturning and northeast Brazilian precipitation. *Paleoceanography*, **32** (6), 622-633, doi:10.1002/2017PA003084.
Munro, D. R. et al., 2015: Recent evidence for a strengthening CO2 sink in the Southern Ocean from carbonate system measurements in the Drake Passage (2002–2015). *Geophysical Research Letters*, **42** (18), 7623-7630, doi:10.1002/2015gl065194.
Murakami, H. et al., 2015: Investigating the influence of anthropogenic forcing and natural variability on the 2014 Hawaiian hurricane season. *Bulletin American Meteorological Society*, **96** (12), S115-S119.
Murakami, H. et al., 2012: Future changes in tropical cyclone activity projected by the new high-resolution MRI-AGCM. *Journal of Climate*, **25** (9), 3237-3260.
Nakamura, J. et al., 2017: Western North Pacific Tropical Cyclone Model Tracks in Present and Future Climates. *Journal of Geophysical Research-Atmospheres*, **122** (18), 9721-9744, doi:10.1002/2017jd027007.
Nalau, J., J. Handmer and M. Dalesa, 2017: The Role and Capacity of Government in a Climate Crisis: Cyclone Pam in Vanuatu. In: Climate Change Adaptation in Pacific Countries. Springer, 151-161.
Newman, M. et al., 2018a: The extreme 2015/16 El Nino, in the context of historical climate variability and change. *[in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **99** (1), S15-S20.
Newman, M. et al., 2018b: The Extreme 2015/16 El Niño, in the Context of Historical Climate Variability and Change. *Bulletin of the American Meteorological Society*, **99** (1), S16-S20, doi:10.1175/bams-d-17-0116.1.
Nieves, V., J. Willis and W. Patzert, 2015: Recent hiatus caused by decadal shift in Indo-Pacific heating. *Science*, **349** (6247), 532-535, doi:10.1126/science.aaa4521.
Nordhaus, W. D., 1992: An optimal transition path for controlling greenhouse gases. *Science*, **258** (5086), 1315-1319.
Nordhaus, W. D., 2017: Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 201609244.
Nyamwanza, A. M. et al., 2017: Contributions of decadal climate information in agriculture and food systems in east and southern Africa. *Climatic Change*, **143** (1-2), 115-128, doi:10.1007/s10584-017-1990-4.
Oey, L. Y. and S. Chou, 2016: Evidence of rising and poleward shift of storm surge in western North Pacific in recent decades. *Journal of Geophysical Research: Oceans*, **121** (7), 5181-5192, doi:doi:10.1002/2016JC011777.
Ohman, M. D. ENSO impacts on ecosystem indicators in the California Current System. [Available at]
Olita, A. et al., 2007: Effects of the 2003 European heatwave on the Central Mediterranean Sea: surface fluxes and the dynamical response. *Ocean Sci.*, **3** (2), 273-289, doi:10.5194/os-3-273-2007.
Oliver, E. C. J. et al., 2017: The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature Communications*, **8**, 16101, doi:10.1038/ncomms16101.
Oliver, E. C. J. et al., 2018a: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9** (1), 1324, doi:10.1038/s41467-018-03732-9.
Oliver, E. C. J. and N. J. Holbrook, 2014: Extending our understanding of South Pacific gyre "spin-up": Modeling the East Australian Current in a future climate. *Journal of Geophysical Research: Oceans*, **119** (5), 2788-2805, doi:doi:10.1002/2013JC009591.
Oliver, E. C. J., T. J. O'Kane and N. J. Holbrook, 2015: Projected changes to Tasman Sea eddies in a future climate. *Journal of Geophysical Research: Oceans*, **120** (11), 7150-7165, doi:doi:10.1002/2015JC010993.
Oliver, E. C. J., S. E. Perkins-Kirkpatrick, N. J. Holbrook and N. L. Bindoff, 2018b: Anthropogenic and natural influences on record 2016 marine heat waves. *[in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **99** (1), S44-S48.
Oliver, E. C. J., S. J. Wotherspoon, M. A. Chamberlain and N. J. Holbrook, 2014a: Projected Tasman Sea Extremes in Sea Surface Temperature through the Twenty-First Century. *Journal of Climate*, **27** (5), 1980-1998, doi:10.1175/jcli-d-13-00259.1.
Oliver, E. C. J., S. J. Wotherspoon and N. J. Holbrook, 2014b: Estimating extremes from global ocean and climate models: A Bayesian hierarchical model approach. *Progress in Oceanography*, **122** (Supplement C), 77-91, doi:10.1016/j.pocean.2013.12.004.
Olshansky, R. B. and L. A. Johnson, 2014: The Evolution of the Federal Role in Supporting Community Recovery After U.S. Disasters. *Journal of the American planning Association*, **80** (4), 293-304, doi:10.1080/01944363.2014.967710.
Oppenheimer, M. et al., 2014: Emergent risks and key vulnerabilities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment

Report of the Intergovernmental Panel of Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1039-1099.

Ortiz, J. C. et al., 2014: Global disparity in the ecological benefits of reducing carbon emissions for coral reefs. *Nature Climate Change*, **4**, 1090, doi:10.1038/nclimate2439.

Overland, J. E., M. Wang and T. J. Ballinger, 2018: Recent increased warming of the Alaskan marine Arctic due to midlatitude linkages. *Advances in Atmospheric Sciences*, **35** (1), 75-84, doi:10.1007/s00376-017-7026-1.

Pal, I., T. Ghosh and C. Ghosh, 2017: Institutional framework and administrative systems for effective disaster risk governance - Perspectives of 2013 Cyclone Phailin in India. *International Journal of Disaster Risk Reduction*, **21**, 350-359, doi:10.1016/j.ijdrr.2017.01.002.

Palter, J. B., T. L. Frölicher, D. Paynter and J. G. John, 2017: Climate, ocean circulation, and sea level changes under stabilization and overshoot pathways to 1.5 K warming. *Earth Syst. Dynam. Discuss.*, **2017**, 1-19, doi:10.5194/esd-2017-105.

Park, D.-S. R. et al., 2017: Asymmetric response of tropical cyclone activity to global warming over the North Atlantic and western North Pacific from CMIP5 model projections. *Scientific Reports*, **7**, 41354.

Paton, D., 2007: Preparing for natural hazards: the role of community trust. *Disaster Prevention and Management: An International Journal*, **16** (3), 370-379.

Paul, B. K., 2009: Why relatively fewer people died? The case of Bangladesh's Cyclone Sidr. *Natural Hazards*, **50** (2), 289-304.

Pearce, A. F. and M. Feng, 2013: The rise and fall of the "marine heat wave" off Western Australia during the summer of 2010/2011. *Journal of Marine Systems*, **111-112**, 139-156, doi:10.1016/j.jmarsys.2012.10.009.

Penaflor, E. L. et al., 2009: Sea-surface temperature and thermal stress in the Coral Triangle's over the past two decades. *Coral Reefs*, **28**, 841-850.

Pepler, A. S., L. V. Alexander, J. P. Evans and S. C. Sherwood, 2016a: The influence of local sea surface temperatures on Australian east coast cyclones. *Journal of Geophysical Research: Atmospheres*, **121** (22), 13,352-13,363, doi:doi:10.1002/2016JD025495.

Pepler, A. S. et al., 2016b: Projected changes in east Australian midlatitude cyclones during the 21st century. *Geophysical Research Letters*, **43** (1), 334-340, doi:doi:10.1002/2015GL067267.

Perkins-Kirkpatrick, S. E. et al., 2016: Natural hazards in Australia: heatwaves. *Climatic Change*, **139** (1), 101-114, doi:10.1007/s10584-016-1650-0.

Persechino, A. et al., 2013: Decadal predictability of the Atlantic meridional overturning circulation and climate in the IPSL-CM5A-LR model. *Climate Dynamics*, **40** (9-10), 2359-2380, doi:10.1007/s00382-012-1466-1.

Pershing, A. J. et al., 2015: Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, **350** (6262), 809-812, doi:10.1126/science.aac9819.

Peterson, T. C., M. P. Hoerling, P. A. Stott and S. Herring, 2013: Explaining extreme events of 2012 from a climate perspective. *Bulletin American Meteorological Society*, **94**, S1–S74.

Peterson, T. C., P. A. Stott and S. Herring, 2012: Explaining extreme events of 2011 from a climate perspective. . *Bulletin American Meteorological Society*, **93**, 1041–1067.

Peterson, W. T. et al., 2017: The pelagic ecosystem in the Northern California Current off Oregon during the 2014–2016 warm anomalies within the context of the past 20 years. *Journal of Geophysical Research: Oceans*, **122** (9), 7267-7290, doi:10.1002/2017jc012952.

Pezza, A. B. and I. Simmonds, 2005: The first South Atlantic hurricane: Unprecedented blocking, low shear and climate change. *Geophysical Research Letters*, **32** (15), doi:doi:10.1029/2005GL023390.

Pickering, M. D. et al., 2017: The impact of future sea-level rise on the global tides. *Continental Shelf Research*, **142** (Supplement C), 50-68, doi:10.1016/j.csr.2017.02.004.

Plummer, R. et al., 2017: Is adaptive co-management delivering? Examining relationships between collaboration, learning and outcomes in UNESCO biosphere reserves. *Ecological Economics*, **140**, 79-88.

Poli, P. et al., 2016: ERA-20C: An atmospheric reanalysis of the 20th century. *Journal of Climate*, **29**, 4083--4097, doi:10.1175/JCLI-D-15-0556.1.

Pomeroy, R. et al., 2015: Status and Priority Capacity Needs for Local Compliance and Community-Supported Enforcement of Marine Resource Rules and Regulations in the Coral Triangle Region. *Coastal Management*, **43** (3), 301-328.

Power, S. et al., 2013: Robust twenty-first-century projections of El Nino and related precipitation variability. *Nature*, **502** (7472), 541-545, doi:10.1038/nature12580.

Press, T., 2016: *Tasmanian Wilderness World Heritage Area Bushfire and Climate Change Report*. Department of Premier and Cabinet, Tasmanian Climate Change Office, 156 pp.

Rahmstorf, S. et al., 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, **5** (5), 475-480, doi:10.1038/nclimate2554.

Rajeevan, M. et al., 2013: On the epochal variation of intensity of tropical cyclones in the Arabian Sea. *Atmospheric Science Letters*, **14** (4), 249-255.

Ramírez, I. J. and F. Briones, 2017: Understanding the El Niño Costero of 2017: The Definition Problem and Challenges of Climate Forecasting and Disaster Responses. *International Journal of Disaster Risk Science*, **8** (4), 489-492, doi:10.1007/s13753-017-0151-8.
Randerson, J. T. et al., 2015: Multicentury changes in ocean and land contributions to the climate-carbon feedback. *Global Biogeochemical Cycles*, **29** (6), 744-759, doi:10.1002/2014gb005079.
Rasquinho, O., J. Liu and D. Leong, 2013: Assessment on disaster risk reduction of tropical storm Washi. *Tropical cyclone research and review*, **2** (3), 169-175.
Rayner, N. A. et al., 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, **108** (D14), 4407, doi:10.1029/2002JD002670.
Reintges, A., M. Latif and W. Park, 2017: Sub-decadal North Atlantic Oscillation variability in observations and the Kiel Climate Model. *Climate Dynamics*, **48** (11), 3475-3487, doi:10.1007/s00382-016-3279-0.
Rexach, M. et al., 2017: *Hurricane Maria's Aftermath: Highlights of Available Government Assistance for Puerto Rico Residents*. [Available at: https://www.littler.com/files/hurricane_marias_aftermath_-_highlights_of_available_government_assistance_for_puerto_rico_residents.pdf].
Rhein, M. et al., 2013: Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 255–316.
Rhein, M. et al., 2017: Ventilation variability of Labrador SeaWater and its impact on oxygen and anthropogenic carbon: a review. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **375** (2102), doi:10.1098/rsta.2016.0321.
Rhodes, R. et al., 2015: Enhanced tropical methane production in response to iceberg discharge in the North Atlantic. *Science*, **348** (6238), 1016-1019, doi:10.1126/science.1262005.
Ridderinkhof, H. et al., 2010: Seasonal and interannual variability in the Mozambique Channel from moored current observations. *Journal of Geophysical Research-Oceans*, **115**, doi:10.1029/2009JC005619.
Ringeval, B. et al., 2013: Response of methane emissions from wetlands to the Last Glacial Maximum and an idealized Dansgaard-Oeschger climate event: insights from two models of different complexity. *Climate of the Past*, **9** (1), 149-171, doi:10.5194/cp-9-149-2013.
Risser, M. D. and M. F. Wehner, 2017: Attributable Human-Induced Changes in the Likelihood and Magnitude of the Observed Extreme Precipitation during Hurricane Harvey. *Geophysical Research Letters*, **44** (24), 12,457-12,464, doi:doi:10.1002/2017GL075888.
Ritz, C. et al., 2015: Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. *Nature*, **528** (7580), 115-+, doi:10.1038/nature16147.
Roberts, M. J. et al., 2015: Tropical cyclones in the UPSCALE ensemble of high-resolution global climate models. *Journal of Climate*, **28** (2), 574-596.
Robson, J. et al., 2017: Decadal prediction of the North Atlantic subpolar gyre in the HiGEM high-resolution climate model. *Climate Dynamics*, doi:10.1007/s00382-017-3649-2.
Robson, J., R. Sutton and D. Smith, 2013: Predictable Climate Impacts of the Decadal Changes in the Ocean in the 1990s. *Journal of Climate*, **26** (17), 6329-6339, doi:10.1175/jcli-d-12-00827.1.
Robson, J. I., R. T. Sutton and D. M. Smith, 2012: Initialized decadal predictions of the rapid warming of the North Atlantic Ocean in the mid 1990s. *Geophysical Research Letters*, **39** (19), n/a-n/a, doi:10.1029/2012gl053370.
Rohini, P., M. Rajeevan and A. Srivastava, 2016: On the variability and increasing trends of heat waves over India. *Scientific Reports*, **6**.
Romanou, A., J. Marshall, M. Kelley and J. Scott, 2017: Role of the ocean's AMOC in setting the uptake efficiency of transient tracers. *Geophysical Research Letters*, **44** (11), 5590-5598, doi:10.1002/2017GL072972.
Rose, B. E. J. et al., 2014: The dependence of transient climate sensitivity and radiative feedbacks on the spatial pattern of ocean heat uptake. *Geophysical Research Letters*, **41** (3), 1071-1078, doi:10.1002/2013gl058955.
Rose, B. E. J. and L. Rayborn, 2016: The Effects of Ocean Heat Uptake on Transient Climate Sensitivity. *Current Climate Change Reports*, **2** (4), 190-201, doi:10.1007/s40641-016-0048-4.
Rosenzweig, C. and W. Solecki, 2014: Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change-Human and Policy Dimensions*, **28**, 395-408, doi:10.1016/j.gloenvcha.2014.05.003.
Rosier, S. et al., 2015: Extreme Rainfall in Early July 2014 in Northland, New Zealand—Was There an Anthropogenic Influence? *Bulletin American Meteorological Society*, **96** (12), S136-S140.
Rosinski, A. et al., 2017: Coral bleaching recovery plan. *University of Hawai'i, Social Science Research Institute*, 47pp.
Rosselló, R., 2017: *Build Back Better Puerto Rico*. Request for Federal Assistance for Disaster Recovery, 94 pp [Available at: http://nlihc.org/sites/default/files/Build_Back_Better_PR_Request_94B.pdf].
Roxy, M. et al., 2017: A threefold rise in widespread extreme rain events over central India. *Nature Communications*, **8** (1), 708.
Roxy, M. K., K. Ritika, P. Terray and S. Masson, 2014: The curious case of Indian Ocean warming. *Journal of Climate*, **27** (22), 8501-8509, doi:10.1175/jcli-d-14-00471.1.
Roxy, M. K. et al., 2015: Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nature Communications*, **6**, 7423, doi:10.1038/ncomms8423.

Rudnick, D. L., K. D. Zaba, R. E. Todd and R. E. Davis, 2017: A climatology of the California Current System from a network of underwater gliders. *Progress in Oceanography*, **154** (Supplement C), 64-106, doi:10.1016/j.pocean.2017.03.002.
Rugenstein, M. A. A., K. Caldeira and R. Knutti, 2016: Dependence of global radiative feedbacks on evolving patterns of surface heat fluxes. *Geophysical Research Letters*, **43** (18), 9877-9885, doi:10.1002/2016gl070907.
Rugenstein, M. A. A. et al., 2013: Northern High-Latitude Heat Budget Decomposition and Transient Warming. *Journal of Climate*, **26** (2), 609-621, doi:10.1175/jcli-d-11-00695.1.
Saba, V. S. et al., 2016: Enhanced warming of the Northwest Atlantic Ocean under climate change. *Journal of Geophysical Research-Oceans*, **121** (1), 118-132, doi:10.1002/2015jc011346.
Saenko, O. A., D. Yang and P. G. Myers, 2017: Response of the North Atlantic dynamic sea level and circulation to Greenland meltwater and climate change in an eddy-permitting ocean model. *Climate Dynamics*, **49** (7-8), 2895-2910, doi:10.1007/s00382-016-3495-7.
Sanseverino, I. et al., 2016: Algal bloom and its economic impact. *EUR 27905 EN; doi: 10.2788*, **660478**.
Santoso, A., M. J. McPhaden and W. Cai, 2017: The defining characteristics of ENSO extremes and the strong 2015/2016 El Niño. *Reviews of Geophysics*, **55**, 1079-1129.
Scaife, A. A. et al., 2017: The predictability of European winter 2015/2016. *Atmos. Sc. Lett.*, **18**, 38-44, doi:DOI: 10.1002/asl/721.
Scannell, H. A. et al., 2016: Frequency of marine heatwaves in the North Atlantic and North Pacific since 1950. *Geophysical Research Letters*, **43** (5), 2069-2076, doi:10.1002/2015GL067308.
Schaeffer, A. and M. Roughan, 2017: Subsurface intensification of marine heatwaves off southeastern Australia: The role of stratification and local winds. *Geophysical Research Letters*, **44** (10), 5025-5033, doi:10.1002/2017gl073714.
Scheffer, M. et al., 2015: Creating a safe operating space for iconic ecosystems. *Science*, **347** (6228), 1317-1319, doi:10.1126/science.aaa3769.
Schlegel, R. W. et al., 2017a: Predominant Atmospheric and Oceanic Patterns during Coastal Marine Heatwaves. *Frontiers in Marine Science*, **4** (323), doi:10.3389/fmars.2017.00323.
Schlegel, R. W., E. C. J. Oliver, T. Wernberg and A. J. Smit, 2017b: Nearshore and offshore co-occurrence of marine heatwaves and cold-spells. *Progress in Oceanography*, **151** (Supplement C), 189-205, doi:10.1016/j.pocean.2017.01.004.
Scolobig, A., 2017: Understanding Institutional Deadlocks in Disaster Risk Reduction: The Financial and Legal Risk Root Causes in Genova, Italy. *Journal of Extreme Events*, **4** (02), 1750010.
Seager, R. et al., 2015: Causes of the 2011–14 California Drought. *Journal of Climate*, **28** (18), 6997-7024, doi:10.1175/jcli-d-14-00860.1.
Seager, R. and I. R. Simpson, 2016: Western boundary currents and climate change. *Journal of Geophysical Research: Oceans*, **121** (9), 7212-7214, doi:doi:10.1002/2016JC012156.
Selkoe, K. A. et al., 2015: Principles for managing marine ecosystems prone to tipping points. *Ecosystem Health and Sustainability*, **1** (5), 1-18, doi:10.1890/EHS14-0024.1.
Sen Gupta, A. et al., 2016: Future changes to the Indonesian Throughflow and Pacific circulation: The differing role of wind and deep circulation changes. *Geophysical Research Letters*, **43** (4), 1669-1678.
Serrao-Neumann, S. et al., 2016: Marine governance to avoid tipping points: Can we adapt the adaptability envelope? *Marine Policy*, **65** (Supplement C), 56-67, doi:https://doi.org/10.1016/j.marpol.2015.12.007.
Sevellec, F., A. V. Fedorov and W. Liu, 2017: Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation. *Nature Climate Change*, **7** (8), 604-610, doi:10.1038/nclimate3353.
Sgubin, G. et al., 2015: Multimodel analysis on the response of the AMOC under an increase of radiative forcing and its symmetrical reversal. *Climate Dynamics*, **45** (5-6), 1429-1450, doi:10.1007/s00382-014-2391-2.
Sgubin, G. et al., 2017: Abrupt cooling over the North Atlantic in modern climate models. *Nature Communications*, **8**, doi:10.1038/ncomms14375.
Shaw, T. A. et al., 2016: Storm track processes and the opposing influences of climate change. *Nature Geoscience*, **9**, 656, doi:10.1038/ngeo2783.
Shay, L. K. et al., 1992: Upper ocean response to Hurricane Gilbert. *Journal of Geophysical Research: Oceans*, **97** (C12), 20227-20248.
Sheen, K. et al., 2017: Skilful prediction of Sahel summer rainfall on inter-annual and multi-year timescales. *Nature Communications*, **8**, doi:10.1038/ncomms14966.
Shimizu, M. and A. L. Clark, 2015: Interconnected risks, cascading disasters and disaster management policy: a gap analysis. *Planet@ Risk*, **3** (2), 260-270.
Shimura, T., N. Mori and H. Mase, 2015: Future Projection of Ocean Wave Climate: Analysis of SST Impacts on Wave Climate Changes in the Western North Pacific. *Journal of Climate*, **28** (8), 3171-3190, doi:10.1175/jcli-d-14-00187.1.
Shuckburgh, E., D. Mitchell and P. Stott, 2017: Hurricanes Harvey, Irma and Maria: how natural were these 'natural disasters'? *Weather*, **72** (11), 353-354, doi:10.1002/wea.3190.
Smale, D. A. and T. Wernberg, 2013: Extreme climatic event drives range contraction of a habitat-forming species. *Proceedings of the Royal Society B: Biological Sciences*, **280** (1754), doi:10.1098/rspb.2012.2829.

Smith, D. et al., 2013: Real-time multi-model decadal climate predictions. *Climate Dynamics*, **41** (11-12), 2875-2888, doi:10.1007/s00382-012-1600-0.
Sobel, A. H. et al., 2016: Human influence on tropical cyclone intensity. *Science*, **353** (6296), 242-246, doi:10.1126/science.aaf6574.
Spalding, M. D. and B. E. Brown, 2015: Warm-water coral reefs and climate change. *Science*, **350** (6262), 769-771, doi:10.1126/science.aad0349.
Spillman, C. M. and A. J. Hobday, 2014: Dynamical seasonal ocean forecasts to aid salmon farm management in a climate hotspot. *Climate Risk Management*, **1**, 25-38, doi:10.1016/j.crm.2013.12.001.
Sprintall, J. et al., 2014: The Indonesian seas and their role in the coupled ocean-climate system. *Nature Geoscience*, **7** (7), 487-492, doi:10.1038/NGEO2188.
Sprintall, J. and A. Revelard, 2014: The Indonesian Throughflow response to Indo-Pacific climate variability. *Journal of Geophysical Research-Oceans*, **119** (2), 1161-1175, doi:10.1002/2013JC009533.
Stock, C. A. et al., 2015: Seasonal sea surface temperature anomaly prediction for coastal ecosystems. *Progress in Oceanography*, **137**, 219-236, doi:10.1016/j.pocean.2015.06.007.
Stott, P. A. et al., 2016: Attribution of extreme weather and climate-related events. *Wiley Interdisciplinary Reviews: Climate Change*, **7** (1), 23-41, doi:doi:10.1002/wcc.380.
Stott, P. A., D. A. Stone and M. R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432**, 610, doi:10.1038/nature03089.
Sugi, M., H. Murakami and K. Yoshida, 2017: Projection of future changes in the frequency of intense tropical cyclones. *Climate Dynamics*, **49** (1-2), 619-632, doi:10.1007/s00382-016-3361-7.
Sun, Q. and C. Miao, 2018: Extreme rainfall (R20mm, Rx5day) in Yangtze-Huai, China in June-July 2016: The role of ENSO and anthropogenic climate change in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S102-S106, doi:doi:10.1175/BAMS-D-17-0118.1.
Susanto, R., A. Ffield, A. Gordon and T. Adi, 2012: Variability of Indonesian throughflow within Makassar Strait, 2004-2009. *Journal of Geophysical Research-Oceans*, **117**, doi:10.1029/2012JC008096.
Susanto, R. and Y. Song, 2015: Indonesian throughflow proxy from satellite altimeters and gravimeters. *Journal of Geophysical Research-Oceans*, **120** (4), 2844-2855, doi:10.1002/2014JC010382.
Sweet, W., C. Zervas, S. Gill and J. Park, 2013: Hurricane Sandy inundation probabilities *today and tomorrow. [in "Explaining Extremes of 2012 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **94** (9), S17-S20.
Sweet, W. V. et al., 2016: In tide's way: Southeast Florida's September 2015 sunny-day flood. *[in "Explaining Extremes of 2015 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **97** (12), S25-S30.
Sweet, W. V. and J. Park, 2014: From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earths Future*, **2** (12), 579-600.
Swingedouw, D. et al., 2013: Decadal fingerprints of freshwater discharge around Greenland in a multi-model ensemble. *Climate Dynamics*, **41** (3-4), 695-720, doi:10.1007/s00382-012-1479-9.
Tàbara, J. D., J. Jäger, D. Mangalagiu and M. Grasso, 2018: Defining transformative climate science to address high-end climate change. *Regional Environmental Change*, 1-12.
Takagi, H. and M. Esteban, 2016: Statistics of tropical cyclone landfalls in the Philippines: unusual characteristics of 2013 Typhoon Haiyan. *Natural Hazards*, **80** (1), 211-222, doi:10.1007/s11069-015-1965-6.
Takahashi, B. and E. C. Tandoc, Jr., 2016: Media sources, credibility, and perceptions of science: Learning about how people learn about science. *Public Underst Sci*, **25** (6), 674-90, doi:10.1177/0963662515574986.
Takahashi, K. and A. G. Martínez, 2017: The very strong coastal El Niño in 1925 in the far-eastern Pacific. *Climate Dynamics*, doi:10.1007/s00382-017-3702-1.
Takayabu, I. et al., 2015: Climate change effects on the worst-case storm surge: a case study of Typhoon Haiyan. *Environmental Research Letters*, **10** (6), 1-9.
Tang, S. and S. Dessai, 2012: Usable science? The UK climate projections 2009 and decision support for adaptation planning. *Weather, Climate, and Society*, **4** (4), 300-313.
Tedeschi, R. G. and M. Collins, 2017: The influence of ENSO on South American precipitation: simulation and projection in CMIP5 models. *International Journal of Climatology*, **37** (8), 3319-3339.
Tett, S. F. B. et al., 2018: Anthropogenic forcings and associated changes in fire risk in western North America and Australia during 2015/16 in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S60-S64, doi:doi:10.1175/BAMS-D-17-0118.1.
The Government of the Commonwealth of Dominica, 2017: *Post-Disaster Needs Assesment: Hurricane Maria*. 20 pp [Available at: https://resilientcaribbean.caricom.org/wp-content/uploads/2017/11/DOMINICA-EXECUTIVE-SUMMARY.pdf].
Thirumalai, K., P. N. DiNezio, Y. Okumura and C. Deser, 2017: Extreme temperatures in Southeast Asia caused by El Nino and worsened by global warming. *Nature Communications*, **8**, 15531.
Thomas, A. R., 2015: *Resettlement in the Wake of Typhoon Haiyan in the Philippines: A Strategy to Mitigate Risk or a Risky Strategy?* The Brookings-LSE Project on Internal Displacement, The Brookings Institution, Washington, D.C., 29 pp [Available at: https://www.brookings.edu/wp-content/uploads/2016/06/Brookings-Planned-Relocations-Case-StudyAlice-Thomas-Philippines-case-study-June-2015.pdf].
Thompson, L. G. et al., 2017: Impacts of recent warming and the El Nino 2015/16 on Peruvian ice fields. *American Geophysical Union*, doi:doi: 10.1002/2017JD026592.

Thompson, P. R., G. T. Mitchum, C. Vonesch and J. Li, 2013: Variability of Winter Storminess in the Eastern United States during the Twentieth Century from Tide Gauges. *Journal of Climate*, **26** (23), 9713-9726, doi:10.1175/jcli-d-12-00561.1.
Thornalley, D. J. et al., 2018: Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature*, **556** (7700), 227.
Tommasi, D. et al., 2017a: Multi-Annual Climate Predictions for Fisheries: An Assessment of Skill of Sea Surface Temperature Forecasts for Large Marine Ecosystems. *Frontiers in Marine Science*, **4** (201), doi:10.3389/fmars.2017.00201.
Tommasi, D. et al., 2017b: Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. *Progress in Oceanography*, **152**, 15-49, doi:10.1016/j.pocean.2016.12.011.
Trenberth, K. E. and J. Fasullo, 2007: Water and energy budgets of hurricanes and implications for climate change. *Journal of Geophysical Research: Atmospheres*, **112** (D23).
Trenberth, K. E. and J. Fasullo, 2008: Energy budgets of Atlantic hurricanes and changes from 1970. *Geochemistry, Geophysics, Geosystems*, **9** (9).
Trenberth, K. E. and D. J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. *Geophysical Research Letters*, **33** (12), doi:doi:10.1029/2006GL026894.
Trossman, D. et al., 2016: Large-scale ocean circulation-cloud interactions reduce the pace of transient climate change. *Geophysical Research Letters*, **43** (8), 3935-3943, doi:10.1002/2016GL067931.
Tuleya, R. E. et al., 2016: Impact of upper-tropospheric temperature anomalies and vertical wind shear on tropical cyclone evolution using an idealized version of the operational GFDL hurricane model. *Journal of the Atmospheric Sciences*, **73** (10), 3803-3820.
Ummenhofer, C. C. and G. A. Meehl, 2017: Extreme weather and climate events with ecological relevance: a review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **372** (1723), doi:10.1098/rstb.2016.0135.
UNISDR, 2015: Sendai framework for disaster risk reduction 2015-2030. In: World Conference on Disaster Risk Reduction, Sendai, Japan, 37 pp.
United Nations, 2017: *North coast of Perú Flash Appeal*. United Nations Office for the Coordination of Humanitarian Affairs, Geneva, Switzerland., 49 pp [Available at: https://reliefweb.int/report/peru/north-coast-peru-2017-flash-appeal-april].
van den Honert, R. C. and J. McAneney, 2011: The 2011 Brisbane Floods: Causes, Impacts and Implications. *Water*, **3** (4), 1149.
van den Hurk, B. et al., 2015: Analysis of a compounding surge and precipitation event in the Netherlands. *Environmental Research Letters*, **10** (3), 035001.
van Hooidonk, R., J. A. Maynard and S. Planes, 2013: Temporary refugia for coral reefs in a warming world. *Nature Climate Change*, **3**, 508, doi:10.1038/nclimate1829.
van Oldenborgh, G. J. et al., 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12** (12), 124009.
Vanniere, B., A. Czaja and H. Dacre, 2017: Contribution of the cold sector of extratropical cyclones to mean state features over the Gulf Stream in winter. *Quarterly Journal of the Royal Meteorological Society*, **143** (705), 1990-2000, doi:10.1002/qj.3058.
Varotsos, C., C. Tzanis and A. Cracknell, 2016: Precursory signals of the major El Nino Southern Oscillation events. *Theoretical and Applied Climatology*, **124** (3-4), 903-912, doi:10.1007/s00704-015-1464-4.
Verlaan, M., S. De Kleermaeker and L. Buckman, 2015: GLOSSIS: Global storm surge forecasting and information System, . In: *Australasian Coasts and Ports Conference,* , Auckland, New Zealand.
Veron, J. C. E. et al., 2011: The coral triangle. In: Coral reefs: an ecosystem in transition. Springer, 47-55.
Veron, J. E. N. et al., 2009: The coral reef crisis: The critical importance of<350ppm CO_2. *Marine Pollution Bulletin*, **58** (10), 1428-1436, doi:10.1016/j.marpolbul.2009.09.009.
Villarini, G. and G. A. Vecchi, 2012: Twenty-first-century projections of North Atlantic tropical storms from CMIP5 models. *Nature Climate Change*, **2**, 604, doi:10.1038/nclimate1530.
Vousdoukas, M. I. et al., 2017: Extreme sea levels on the rise along Europe's coasts. *Earth's Future*, **5** (3), 304-323.
Wadey, M., S. Brown, R. J. Nicholls and I. Haigh, 2017: Coastal flooding in the Maldives: an assessment of historic events and their implications. *Natural Hazards*, **89** (1), 131-159, doi:10.1007/s11069-017-2957-5.
Wahl, T. et al., 2015: Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change*, **5** (12), 1093-1097.
Wahl, T., N. G. Plant and J. W. Long, 2016: Probabilistic assessment of erosion and flooding risk in the northern Gulf of Mexico. *Journal of Geophysical Research: Oceans*, **121** (5), 3029-3043, doi:10.1002/2015JC011482.
Walsh, J. E. et al., 2017: The Exceptionally Warm Winter of 2015/16 in Alaska. *Journal of Climate*, **30** (6), 2069-2088, doi:10.1175/jcli-d-16-0473.1.
Walsh, J. E. et al., 2018: The high latitude marine heat wave of 2016 and its impacts on Alaska. *[in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **99** (1), S39-S43, doi:doi:10.1175/bams-d-17-0105.1.
Walsh, K. J. E. et al., 2016: Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **7** (1), 65-89, doi:10.1002/wcc.371.

Wang, B. et al., 2013: Northern Hemisphere summer monsoon intensified by mega-El Niño/southern oscillation and Atlantic multidecadal oscillation. *Proceedings of the National Academy of Sciences*, **110** (14), 5347-5352.
Wang, G. et al., 2017: Continued increase of extreme El Niño frequency long after 1.5° C warming stabilization. *Nat Clim Chang*, **7** (8), 568-72.
Wang, S. and R. Toumi, 2016: On the relationship between hurricane cost and the integrated wind profile. *Environmental Research Letters*, **11** (11), doi:10.1088/1748-9326/11/11/114005.
Wang, S. Y., L. Hipps, R. R. Gillies and J. H. Yoon, 2014a: Probable causes of the abnormal ridge accompanying the 2013–2014 California drought: ENSO precursor and anthropogenic warming footprint. *Geophysical Research Letters*, **41** (9), 3220-3226, doi:doi:10.1002/2014GL059748.
Wang, X. and H. Liu, 2014: PDO modulation of ENSO effect on tropical cyclone intensification in the western North Pacific. *Climate Dynamics*, doi:DOI: 10.1007/s00382-615-2563-8.
Wang, Y. et al., 2014b: Assessing the effects of anthropogenic aerosols on Pacific storm track using a multiscale global climate model. *Proceedings of the National Academy of Sciences*, **111** (19), 6894-6899, doi:10.1073/pnas.1403364111.
Wang, Y., R. Zhang and R. Saravanan, 2014c: Asian pollution climatically modulates mid-latitude cyclones following hierarchical modelling and observational analysis. *Nature Communications*, **5**, 3098, doi:10.1038/ncomms4098.
Ward, P. et al., 2014: Strong influence of El Nino Southern Oscillation on flood risk around the world. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (44), 15659-15664, doi:10.1073/pnas.1409822111.
Ward, P. J., M. Kummu and U. Lall, 2016: Flood frequencies and durations and their response to El Nino. *J. Hydrol.*, **539**, 358-378, doi:doi.
Weaver, C. et al., 2013: Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews-Climate Change*, **4** (1), 39-60, doi:10.1002/wcc.202.
Wehner, M. et al., 2015: Resolution Dependence of Future Tropical Cyclone Projections of CAM5.1 in the US CLIVAR Hurricane Working Group Idealized Configurations. *Journal of Climate*, **28** (10), 3905-3925, doi:10.1175/JCLI-D-14-00311.1.
Weijer, W. et al., 2012: Response of the Atlantic Ocean circulation to Greenland Ice Sheet melting in a strongly-eddying ocean model. *Geophysical Research Letters*, **39**, doi:10.1029/2012gl051611.
Weijerman, M. et al., 2015: An Integrated Coral Reef Ecosystem Model to Support Resource Management under a Changing Climate. *PLoS ONE*, **10** (12), doi:ARTN e0144165
10.1371/journal.pone.0144165.
Weijerman, M. et al., 2016: Atlantis Ecosystem Model Summit: Report from a workshop. *Ecological Modelling*, **335**, 35-38, doi:10.1016/j.ecolmodel.2016.05.007.
Weinkle, J., R. Maue and R. Pielke, 2012: Historical Global Tropical Cyclone Landfalls. *Journal of Climate*, **25** (13), 4729-4735, doi:10.1175/Jcli-D-11-00719.1.
Weller, E. et al., 2015: Human Contribution to the 2014 Record High Sea Surface Temperatures Over the Western Tropical And Northeast Pacific Ocean. *Bulletin of the American Meteorological Society*, **96** (12), S100-S104, doi:10.1175/bams-d-15-00055.1.
Wendel, J., 2015: Dengue epidemics linked with El Nino. *Eos*, **96**, doi:doi: 10.1029/2015 EO037169.
Wernberg, T. et al., 2016: Climate-driven regime shift of a temperate marine ecosystem. *Science*, **353** (6295), 169-172, doi:10.1126/science.aad8745.
Wernberg, T. et al., 2013: An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Clim. Change*, **3** (1), 78-82.
Wethey, D. S. et al., 2011: Response of intertidal populations to climate: Effects of extreme events versus long term change. *Journal of Experimental Marine Biology and Ecology*, **400** (1), 132-144, doi:10.1016/j.jembe.2011.02.008.
Whan, K. and F. Zwiers, 2017: The impact of ENSO and the NAO on extreme winter precipitation in North America in observations and regional climate models. *Clim Dyn*, **48**, 1401–1411, doi:DOI 10.1007/s00382-016-3148-x.
White, A. T. et al., 2014: Marine Protected Areas in the Coral Triangle: Progress, Issues, and Options. *Coastal Management*, **42** (2), 87-106, doi:10.1080/08920753.2014.878177.
Whitney, F. A., 2015: Anomalous winter winds decrease 2014 transition zone productivity in the NE Pacific. *Geophysical Research Letters*, **42** (2), 428-431, doi:10.1002/2014gl062634.
Winton, M. et al., 2014: Has coarse ocean resolution biased simulations of transient climate sensitivity? *Geophysical Research Letters*, **41** (23), 8522-8529, doi:10.1002/2014gl061523.
Winton, M. et al., 2013: Connecting Changing Ocean Circulation with Changing Climate. *Journal of Climate*, **26** (7), 2268-2278, doi:10.1175/jcli-d-12-00296.1.
Winton, M., K. Takahashi and I. M. Held, 2010: Importance of Ocean Heat Uptake Efficacy to Transient Climate Change. *Journal of Climate*, **23** (9), 2333-2344, doi:10.1175/2009jcli3139.1.
Wouters, B. et al., 2013: Multiyear predictability of the North Atlantic subpolar gyre. *Geophysical Research Letters*, **40** (12), 3080-3084, doi:10.1002/grl.50585.

Wridt, P., J. E. Seley, S. Fisher and B. DuBois, 2016: Participatory mapping approaches to coordinate the emergency response of spontaneous volunteers after hurricane sandy. In: E-Health and Telemedicine: Concepts, Methodologies, Tools, and Applications. IGI Global, 1361-1378.
Wu, W. et al., 2018: Mapping Dependence Between Extreme Rainfall and Storm Surge. *Journal of Geophysical Research: Oceans*.
Yamada, Y. et al., 2017: Response of Tropical Cyclone Activity and Structure to Global Warming in a High-Resolution Global Nonhydrostatic Model. *Journal of Climate*, (2017).
Yamamoto, A. and J. B. Palter, 2016: The absence of an Atlantic imprint on the multidecadal variability of wintertime European temperature. *Nature Communications*, **7**, doi:10.1038/ncomms10930.
Yang, H. et al., 2016a: Intensification and poleward shift of subtropical western boundary currents in a warming climate. *Journal of Geophysical Research: Oceans*, **121** (7), 4928-4945, doi:doi:10.1002/2015JC011513.
Yang, Q. et al., 2016b: Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. *Nature Communications*, **7**, doi:10.1038/ncomms10525.
Yeager, S., A. Karspeck and G. Danabasoglu, 2015: Predicted slowdown in the rate of Atlantic sea ice loss. *Geophysical Research Letters*, **42** (24), 10704-10713, doi:10.1002/2015GL065364.
Yeh, E. T., 2016: 'How can experience of local residents be "knowledge"?'Challenges in interdisciplinary climate change research. *Area*, **48** (1), 34-40.
Yletyinen, J., J. Tylianakis, P. Brown and R. Pech, 2017: *Planning for tipping points and enhancing resilience in production landscapes*. Tipping Points, Landcare Research Manaaki Whenua.
Yonekura, E. and T. Hall, 2014: ENSO Effect on East Asian Tropical Cyclone Landfall via Changes in Tracks and Genesis in a Statistical Model. *Journal of Applied Meteorology and Climatology*, **53** (2), 406-420, doi:10.1175/JAMC-D-12-0240.1.
Yoshida, K. et al., 2017: Future Changes in Tropical Cyclone Activity in High-Resolution Large-Ensemble Simulations. *Geophysical Research Letters*, **44** (19), 9910-9917.
Yuan, X., S. Wang and Z. Z. Hu, 2018: Do climate change and El Nino increase likelihood of Yangtze River extreme rainfall? in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S113-S117, doi:doi:10.1175/BAMS-D-17-0118.1.
Zhai, P. et al., 2016: The strong El Nino of 2015/16 and its dominant impacts on global and China's climate. *Journal of Meteorological Research*, **30 (3)**, 283–297, doi:doi.
Zhan, R., 2017: Intensified mega-ENSO has increased the proportion of intense tropical cyclones over the western northwest Pacific since the late 1970s. *Geophys. Res. Lett.*, **44 (23)**, doi:Doi:10.1002/2017glo75916.
Zhang, H. and Y. Guan, 2014: Impacts of four types of ENSO events on tropical cyclones making landfall over mainland china based on three best-track datasets. *Advances in Atmospheric Sciences*, **31** (1), 154-164, doi:10.1007/s00376-013-2146-8.
Zhang, L. and K. B. Karnauskas, 2017: The role of tropical interbasin SST gradients in forcing Walker circulation trends. *Journal of Climate*, **30** (2), 499-508.
Zhang, L., K. B. Karnauskas, J. P. Donnelly and K. Emanuel, 2017a: Response of the North Pacific Tropical Cyclone Climatology to Global Warming: Application of Dynamical Downscaling to CMIP5 Models. *Journal of Climate*, **30** (4), 1233-1243, doi:10.1175/jcli-d-16-0496.1.
Zhang, R., 2017: On the persistence and coherence of subpolar sea surface temperature and salinity anomalies associated with the Atlantic multidecadal variability. *Geophysical Research Letters*, **44** (15), 7865-7875, doi:10.1002/2017gl074342.
Zhang, R. and T. R. Knutson, 2013: The role of global climate change in the extreme low summer Arctic sea ice extent in 2012. *[in "Explaining Extremes of 2012 from a Climate Perspective"]. Bull. Amer. Meteor. Soc.*, **94** (9), S23-S26.
Zhang, W. et al., 2016: The Pacific Meridional Mode and the Occurrence of Tropical Cyclones in the Western North Pacific. *Journal of Climate*, **29** (1), 381-398, doi:10.1175/jcli-d-15-0282.1.
Zhang, X., J. A. Church, D. Monselesan and K. L. McInnes, 2017b: Sea level projections for the Australian region in the 21st century. *Geophysical Research Letters*, **44** (16), 8481-8491, doi:10.1002/2017gl074176.
Zhou, C., K. Wang and D. Qi, 2018: Attribution of the July 2016 extreme precipitation event over Wuhan, China in "Explaining Extreme Events of 2016 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, **99 (1)**, S106-S112, doi:doi:10.1175/BAMS-D-17-0118.1.
Zhou, C., M. Zelinka, A. Dessler and S. Klein, 2015: The relationship between interannual and long-term cloud feedbacks. *Geophysical Research Letters*, **42** (23), doi:10.1002/2015GL066698.
Zhou, X. et al., 2016: Catastrophic drought in East Asian monsoon region during Heinrich event 1. *Quaternary Science Reviews*, **141**, 1-8, doi:10.1016/j.quascirev.2016.03.029.
Zickfeld, K., M. Eby and A. Weaver, 2008: Carbon-cycle feedbacks of changes in the Atlantic meridional overturning circulation under future atmospheric CO2. *Global Biogeochemical Cycles*, **22** (3), doi:10.1029/2007GB003118.
Zinke, J. et al., 2015: Coral record of southeast Indian Ocean marine heatwaves with intensified Western Pacific temperature gradient. *Nature Communications*, **6**, doi:10.1038/ncomms9562.
Zscheischler, J. and S. I. Seneviratne, 2017: Dependence of drivers affects risks associated with compound events. *Science Advances*, **3** (6), e1700263.

Zuo, X. L. et al., 2015: Spatial and temporal variability of thermal stress to China's coral reefs in South China Sea. *Chinese Geographical Science*, **25** (2), 159-173, doi:10.1007/s11769-015-0741-6.