Chapter 1: Framing and Context of the Report

Coordinating Lead Authors: Nerilie Abram (Australia), Jean-Pierre Gattuso (France), Anjal Prakash (India)

Lead Authors: Lijing Cheng (China), Maria Paz Chidichimo (Argentina), Susie Crate (USA), Hiroyuki Enomoto (Japan), Matthias Garschagen (Germany), Nicolas Gruber (Switzerland), Sherilee Harper (Canada), Elisabeth Holland (Fiji), Raphael Martin Kudela (USA), Jake Rice (Canada), Konrad Steffen (Switzerland), Karina von Schuckmann (France)

Contributing Authors: Nathaniel Bindoff (Australia), Sinead Collins (UK), Daniel Farinotti (Switzerland), Nathalie Hilmi (France), Jochen Hinkel (Switzerland), Alexandre Magnan (France), Michael Meredith (UK), Mandira Singh Shrestha (Nepal), Anna Sinisalo (Finland), Catherine Sutherland (South Africa), Phil Williamson (UK)

Review Editors: Monika Rhein (Germany), David Schoeman (Australia)

Chapter Scientist: Avash Pandey (Nepal)

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Executive Summary

This Special Report focuses on how climate change is altering the ocean and cryosphere (the frozen parts of our planet). It assesses knowledge of the ocean and the cryosphere, their role in the Earth system and how they are expected to respond in a changing climate. The storyline of this Special Report also covers the factors that affect resilience and vulnerability of natural and human systems to ocean and cryosphere change, and scope for responding to future changes within relevant governance frameworks {Chapter 1 and all subsequent SROCC chapters}.

Human-induced greenhouse gas emissions are warming our climate and altering the ocean and cryosphere. The ocean has taken up more than 90% of the heat accumulated in the Earth system due to rising atmospheric greenhouse gas concentrations, leading to ocean warming as well as expansion that contributes to global sea level rise. Dissolution of atmospheric CO_2 in seawater is further causing ocean acidification. Additional heat in the Earth system is resulting in ice loss in polar and high mountain regions, including worldwide retreat of glaciers, loss of Arctic sea ice, melting of ice shelves and contributions to global sea level rise by ice sheet, ice cap and glacier reductions. Ice loss also acts to amplify human-induced climate warming by altering the capacity of environments to absorb heat. Ocean and cryosphere changes result in hazards and opportunities for people and ecosystems {1.2 and 1.3}.

Important aspects of ocean and cryosphere change, including the size of polar ice sheets and sea level rise, may be irreversible on human time-scales. These elements are slow to respond to anthropogenic driven changes in radiative forcing, but are expected to continue to change for centuries or more after the forcing is stabilized {1.3.1}.

The ocean and cryosphere, and the ecosystems they support, are essential for humans. Individuals, communities and populations that directly depend on ocean and/or cryosphere resources for livelihoods, culture, health, and wellbeing are particularly vulnerable to ocean and cryosphere risks and impacts related to climate change. This includes people residing in high mountain areas, polar regions, low lying islands, and coastal settlements and cities. The vulnerability of people to ocean and cryosphere change is also related to social, political, cultural, economic, institutional, geographical and demographic factors {1.4}.

Climate change related impacts on the ocean and cryosphere are expected to compound the environmental risks already faced by many humans and natural systems, particularly in coastal, polar and mountain areas. Charting climate resilient development pathways, which combine efforts for climate change mitigation and adaptation, will therefore be needed to enable sustainable development. Decisions for profound economic and institutional transformations are necessary to initiate and pursue such pathways {1.4; Cross-Chapter Box 1}.

Societies need to mitigate and adapt to climate change and its effects on natural and human systems. Measures to reduce the impact of climate change on the ocean and cryosphere include: addressing the causes of climate change, managing solar radiation, supporting biological and ecological adaptation, and enhancing societal adaptation. The effectiveness of specific global measures to address climate change remains highly uncertain, with the exception greenhouse gas emission reductions. Local measures provide low-regret options but are insufficient to fully address the overarching global problem. The greatest benefit is likely to be derived from the combination of global and local measures {1.5}.

International cooperation for governance of the oceans, the coasts and the cryosphere is critical in the face of existing and new climate change challenges. Ocean and cryosphere changes are interconnected across geographies that extend across a range of legal frameworks, governance structures and institutions. In addition to broad governance and institutional options, local level adaptation provides space for communities to respond to climate change. Case studies of adaptive and transformative governance design offer possibilities for addressing future ocean and cryosphere-related changes {1.6; Cross-Chapter Box 2}.

Observations and models are the foundation for assessing past, current and possible future changes in the ocean and cryosphere, and their maintenance and extension is key to inform and support decision-making. Capabilities for observing the ocean and cryosphere, including in situ observations, remote sensing and palaeoclimate evidence, have developed considerably during the past century. Observation networks have allowed for detection of anthropogenic climate change in many ocean and cryosphere components, but some key regions remain undersampled and in some settings observations are still very short relative to the time-scales of natural variability and anthropogenic change. Climate models provide the only available data for assessing future climate change under different plausible greenhouse gas emission trajectories and scenarios of socio-economic growth and development {1.7.2; 1.8.2}.

Indigenous and local knowledge is used by human populations to observe, respond to and coordinate governance for the ocean and cryosphere. Indigenous and local knowledge remains incompletely utilised in climate change assessments, but its use alongside scientific knowledge can aid holistic understandings, and the development of effective responses and policies {1.7; Table 1.1; Cross-Chapter Box 3}.

Certainty in assessments of ocean and cryosphere change evolve as the availability of data and knowledge of physical and ecological processes develops. Some aspects of the rate, timing, magnitude, and cascading elements of ocean and cryosphere change remain deeply uncertain, but comprehensive risk assessment that informs adaptation planning can address highly uncertain changes that would have catastrophic consequences if not managed {1.8; Cross-Chapter Box 4}.

1.1 Why this Special Report?

The ocean and cryosphere play fundamental roles in the Earth system. The ocean represents the vast expanses of liquid, salty water on Earth, and cryosphere refers to the frozen water elements on Earth. Everyone benefits from the services provided by the ocean and the cryosphere: the ocean regulates rainfall, carbon, oxygen and heat, and provides livelihoods, food security and cultural identity to people and communities. It is also a source of hazards, particularly in low-lying coastal zones. More than 45% of the global population currently lives on land less than 200 m above the ocean (Crossland et al., 2005) and the coastal population is expected to increase by at least 58% between 2000 and 2050 according to the Shared Socioeconomic Pathways (Merkens et al., 2016). High mountain areas and the Arctic are much less densely populated than the coastal zones, but the people living in and near these areas similarly depend directly upon the Earth's cryosphere for food, water, resources and identity, and are exposed to hazards related to it.

Earth's ocean and cryosphere are changing in response to climate change, and they also play roles in amplifying or mitigating the regional to global magnitude of climate change. Some elements of the ocean and cryosphere may exhibit rapid changes in response to even modest global temperature increases, and once changes in these parts of the Earth system have been initiated they may be irreversible on timescales relevant to human societies. This means that adaptation strategies of people and economies to ocean and cryosphere change must be nimble and effective, presenting special challenges to cultures highly adapted to the polar, montane and coastal environments of past centuries and millennia.

This IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) recognises the interconnectivity of the ocean and cryosphere in the Earth system, in their responses to climate change, and in the dependence (either directly or indirectly) of all people and ecosystems on them. It reports on specific aspects where knowledge has emerged since the IPCC Fifth Assessment Report (2013–2014; AR5), and on providing an integrated approach across the three IPCC working groups, linking physical changes with their ecological and human impacts and the strategies to respond and adapt to these impacts. This Special Report represents one of the products to be produced by the IPCC during its Sixth Assessment Cycle. The concurrent IPCC Special Report on Global Warming of 1.5°C (SR15) is relevant to this report as there are key elements of the ocean and cryosphere, such as ice sheet collapse and coral bleaching, where rapid and possibly irreversible changes may occur as global climate warming approaches or exceeds the 1.5°C aspirational threshold that forms part of the Paris Agreement (UNFCCC, 2015). The IPCC Special Report on Climate Change and Land (SRCCL) will also have linkages to this assessment, particularly where the terrestrial environment interacts closely with elements of the ocean and cryosphere, such as in high mountains, the Arctic and coastal regions.

This framing chapter presents the background context required for subsequent chapters of this Special Report. This includes descriptions of the ocean and cryosphere (Box 1.1); how they operate and are changing due to human-induced climate changes (Sections 1.2 and 1.3); the opportunities and hazards this brings for natural and human systems (Sections 1.3 and 1.4); the risk and resilience framework used throughout the report (Section 1.4, Cross-Chapter Box 1); adaptation and governance options relevant to responding to change (Sections 1.5 and 1.6, Cross-Chapter Box 2); knowledge systems for understanding ocean and cryosphere change (Section 1.7, Cross-Chapter Box 3); and the methodological approaches and storyline used within the chapters of this Special Report (Sections 1.8 and 1.9, Cross-Chapter Box 4).

[START BOX 1.1 HERE]

Box 1.1: Major Components and Characteristics of the Ocean and Cryosphere

Ocean

The global ocean covers more than 70% of the Earth surface. It is an interconnected body of saline water that encompasses polar to equatorial climate zones. It includes the Arctic, Pacific, Atlantic, Indian and Southern oceans, and their associated seas.

The coastal zone is a region where ocean and land processes interact. Coastal regions - including coastal cities, estuaries and low-elevation areas - are particularly vulnerable to ocean-related climate change impacts.

Beyond coastlines, shallow seas occur above areas of continental shelf. Open ocean is the area overlying the continental slope and the abyssal plain. Features of ocean depth and distance from the coast determine the governance that applies to particular ocean areas (Cross-Chapter Box 2).

The average depth of the global ocean is about 3800 m, with a maximum depth of more than 10,000 m in the Mariana Trench. The surface of the ocean is in direct contact with the atmosphere, and the layer below is well mixed by winds and extends from the sea surface down to the thermocline (i.e., where ocean temperature decreases rapidly with depth). The upper ocean covers both the epipelagic zone (less than 200 m depth; where sunlight penetrates the water column) and the mesopelagic zone (200 to 1000 m). Areas below 1000 m depth belong to the deep ocean.

Ocean water is often stratified with less dense water sitting above more dense layers. Density is determined by seawater temperature and salinity, and the thermohaline circulation refers to the large-scale overturning of the global ocean driven by density differences. The most dense ocean waters on Earth are formed in polar oceans where cold and saline waters are produced by sea ice formation. Seawater has a very high heat capacity (ability to absorb heat energy) and holds large amounts of dissolved and particulate carbon (including CO_2 absorbed from the atmosphere), which makes the ocean a fundamental climate regulator on seasonal to millennial time scales. Ocean currents caused by winds, tides, eddies and density are responsible for the redistribution of heat, freshwater and biogeochemical substances throughout the global ocean (Winton et al., 2013).

In this Special Report, Chapter 3 assesses climate-related ocean changes specific to the Polar Regions, which are flexibly defined as encompassing the Arctic Ocean and areas within the Arctic large marine ecosystem in the Northern Hemisphere, and the area south of the Subantarctic Front in the Southern Ocean. Chapter 4 examines the implications for coastal regions and communities of rising global sea levels caused by ice melt and thermal expansion of the ocean, including the spatial and temporal modulation of sea level impacts by factors such as subsiding/uplifting coasts, tides, storm surges, and waves. Chapter 5 assesses how oceans are changing (excluding changes in polar oceans; which are considered in chapter 3), the impacts on marine ecosystems and dependent communities, as well as responses to these impacts including blue carbon and human and natural adaptation. Finally, Chapter 6 presents information on ways in which the oceans can contribute to abrupt and extreme climate events, including potentially irreversible changes in the Earth system.

Cryosphere

The cryosphere refers to components of the Earth system that contain frozen water, including glacier ice, seasonal snow, sea, lake and river ice, and frozen ground. Cryosphere is common in the Polar Regions (Chapter 3), as well as in High Mountain areas (Chapter 2; which includes all mid-latitude and sub-arctic mountain areas where glaciers, snow or permafrost are persistent features), but changes in the cryosphere can have global impacts (Chapters 4, 5 and 6). Some elements of the cryosphere are not assessed in this Special Report, such as permafrost and snow outside of polar and high mountain areas.

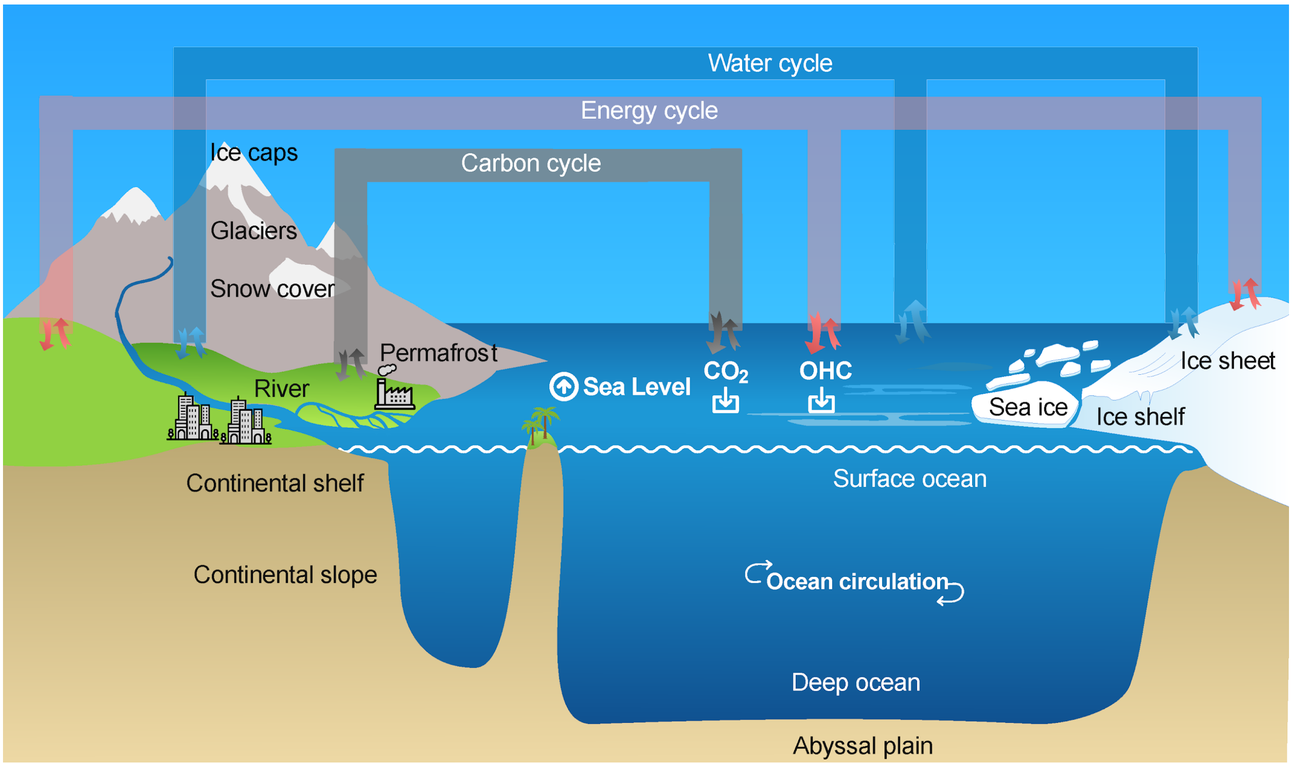
The largest ice bodies on Earth are the Greenland and Antarctic ice sheets. The Antarctic ice sheet is often divided in studies into the West Antarctic and East Antarctic ice sheets, separated by the Transantarctic mountains. Ice sheets are built up by accumulating snowfall on their surface that compresses to ice over time. They flow outward from a high central ice plateau and at their margins ice is discharged into the ocean or to floating ice shelves through fast flowing ice streams or glaciers. Marine-based ice sheets, such as the West Antarctic Ice Sheet, sit upon bedrock that largely lies below sea level and are expected to be more susceptible to rapid and potentially irreversible ice loss than ice sheets grounded above sea level.

Glaciers and ice caps are land ice that is smaller than an ice sheet. They are maintained by snowfall in high mountains and polar regions, or by ice flow at the margins of ice sheets. Ice sheets, glaciers and ice caps in High Mountain (Chapter 2) and Polar Regions (Chapter 3) that lose more ice than they accumulate are said to have a negative mass balance and contribute to global sea level rise (Chapter 4). Glaciers and ice caps in High Mountains are also critical for downstream communities as a source of freshwater (Chapter 2).

Ice shelves are the floating extension of ice sheets, glaciers and ice caps, where ice flow reaches the polar oceans. Ice shelves help to reduce the speed of land ice discharge (and its contribution to sea level rise), but are vulnerable to melting of their surface by warm air temperatures, or of their base by warm ocean temperatures.

Sea ice forms from freezing of the sea surface. Sea ice may be discontinuous pieces moved on the ocean surface by wind and currents, or a motionless sheet attached to the coast (land-fast ice). Sea ice provides many critical functions in the Earth system; providing essential habitat for polar species, affecting climate change through amplification of surface warming via albedo effects, driving global deep ocean circulation via dense water formation, and providing livelihoods for people in the Arctic.

Permafrost, or permanently frozen ground, is soil, sediment, or rock that remains at or below 0°C for at least two consecutive years. It occurs on land in polar and high mountain areas, and beneath offshore Arctic continental shelves. Its thickness ranges from less than 1 m to greater than 1000 m. Permafrost is important for low-lying coastal regions in the Arctic vulnerable to coastal erosion (Chapters 3 and 4), and its decay can cause hazards in mountain areas (Chapter 2) and the release of stored greenhouse gases to the atmosphere (Chapter 3, Cross-Chapter Box 4).



Box 1.1, Figure 1: Schematic illustration of key components of the ocean and cryosphere, and their linkages through the energy, water, and biogeochemical cycles. The redistribution and storage of heat (OHC: ocean heat content) and carbon (CO_2) through ocean circulation are key mechanisms for the regulation of these cycles.

[END BOX 1.1 HERE]

1.2 Role of Ocean and Cryosphere

1.2.1 Characteristics of Ocean and Cryosphere in the Earth System

The ocean contains about 97% of the Earth's water (Durack et al., 2016), and provides roughly half of the primary production on Earth (Field et al., 1998). Fundamental characteristics of the ocean include its large specific heat capacity and its huge mass. Together, these have enabled the ocean to store the majority (more than 90%) of extra thermal energy in Earth's climate system caused by greenhouse gas buildup in the atmosphere (Hansen et al., 2005; Rhein et al., 2013). The ocean also stores about 25% of the anthropogenic CO_2 that has been released to the atmosphere during the period 1750–2016 (Le Quéré et al., 2018). Thus, the ocean is a key regulating agent for Earth's climate (Von Schuckmann et al., 2016). Ocean circulation redistributes heat and freshwater over great distances, modulating local weather and climate through heating and cooling of the overlying atmosphere. A substantial part of this redistribution is accomplished by the meridional overturning circulation, which interconnects the two hemispheres, as well surface and deep ocean layers. This circulation involves the transformation of low-density surface ocean waters into higher-density (cold and/or salty) waters that sink to intermediate and deep layers of the ocean and are important for the transfer of anthropogenic heat (Kuhlbrodt and Gregory, 2012) and carbon (Mikaloff Fletcher et al., 2006) into subsurface layers of the ocean at timescales from decades to hundreds of years (Buckley and Marshall, 2016).

Presently, 10% of Earth's land area is covered with glacial ice. This includes mountain glaciers, ice caps, and the ice sheets of Greenland and Antarctica, which together account for about two-thirds of Earth's freshwater (Durack et al., 2016). Because snow and ice are very reflective they play an important role in regulating climate via the albedo effect, by reflecting incoming sunlight back into space and cooling the planet. The melting of glacial ice also absorbs some of the excess heat generated by the increase in atmospheric greenhouse gases (Rhein et al., 2013; Trenberth et al., 2016). The cryosphere responds strongly to Earth's seasonal cycles, including the seasonal growth and decay of sea ice that covers vast areas of polar oceans in winter, and winter snowfall that sustains glaciers and snow cover in high mountain areas and is released as freshwater during the spring and summer melt.

The ocean and cryosphere are very active elements of the Earth's system. Huge quantities of energy, water and biogeochemical substances (in particular carbon, nitrogen, oxygen, and hydrogen) are exchanged between them, and with other parts of the Earth system including the atmosphere, lithosphere and biosphere (Box 1.1, Figure 1). These exchanges are largely set in motion by the absorption of solar radiation within the atmosphere and at the Earth's surface, where it is transformed into various forms of energy (heat, potential, latent, kinetic and chemical energy). While most (but not all) of this energy is eventually radiated back to space as longwave radiation (L'Ecuyer et al., 2015; Trenberth et al., 2016), it first induces large-scale motions in the atmosphere and oceans, provides energy for evaporating water, melting ice, and also fuels photosynthesis, which converts solar energy into chemical energy contained in organic matter. The evaporation of water from the ocean's surface is the starting point for Earth's hydrological cycle, which provides precipitation over land, the cryosphere and the ocean (Trenberth et al., 2007). The cycle is closed by the rain and snow water input to the land and cryosphere being returned to the ocean through rivers, streams and groundwater, as well as through ice discharge from ice sheets, ice caps and glaciers (Box 1.1, Figure 1). Primary production subsequently fuels complex food-webs and intense biochemical and geochemical transformation processes with major implications for global climate.

1.2.2 Interactions Between Ocean and Cryosphere

The ocean and cryosphere are interconnected in many ways (Box 1.1, Figure 1). Evaporation of the ocean provides snowfall to the ice sheets, ice caps and glaciers that store large amounts of frozen water on land. The amount of water stored as ice on land controls the sea level and salinity (and hence also density) of the ocean. The vast ice sheets in Antarctica and Greenland currently contain approximately 66 m of global sea level rise equivalent (Fretwell et al., 2013; Frezzotti and Orombelli, 2014), although the majority of this is still considered as stable over foreseeable time scales (Church et al., 2013). The temperature and level of the ocean is critical for ice sheet stability in places where the base of ice sheets (and their associated ice shelves) are in direct contact with ocean water, and here even slight increases in ocean temperature have the potential to rapidly melt and destabilise large sections of an ice sheet (Spence et al., 2014; Fenty et al., 2016; Rintoul et al., 2016; Truffer and Motyka, 2016).

The formation and melting of sea ice is an important process governing the production of dense ocean waters, thereby constituting a major driving component of deep ocean circulation (Abernathey et al., 2016; Haumann et al., 2016; Sévellec et al., 2017). Ocean temperature also needs to be cold enough for sea ice to form, representing another ocean-ice connection. The high albedo of snow and ice (including sea ice) reflects incoming shortwave radiation back towards space, thus contributing to the regulation of the Earth's energy budget including energy taken up by the ocean. The cryosphere and ocean also interact biogeochemically through the exchange of nutrients. For example, iron is accumulated in sea-ice and is released to the ocean during the spring and summer melt, helping to fuel ocean productivity in the seasonal sea ice zone (Tagliabue et al., 2017), and nutrient-rich sediments delivered to the ocean by glaciers similarly connect cryosphere processes with ocean productivity (Arrigo et al., 2017).

1.2.3 Importance of Ocean and Cryosphere for Ecosystems and Human Systems

Humans have depended upon the Earth's oceans (Kubiszewski et al., 2017) and cryosphere (Hovelsrud et al., 2011) to provide services such as coastal protection, food, fresh water, climate regulation, transportation, and migration for millennia (Redman, 1999). Most contemporary human populations still depend directly on elements of the oceans and cryosphere, and the ecosystem services they provide, but at a much grander scale and with a proportionally larger environmental impact than in pre-industrial times (Inniss and Simcock, 2017).

The ocean's biosphere is responsible for half of the global primary production, forming the basis of a complex food web that ultimately sustains global fisheries. The biodiversity of the world's oceans support ocean productivity, resource availability, water quality, and the ability to of ecosystems to recover from perturbations (Worm et al., 2006).

Snow and ice also support life in many ways. For example, sea ice provides the hunting ground of polar bears, and large snow drifts provide hibernation dens for pregnant female polar bears. Sea ice also provides a traditional hunting area used by Indigenous cultures in the Arctic, and protects low-lying Arctic coastlines that are vulnerable to coastal erosion. Thinning and melting sea ice provides for massive phytoplankton blooms to occur in the polar oceans, as an essential starting point of food webs in these regions (Arrigo et al., 2012). Melting of seasonal snow and glaciers in high mountains provides water for drinking and irrigating crops in many parts of the world. This water resource is further valuable in power generation and industries downstream of cryosphere regions, but can also lead to springtime floods that bring hazards to downstream communities.

1.3 Changes in Ocean and Cryosphere

The Fifth Assessment Report (AR5) of the IPCC provides ample evidence of profound and global-scale changes that occurred in both the ocean and the cryosphere in the past 100 years (IPCC, 2014). These long-term changes have occurred against a backdrop of substantial natural variability, on year-to-year and up to multidecadal timescales, making the detection of anthropogenic changes challenging (Bindoff et al., 2013). This may no longer be true in the coming decades since the projected changes, especially under high emission scenarios, may soon exceed the envelope of natural variability (Collins et al., 2013).

1.3.1 System Change Concepts Relevant to Ocean and Cryosphere

Large inertia and long response times are key characteristics of the ocean and cryosphere. The timescales associated with deep ocean circulation are of the order of hundreds or more years (Buckley and Marshall, 2016), and the renewal rate of the large ice sheets requires many thousands of years (Huybrechts and de Wolde, 1999). These long response times mean that the ocean and cryosphere tend to lag behind in their response to a rapidly changing forcing. Consequently, even once this forcing is stabilized, these systems will continue to evolve for hundreds of years (Figure 1.1a) (e.g., Golledge et al., 2015). This also implies that these systems will also change very slowly in response to a reversal of the forcing, making many of the changes essentially irreversible on the timescale of humans.

Rapid and abrupt changes in response to the passing of critical thresholds are a second hallmark of the ocean and cryosphere, even when the underlying forcing is changing smoothly (Figure 1.1a). Critical tipping elements can potentially create rapid and abrupt changes, including the rapid disappearance of Arctic sea ice, the collapse of ocean overturning circulation, or the onset of a rapid ice-surges once the bottom of a glacier is no longer frozen to the underlying ground (Lenton et al., 2008). The interconnectedness of ocean and cryosphere (Section 1.2.2) leads to a myriad of cascading hazards, where changes in one element trigger a response in completely different but connected elements of the system (Figure 1.1c).

The final key characteristic is the presence of both forced and unforced variability. Forced variability in the present-day climate is associated primarily with the anthropogenic increase in the concentration of atmospheric CO_2 and other greenhouse gases (although natural processes such as volcanic eruptions and solar modulation can also force climate). Unforced variability emerges from natural variability internal to the climate system. An example of unforced (natural) variability is the ocean-atmosphere oscillation that produces the El Niño-Southern Oscillation (ENSO). The presence of unforced variability can mask forced trends, which take time to emerge and be detectable from the background 'noise' of unforced variability. The 'Time of Emergence' is the point in time when a particular element of the Earth system has changed to a level that is significantly detectable above or below the range of unforced variability (Figure 1.1b) (Hawkins and Sutton, 2012). Extreme events (e.g., marine heat waves) lay well outside the normal variability of a system (Figure 1.1b), and in a changing climate state the recurrence and intensity of these extreme events can change much faster and have greater impacts than changes of the overall system state.

Attribution of a detected change to anthropogenic climate change requires a formal attribution procedure, as outlined in Bindoff et al. (2013). For example, this can involve the consideration of two contrasting scenarios; the first with all forcings considered, and the second with a particular forcing (e.g., greenhouse gases) removed. An attribution to that particular forcing can be made when the scenario with all forcings is consistent with the observed evolution of the system and the scenario without that particular forcing is inconsistent with the observations (Figure 1.1d).

The capacities of economies and cultures to adapt and potentially benefit from ocean and cryosphere change are challenged by these complex system characteristics. For example, the thinning of Arctic sea ice over past decades has reached a point where breakup of coastal ice may occur so early that access to seasonal hunting grounds for marine mammals becomes unsafe. This incremental loss of ice thickness has now seriously disrupted the basic food security of those hunting communities (Watt-Cloutier, 2015). Such tipping points are hard to predict until they are very close or have been passed. Adaptation often must be done under high uncertainty about when and how intensively the changes will occur (Cross-Chapter Box 4). Failure to make adequate and timely investments to deal with large and abrupt changes in major hazards can have high costs in loss of life and property. Against this background of uncertainty, large capital investments in adaptation for tipping point changes that are less imminent than expected may appear fiscally wasteful and undermine popular support for the programs. Subsequent chapters develop the trade-offs embedded in such uncertainties, weighing the risks of misses versus false alarms, to more fully develop when precautionary investments require consideration.

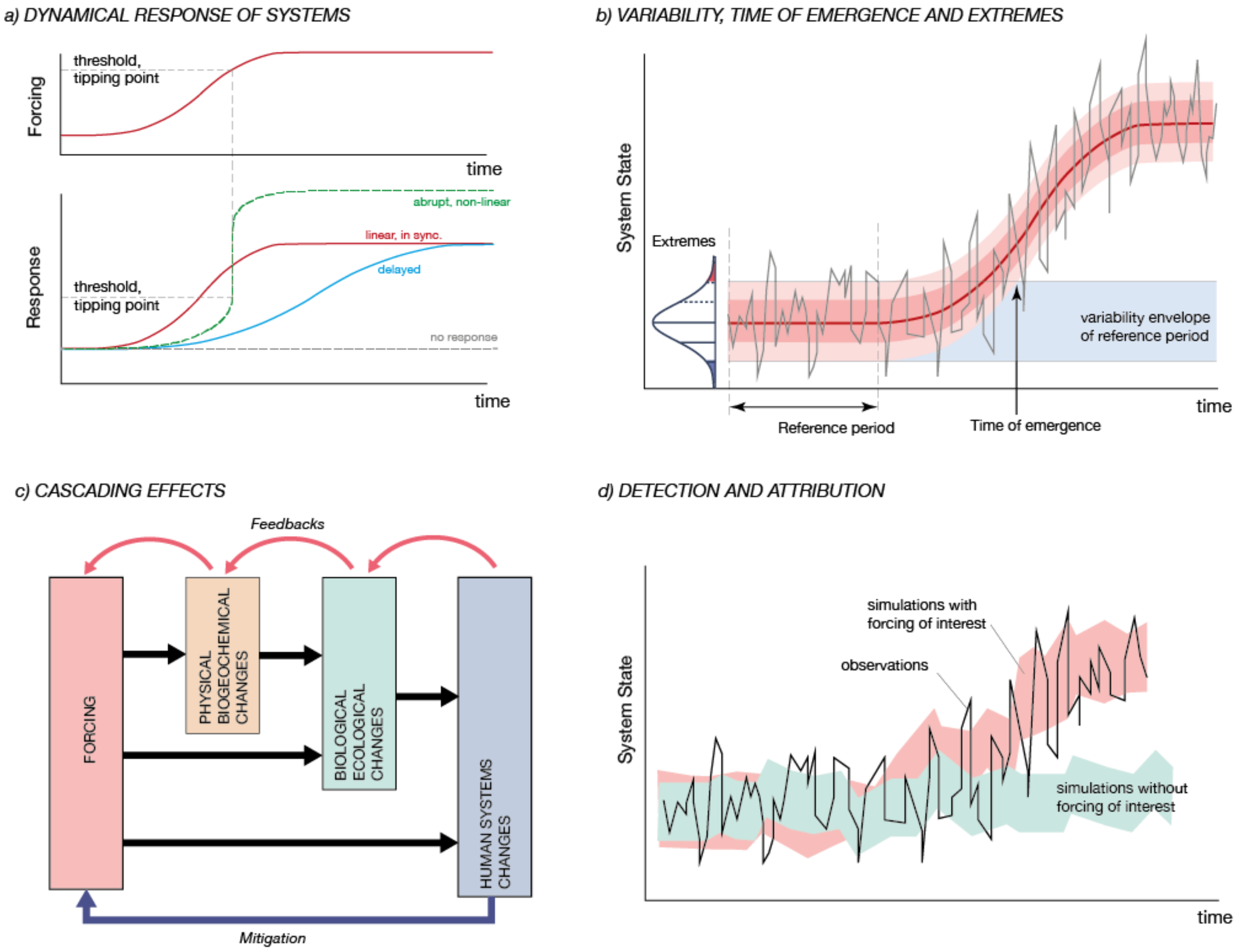


Figure 1.1: Schematic illustration of key concepts and challenges associated with the assessment of changes in the ocean and cryosphere.

1.3.2 *Physical and Biogeochemical Changes*

1.3.2.1 Observed and Projected Changes in the Ocean

Scientific progress over the last decades has demonstrated that the oceans are warming, that sea level is rising, and that ocean acidity is increasing (Rhein et al., 2013).

Globally, the mean ocean surface temperature has increased by about 0.6°C since 1850, with most of the increase having taken place since the 1970s (Cheng et al., 2017). Alongside ocean warming, substantial changes in salinity have been observed reflecting the expected acceleration of the Earth's hydrological cycle in response to global warming (Durack, 2015). Rainfall-dominated ocean regions, such as the equatorial western Pacific, have undergone a long-term freshening, while subtropical ocean regions in the evaporation-dominated ‘desert latitudes’ have generally increased in salinity. AR5 projected that this pattern of change continues in the future with the magnitude of change corresponding largely with the magnitude of the cumulative greenhouse gas emissions (Collins et al., 2013).

Global mean sea level has risen in the last 100 years by about 20 cm caused by the ocean’s expansion due to warming, from increasing amounts of freshwater added to the ocean by melting of glaciers, ice caps and ice sheets, and from changes of land-ocean water transport (Church et al., 2011; Chambers et al., 2017; Dieng et al., 2017; Nerem et al., 2018). Continued rises of sea level are expected (Church et al., 2013), but the magnitude of change varies substantially with different greenhouse gas emission scenarios and different representations of ice sheet dynamics within models (Chapter 4). The committed sea level rise over millennia is estimated to be many meters under a high greenhouse gas emission future (Golledge et al., 2015; DeConto and Pollard, 2016).

During the decade 2017-2016, the ocean has taken up about 22% of the global CO_2 emissions caused by anthropogenic activities (Le Quéré et al., 2018). As CO_2 is absorbed in the ocean, the ocean acidifies (its pH decreases) and the saturation state with respect to carbonate minerals decreases (Orr et al., 2005). Ocean acidification is expected to substantially affect marine ecosystems, with consequences on ecosystem services and societies, as organisms building structures out of carbonate minerals, such as corals, are sensitive to even subtle changes in ocean pH (Gattuso et al., 2014). Many other oceanic changes may emerge in the future but were still difficult to attribute to anthropogenic activities at the time of AR5, including changes in ocean circulation such as the Atlantic meridional overturning circulation (Rahmstorf et al., 2015), decreases in the ocean's oxygen content ('ocean deoxygenation') (Keeling et al., 2010; Schmidtko et al., 2017; Breitburg et al., 2018), and changes in ocean productivity (Bopp et al., 2013).

1.3.2.2 Observed and Projected Changes in the Cryosphere

Many cryosphere changes are now clear: there is widespread retreat of mountain glaciers, Arctic sea ice is declining, Antarctic ice shelves are thinning, and the Greenland and Antarctic ice sheets are losing mass (Vaughan et al., 2013).

One of the most visible changes in Earth's cryosphere is the decline in Arctic sea-ice (Harada, 2016). This is manifest as a retreat in sea ice extent in all seasons, thinning of the Arctic sea ice pack, and the loss of multi-year ice (Serreze and Stroeve, 2015; Chapter 3). Future projections are for Arctic sea-ice loss to continue and within this century the Arctic ocean could become essentially ice free in the summer. This will have dire impacts for Arctic ecosystems and people who depend upon sea ice, but will also bring opportunities for new shipping routes and access to new mineral resources. Declines in Antarctic sea ice are projected from climate model simulations, but are not yet detectable outside of the large range of Antarctic sea ice variability (Jones and O'Neill, 2016) and may point towards an area of deep uncertainty in our understanding of this aspect of the cryosphere system (Cross-Chapter Box 4; Chapter 3).

The Greenland Ice Sheet, West Antarctic Ice Sheet and Antarctic Peninsula are all losing ice mass that is contributing to global sea level rise (Shepherd et al., 2012). Ice loss from Greenland is projected to continue, with new models resulting in even faster response. The future of the Antarctic ice sheet is less well established, but model-based studies suggest the potential for possibly irreversible change in the West Antarctic ice sheet (Joughin et al., 2014; Rignot et al., 2014) and studies since AR6 suggest that parts of the East Antarctic Ice Sheet may also become vulnerable with continued climate warming (Aitken et al., 2016; Golledge et al., 2017). Rapid thinning of ice shelves abutting the West Antarctic ice sheet has been attributed to ocean-driven basal melt (Pritchard et al., 2012) which is projected to increase further (Spence et al., 2014). Ice shelf retreat along the Antarctic Peninsula is attributed to atmospheric-driven surface melting. Modelling under a high-emissions scenario indicates that surface melting could compromise ice shelf stability around much of Antarctica by the end of the century (Trusel et al., 2015).

Glaciers are retreating essentially everywhere (Marzeion et al., 2014; Kraaijenbrink et al., 2017). Snow cover in the parts of the Northern Hemisphere has also decreased since the mid-20th century (Robinson, 2016; Hori et al., 2017). Permafrost degradation has been observed (Peng et al., 2016; McGuire et al., 2018) and causes cascading effects. Permafrost degradation releases methane that contributes to further increases in air temperatures (McGuire et al., 2010; Bohn et al., 2015), and the loss of the structural support permafrost provides leads to erosion and landslides (Couture et al., 2018). Future model-based projections suggest that the ice loss from mountain glaciers will continue, with glaciers disappearing completely in many regions within decades. Further melting cannot be prevented in the current century even if greenhouse gas emissions were to stop immediately (Marzeion et al., 2018).

1.3.3 Opportunities and Hazards

The changes in the ocean and cryosphere attributed to climate change described in Sections 1.3.2 have many implications for the well-being and security of people and cultures in coastal, montane and polar environments (Pecl et al., 2017). Some impacts are direct, such as sea level rise displacing coastal residents in some low-lying coastal areas, where the burden of displacement falls disproportionately on the economically and socially disadvantaged (FitzGerald et al., 2008; McLeman and Brown, 2011; Collins et al., 2017; Otto et al., 2017). Thawing permafrost and loss of coastal ice in the Arctic is also impeding access to hunting grounds fundamental to the livelihoods of Inuit and other Northern cultures (Watt-Cloutier, 2015). Other impacts are indirect; climate change will cause a likely increase in both maximum wind speed and rainfall rates in global mean tropical cyclones (Stocker et al., 2013), increasing hazards for natural and human systems. For example, the five category 4 or 5 hurricanes that formed in the Atlantic in 2017 caused over 170 lives to be lost and more than 150 billion US$ in economic damages (https://coast.noaa.gov/states/fast-facts/hurricane-costs.html; [REFERENCE TO BE ADDED].

Climate change impacts on the ocean and cryosphere also present opportunities. For example in Nepal the warming of high montane environments and accelerated melting of ice fields is extending growing seasons and crop yield for local farmers (Gaire et al., 2015; Merrey et al., in press). The redistribution of marine fish in response to rising ocean temperatures is changing the fishing opportunities in western Europe, North America and elsewhere, with new fisheries opening and traditional ones being reduced or closed (Fenichel et al., 2016). To both gain from new opportunities for improving the well-being of people, and to avoid or mitigate the new or increasing hazards, it is necessary to be informed of what may be coming in the future and to have options to address the opportunities and hazards effectively. Chapters 2 to 6 of this Special Report provide the best knowledge available on ocean and cryosphere changes expected in the near and medium term, and the enabling and limiting conditions for potential adaptation strategies.

1.4 Risk and Impacts Related to Ocean and Cryosphere Change

1.4.1 Risk Framework

Climate change impacts on the ocean and cryosphere are compounding the risks already faced by many communities living on low-lying coasts, in polar regions and high mountain areas. Exposure and vulnerability to climate and non-climate hazards can result in severe impacts in these regions and beyond. The need to reduce climate change risks, adapt to climate change and chart climate resilient development pathways is therefore urgent (Cross-Chapter Box 1; [PLACEHOLDER FOR SR1.5]). In doing so, the anticipation of risks and adaptation to climate change shapes development pathways, and vice versa.

Building resilience of linked societal and ecological systems in a forward-looking way, across local to global scales, will ultimately be key to achieving sustainable development trajectories in the face of a changing climate and its effects on the ocean and cryosphere. This process requires transformations in the ways that human-environment relations are institutionally governed (Pelling, 2010; O'Brien, 2012; Pelling et al., 2015; Few et al., 2017; Solecki et al., 2017). However, key concepts are often defined in different and even contradictory ways, including definitions of risk, adaptation and resilience, and the relationships between them (Miller et al., 2010; Brown et al., 2013; MacAskill and Guthrie, 2014; Weichselgartner and Kelman, 2015). Definitions of these concepts will continue to evolve with advances in understanding. Cross-Chapter Box 1 explains how terms related to risk, adaptation and resilience are used in this Special Report and how the different concepts relate to each other. The Glossary provides precise definitions of key terms, drawing on past IPCC work and, where appropriate, developing these further in consideration of new knowledge and literature.

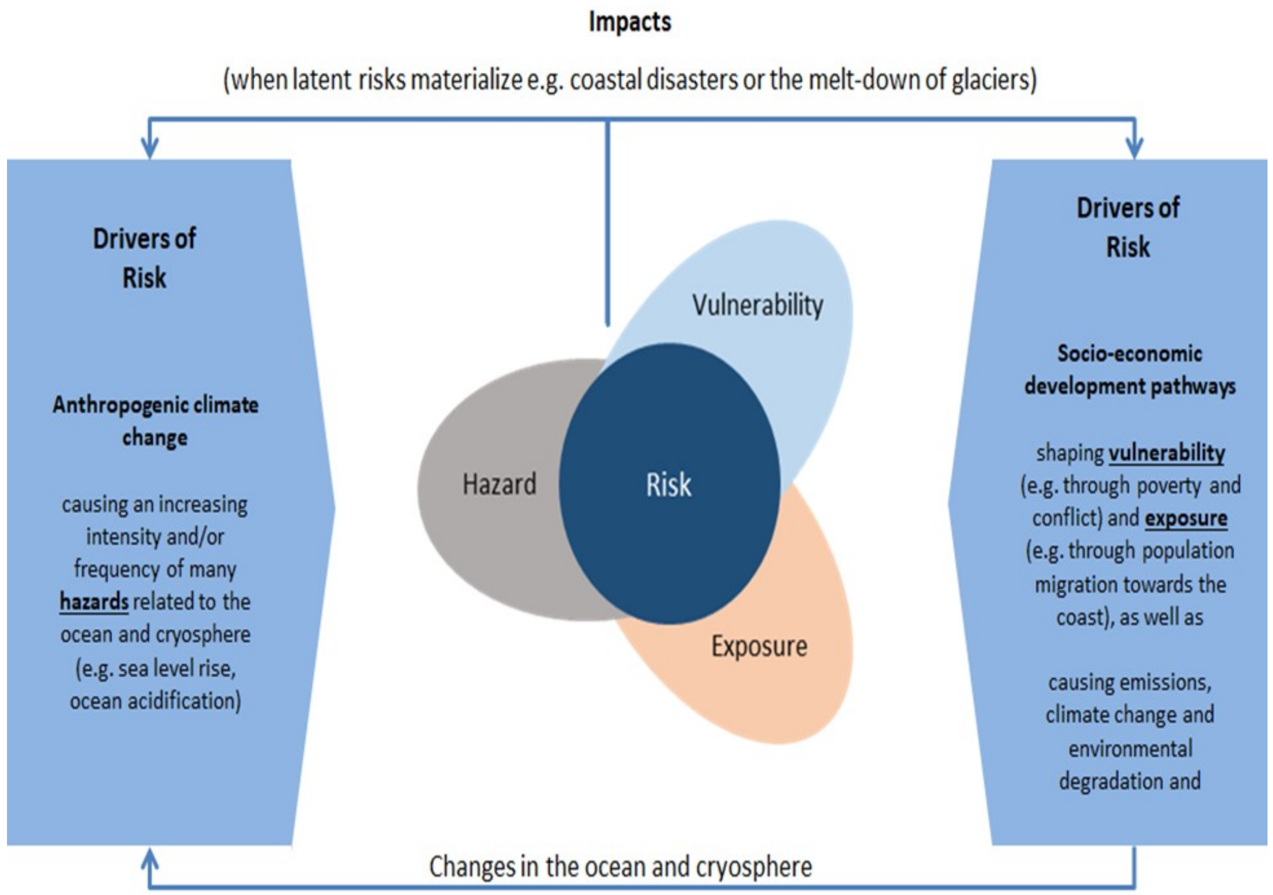


Figure 1.2: Conceptual framework of risk, its components and drivers.

Risk is a product of the interaction between a hazard and an exposed and vulnerable element (e.g., a human community, ecosystem, infrastructure asset) (Agard et al., 2014; Figure 1.2). Many ocean and cryosphere-dependent communities face interacting drivers of risk from climate and non-climate processes (section 2.5 for high mountain areas; Sections 3.3.3, 3.3.4, 3.3.5, 3.4.3 for polar regions; Section 5.3.2 for ocean related risks; Box 6.1). Drivers of change can affect single or multiple elements of risk. For example, climate change is causing and/or exacerbating hazards such as sea level rise and its consequential impacts including coastal flooding, erosion and salinization (Chapter 4). At the same time, the exposure of coastal communities to such hazards is often increased when human settlements and industrial assets sprawl into hazard-prone areas (Sudmeier-Rieux et al., 2015). Vulnerability of the exposed elements can be driven by both direct socio-economic processes (e.g., income distribution, health care access, marginalisation etc.) and climatic effects (e.g., rising food insecurity through the loss of traditional food systems in parts of the Arctic) (Beaumier et al., 2015).

Figure 1.2 indicates how development patterns (right hand panel) determine net greenhouse gas emissions that in turn shape climate variability and change (left hand panel). Furthermore, development outcomes are reflected in positive and negative environmental and development impacts. Poverty and inequity, for example, deepen vulnerability to both climate and non-climate hazards in exposed locations. Coastal habitat loss, for instance, accelerates biodiversity loss and reduces the protective role of coastal vegetation against storms (Barbier et al., 2013). Climate resilient development deploys effective disaster risk management, enables effective adaptation, limits and mitigates greenhouse gas emissions, and fosters environmental and human well-being. Among other things, this includes charting resilient development pathways over time to facilitate the attainment of the Sustainable Development Goals (SDGs) (United Nations, 2015).

[INSERT CROSS-CHAPTER BOX 1 HERE]

1.4.2 Natural Systems

In this report the term 'Natural System' is used to describe a system that exists in nature, independent of any human involvement but which may be affected by human activities. This includes organisms and ecosystems, but can also describe physical systems (e.g., an ocean upwelling system) without necessarily considering the organisms within that system.

1.4.2.1 Risks to Natural Systems

Climate change has implications for ecosystem services, biodiversity, and modification of habitat. This report emphasizes the interactive effects of risks and impacts within the ocean and cryosphere and updates the attribution and confidence in relevant trends for emerging risks in extreme events (Chapter 6), as well as changes to major ocean and cryosphere components including the Atlantic Meridional Overturning Circulation (Chapter 6), marine heat waves (Chapter 5), and ice sheet collapse (Chapters 3 and 4).

There is increasing confidence in attributing extreme ocean and cryosphere events to climate change (Chapter 6). Associated ecosystem risks from AR5 included degradation of coral reefs (*high confidence*), oceanic deoxygenation (*medium confidence*), and ocean acidification (*virtually certain*). Shifts in plankton and fish ranges were identified with *high confidence* at the regional level, but with no clear trend globally. Since AR5 there is more evidence for global shifts in marine organisms with *very high confidence* that distribution and phenology of animals is responding to warming. There is *high confidence* that the signature of climate change is detected in almost all marine ecosystems, particularly for coral reef, sandy beach, pelagic surface, and seamount ecosystems. Similar trends of changing habitat are reported for the cryosphere (Section 2.5), but may also lead to habitat expansion in polar systems (Section 3.2.5).

1.4.2.2 Vulnerabilities that Increase Risks to Natural Systems

A wide range of non-climate anthropogenic pressures magnify the vulnerability of ocean and cryosphere ecosystems to climate-related changes (Section 5.3.1). Examples include overfishing, overexploitation of mineral resources and coastal development and pollution. Risks faced by marine and coastal organisms, and the ecosystem services they provide, are dependent on future CO_2 emission pathways. Many (except warm-water corals and bivalves) would have moderate risks of impacts under a low emission future (RCP2.6; section 1.8.2), but almost all would have high to very high risks of impacts under higher emission scenarios (Mora et al., 2013; Gattuso et al., 2015).

1.4.2.3 Spatial Distribution of Risks to Natural Systems

Cryosphere: Risks on natural systems can occur locally in the immediate vicinity of components of the cryosphere, or cryosphere changes can lead to regional or global scale risks for natural systems. Decreasing Arctic sea ice cover forms a local risk to ecosystems that depend on sea ice for habitat, but may also have far-reaching impacts on increasing surface melt of the Greenland ice sheet (Liu et al., 2016; Stroeve et al., 2017) and through the direct albedo feedback that amplifies Arctic climate warming (e.g., Pistone et al., 2014). Ice sheet loss is another example of cryosphere change causing global-scale sea level rise and direct risks to coastal ecosystems (Chapters 3 and 4), leading to modification and loss of habitat. Interactions within and between natural systems also influence the spatial reach of risks associated with cryosphere change. Changing permafrost, for example, interacts with ecosystems and climate on various spatial (and temporal) scales and the feedbacks resulting from these interactions range from local impacts on topography, hydrology and biology, to complex influences on global scale biogeochemical cycling and climate (Grosse et al., 2016; Phillips et al., 2017).

Coastal ocean: Risks from climate change exist for virtually all coastal organisms (Section 5.2.3). Coastal ecosystems are expected to experience increases in harmful algal blooms (Glibert et al., 2014), while coral reef systems are under increasing pressure from both rising temperature and lowering pH (Hoegh-Guldberg et al., 2017). Ocean acidification and deoxygenation further impact organisms (Section 5.2.3), and multidriver impacts are dramatically altering ecosystem structure and function in both the coastal and open ocean (Boyd et al., 2015).

Open ocean: Risks to natural systems include ocean acidification (O'Neill et al., 2017; Section 5.2.1.3), changes in ocean ventilation, and deoxygenation (Shepherd et al., 2017; Section 5.2.2.4). Ocean warming is the risk that is the most investigated. Heat content is rapidly changing at depth, with over one third of the industrial-era heat increases occurring below 700 m (Gleckler et al., 2016), and there is evidence that global models may severely underestimate the rate and range of these changes at regional scales (Saba et al., 2016). These changes lead to direct impacts on natural systems at regional scales; for example, about half of species assessed on the northeast United States continental shelf exhibited high to very high climate vulnerability (Hare et al., 2016), with corresponding northward shifts for many species (Kleisner et al., 2017).

1.4.2.4 Future Dynamics of Risk and Exposure to Natural Systems

Climate change is restructuring natural systems globally. Fundamental changes are taking place throughout the cryosphere, substantially increasing the risk of related hazards related to the cryospheric processes at all spatial and temporal scales worldwide (Haeberli and Whiteman, 2015). There is considerable uncertainty at how these risks and impacts will manifest regionally, and how multiple drivers result in emerging and cascading risks (Boyd et al., 2015; Behrenfeld et al., 2016; Kroeker et al., 2017; Musselman et al., 2017). Permafrost, ice and snow are particularly vulnerable in the current period of rapid global warming (Stewart, 2009; Rohrer et al., 2013; Chadburn et al., 2017; Marzeion et al., 2018). It is, however, clear that global redistribution of phytoplankton and higher trophic levels is occurring, with increasing extinction risk and loss of both ecosystem and human health (Molinos et al., 2016; Pecl et al., 2017).

1.4.3 Human Systems

In this report we use the term ‘Human System’ to refer to any system in which human organizations and institutions play a major role (Agard et al., 2014). Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, political systems, technological systems, and economic systems are all human systems in the sense applied in this report.

1.4.3.1 Risks to Human Systems

Human systems impact and are impacted by the ocean and cryosphere in a changing climate. Key climate change risks to human systems include infrastructure damage and failure; increased morbidity and mortality due to unintentional injury, infectious disease, and mental health; compromised food security; economic impacts due to reduced production and social system disruption; and widespread human migration (Oppenheimer et al., 2014). These risks are exacerbated by other socio-economic changes, including, for example, coastal urbanization, which may also be a driver of climate change (Jones and O'Neill, 2016; Merkens et al., 2016).

Not all of these risks are hypothetical or projected to occur only in the future; rather, many of these risks have already become impacts for some people residing in coastal and cryosphere regions. Furthermore, some of these changes are non-linear interactions, tipping points, and irreversible changes (Section 1.3.1) in coastal and cryosphere regions, from which additional risks emerge (Chapter 6).

1.4.3.2 Vulnerabilities that Increase Risks to Human Systems

Those who depend directly on oceans and cryosphere resources for their livelihoods are particularly vulnerable to climate change (Romero-Lankao et al., 2014). Although these communities are exposed to various climate change related hazards, their vulnerability to climate change risk is a function of social, political, cultural, economic, institutional, geographical, and/or demographic factors. As established in AR5, social exclusion, inequalities, and differential access to and control over social, financial, and environmental resources based on gender, age, race, class, caste, indigeneity, and disability shape multidimensional vulnerability and constrain climate change adaptation and transformation. Disparities and inequities present a context of non-climatic challenges to health and wellbeing, economic development, and basic human rights. People disadvantaged by such disparities and inequities have limited options for coping and adapting, resulting in those already favoured by the disparities also benefiting most from adaptation strategies (Hijioka et al., 2014). Those with greater wealth and privilege, however, are not necessarily less vulnerable to climate change risks (Cardona et al., 2012; Smith et al., 2014).

Institutions and governance shape vulnerability and adaptive capacity, with weaker institutions and governance often challenged to respond to extreme or persistent climate change hazards (Berrang-Ford et al., 2014; Hijioka et al., 2014). For example, the 2017 hurricane in Puerto Rico illustrates how weak institutions and governance challenge responses to extreme events (Alcorn, 2017; Vandermeer, 2017) (Chapter 6). Furthermore, populations can be negatively impacted by inappropriate climate change policies that further marginalize their knowledge, culture, values, and livelihoods (Field et al., 2014; Cross-Chapter Box 2).

1.4.3.3 Spatial Distribution of Risks to Human Systems

Cryosphere: Increased snow and ice melt (You et al., 2017) and formation of glacial lakes (Gurung et al., 2017; Shrestha et al., 2017) in high mountains increase the risks of glacial lake outburst floods (Riaz et al., 2014; Cook et al., 2017; Gurung et al., 2017) and landslides (Huggel et al., 2012) that threaten mountain communities. Hydrological system changes impact water availability (Field et al., 2014), with implications for societal needs such as drinking water, irrigation, livestock grazing, mining, hydropower production and tourism (Lutz et al., 2014; Huss et al., 2017). Declining glaciers have socio-cultural impacts, as many glaciers hold sacred and symbolic meanings for mountain communities (Cruikshank, 2005; Allison, 2015; Shijin and Dahe, 2015; Chapter 2). In the Arctic, extreme warming has significantly reduced multi-year ice and summer sea ice extent, and increased thawing permafrost (Vihma, 2014; Schuur et al., 2015), presenting risks and impacts for ecosystems and human communities. These risks and impacts, in combination with and exacerbated by non-climate vulnerabilities, are particularly challenging for indigenous communities, due to close interdependent relationships with the sea ice for livelihoods, food security, transportation, culture, and health and wellbeing (Larsen et al., 2014; Cunsolo Willox et al., 2015; Chapter 3). Permafrost thawing presents risks to already challenged infrastructure, including drinking water systems, buildings and transportation (Adams et al., 2013).

Coastal Ocean: Billions of people live in coastal areas, and the population living in low elevation coastal zones is projected to increase across all SSPs by 2050 (Merkens et al., 2016). Those who are dependent on ocean systems for subsistence, as well as fishery and tourism dependent economies are especially vulnerable to climate change impacts on oceans (Hoegh-Guldberg et al., 2014). Increasing ocean temperatures, frequency of marine heat waves, and ocean acidification can disrupt marine species populations with risks for fisheries, tourism, coastal protection, and food security, including loss of life and damaged assets, as well as emerging risks to disruption of basic services including safe water supplies, sanitation, energy, and transportation networks. Coastal shipping and industrial infrastructure are also vulnerable to changes in sea level, wind, wave height, and storm intensity. For instance, in North America, coastal flooding and extreme weather events can result in property damage, and cause damage to aging infrastructure with consequences for drinking water, energy, telecommunications, trade, and social service provision. In Australasia, sea level rise is increasing risks to coastal infrastructure and low-lying ecosystems with widespread damages projected (Hallegatte et al., 2013; Hinkel et al., 2014; Chapter 4), and even small sea level rise presents major risks to indigenous Torres Strait islanders (Reisinger et al., 2014).

1.4.3.4 Future Dynamics of Risk and Exposure

Despite advances in engaging the human dimension in risk and exposure analyses and future projections at a sub-national level, there remains a strong focus on biophysical dynamics (Jurgilevich et al., 2017). Local-level initiatives are increasing awareness to the risks associated with ocean and cryosphere change and increasing ownership in developing and implementing local strategies to mitigate and respond to these risks. However, these efforts are often hindered by lack of data and resources to carry such efforts forward (Cardona et al., 2012).

1.5 Addressing Consequences of Climate Change for the Ocean and Cryosphere

Societies worldwide need to mitigate and adapt to climate change, and its effects on the ocean and cryosphere, if they want to enable climate resilient development pathways that keep residual risk, loss and damage from climate change at a minimum (Cross-Chapter Box 1). *Mitigation* refers to human intervention to reduce atmospheric greenhouse gases (by reducing the sources and/or enhancing the sinks), whereas *adaptation* is the process of adjustment to actual, expected, and partly unavoidable impacts of climate change (Agard et al., 2014). Deep societal transformations will be needed to effectively facilitate climate change mitigation and adaptation at the level required for the achievement of the Paris Agreement (UNFCCC, 2015).

Several measures have the potential to reduce climate change and its impacts: addressing the causes of climate change (mitigation), managing solar radiation, supporting biological and ecological adaptation, and enhancing societal adaptation (Figure 1.3). Mitigation pathways to avoid dangerous climate change are considered in the IPCC Special Report on Global Warming of 1.5°C (SR1.5). Options for solar radiation management and other forms of geo-engineering have not been included in IPCC scenarios and are not addressed in this report. This report focuses on the ocean and cryosphere, considering the scope for managing natural sources and sinks of greenhouse gases, supporting biological and ecological adaptation, and enhancing societal adaptation. Syntheses of these and other ocean-based approaches (Gattuso et al., Submitted) suggest that most proposed global measures of climate counter-action currently exhibit too many uncertainties for large-scale deployment, and the best investment in mitigation is to reduce anthropogenic emissions (IPCC, 2014). Local ocean-based measures provide low-regret options with significant co-benefits that could be rapidly scaled-up, but are less effective in addressing the global problem.

Linkages and feedbacks in ecosystem processes provide natural systems with some adaptive capacity to climate change. In addition, human interventions in natural systems can enhance natural adaptive capacities. For example, manipulating ecosystem structural or functional properties can minimize climate change pressures, enhance natural resilience and/or re-direct ecosystem responses to reduce societal risks. In human systems, adaptation can involve both infrastructure (e.g., enhanced sea defences) and community-based action (e.g., changes in policies and practices).

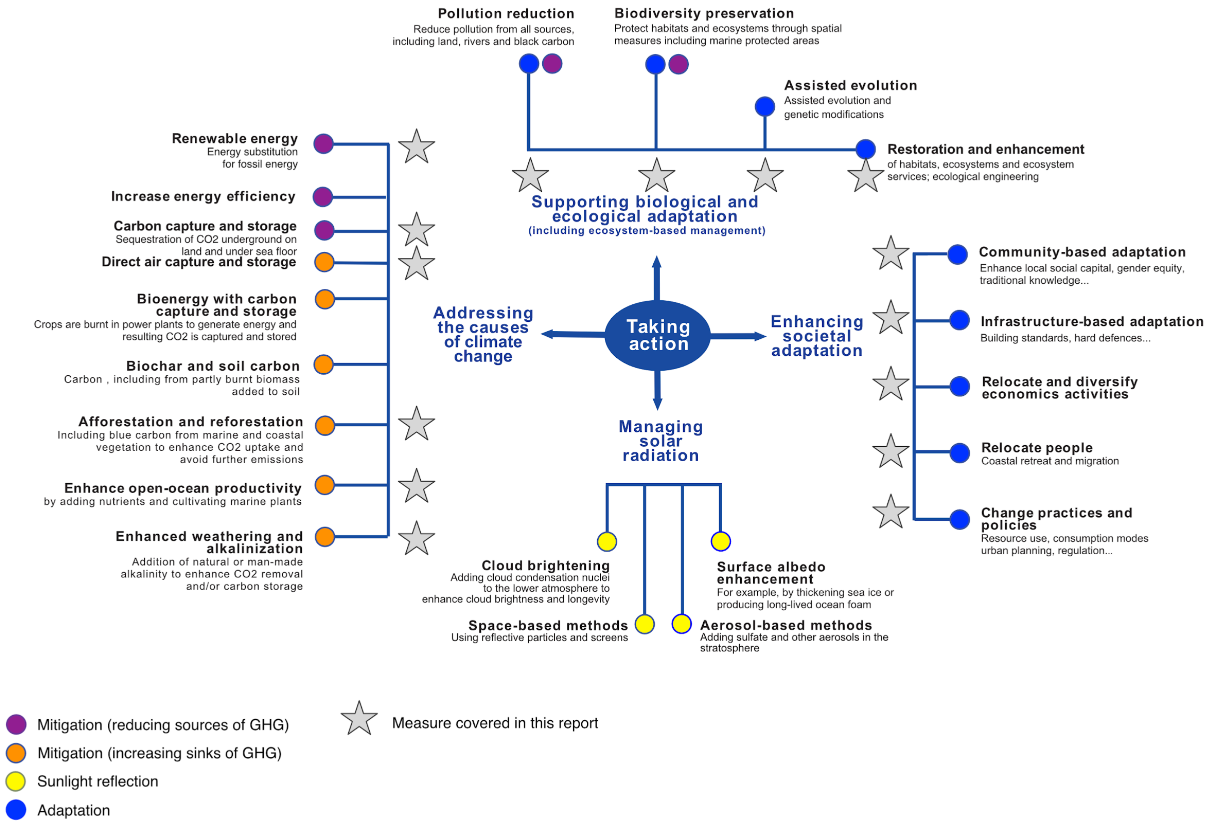


Figure 1.3: Overview of human responses to climate change. Responses to observed and expected changes in the ocean and cryosphere in a changing climate comprise mitigation and adaptation domains. Solar radiation management techniques are mentioned for the sake of completeness but direct geo-engineering techniques are outside the scope of this report. Governance-based solutions (e.g., institutional arrangements) are not included in this figure but are covered

in several chapters of this report as well as in Cross-Chapter Box 2. Appendix 1.A, Table 1 indicates in which chapters the efficiency, readiness, benefits, and/or disbenefits of the measures are addressed. Modified from Gattuso et al. (Submitted).

1.5.1 Mitigation

There are several options to mitigate the build-up of greenhouse gases (GHG) emissions in Earth's atmosphere by reducing the emission sources and by increasing the sinks that drawdown and store greenhouse gases out of the atmosphere. In-depth discussion of mitigation is outside the scope of this report, but the measures that involve the ocean and the cryosphere are addressed (Figure 1.3; Appendix 1.A, Table 1). Other indirect measures involving biological and ecological adaptation, such as pollution reduction (which moderates ocean acidification in eutrophied areas) and preservation of biodiversity in coastal habitats (which can also protect carbon stored in soils and sediment) can also contribute to reducing sources of GHG (e.g., Chapter 5). Investment in reducing emissions through mitigation creates opportunities for long term solutions which could reduce the need for adaptation strategies (IPCC, 2014).

1.5.2 Adaptation

1.5.2.1 Adaptation in Natural Systems

Natural systems of both the ocean and cryosphere have changed in response to climate change and other human pressures as reflected in Appendix 1.A, Table 2 (Cramer et al., 2014). Changes in populations, habitats and ecosystems can be linked to pressures associated with climate change, some with medium or high confidence. Climate change impacts on marine, coastal, coral reefs, Himalayan, polar, and high altitude ecosystems have been variable in both space and time. The multiplicity of pressures make it hard to attribute a specific population or ecosystem response to an individual pressure from ocean and cryosphere change as a more general driver. The complex interconnectivity of populations and their environments means that an 'adaptive response' of a population or the aggregate response of an ecosystem (comprising the adaptive responses of the component populations), is influenced not just by the direct pressure of climate-change, but also by the adaptive responses of the other species with which any one population interacts.

Since AR5, much effort has gone into better resolution of the mechanisms, the interactions, and the feedbacks of natural systems associated with the ocean and cryosphere. New knowledge is emerging in all these systems, and is presented and interpreted in the chapters of this Special Report. For example, in addition to all the impacts and potential adaptive responses to ocean warming included in Appendix 1.A, Table 2, there is substantial new information emerging that marine heat waves and large pools of anomalously warm water are occurring in many ocean settings (Oliver et al., 2018). The adaptive responses for wetlands, coral reefs, other coastal habitats, and for the populations of marine organisms encountering these increasing ocean temperature extremes are reviewed in Chapters 4, 5, and 6. Likewise, emerging knowledge on the polar and high-mountain systems is featured in Chapters 2 and 3.

New data focusing on evolutionary adaptation (i.e., change in functional characteristics as a result of natural selection acting on heritable traits) for a population or species is emerging. Importantly, changes in the average environment (Schlüter et al., 2016) as well as the range of variation in environments have been shown to drive evolution in phytoplankton (Schaum et al., 2016). Trait evolution can be life-stage specific, or alter life histories (Pespeni et al., 2013; Hinners et al., 2017). While there is evidence that populations can evolve in response to climate-related changes (Collins et al., 2014; Hutchins and Fu, 2017) there is little data on how evolutionary change is likely to impact ecosystem or community function, and whether trait evolution is stable (Schaum et al., 2016; Schlüter et al., 2016). Projection methods are needed for non-model or long-lived taxa (Runcie et al., 2016). Because evolution can extend or change the range of environments where populations persist, assisted evolution is one strategy under discussion for populations living at the limit of their environment, such as symbionts in warm-water corals (van Oppen et al., 2015).

1.5.2.2 Adaptation in Human Systems

There are a number of key human adaptation options for climate change impacts on oceans and the cryosphere. AR5 identified three main modes of adaptation for sea level rise and storms in low-lying areas:

protection, accommodation and retreat (Wong et al., 2014). All three modes of adaptation can include mixes of institutional, sociocultural, engineered and/or ecosystem-based measures. In mountain communities, adaptation responses have been primarily coping strategies (Behringer et al., 2000). For Pacific communities, local marine resource management acts as an ecosystem-based adaptation (Jupiter et al., 2014).

As affected individuals, communities and nations increasingly implement, test and evaluate adaptive responses, research generates new evidence on adaptation processes and outcomes. Examples include nature-based approaches (Renaud et al., 2016) and managed retreat (Hino et al., 2017). As such, there is emerging evidence related to the effectiveness and performance of different adaptation options, as well as their social acceptance, political feasibility, cost-efficiency, co-benefits and trade-offs (Adger et al., 2005). However, scientific evaluation of adaptation to changes in the ocean and cryosphere is complex and under-researched, and evidence will be urgently needed to document progress towards the global adaptation goal (Magnan and Ribera, 2016). The priorities for adaptation will depend on the risk attitudes of investment institutions (Lobell et al., 2008).

Since AR5, a growing conceptual emphasis and empirical interest has included analysing transformational adaptation, referring to the need for both radical changes and flexible decision-making processes to face climate change consequences. The recent literature, often using case studies, documents how societies, institutions or individuals increasingly assume a readiness to engage in transformative change, accepting and promoting fundamental alterations in system configurations (Klinsky et al., 2016). Those living in coastal, mountain, and river basin areas often pioneer these types of transformations, since they are at the frontline of ocean and cryosphere change (e.g., Solecki et al., 2017). In exploring the timing and design of adaptation and shifts towards transformation, the concepts of scenario planning and 'adaptation pathway' design has gained traction since AR5, especially in the context of development planning in coasts and deltas (Haasnoot et al., 2013; Wise et al., 2014; Maier et al., 2016; Flynn et al., 2018). Such concepts are helpful in choosing between different options and planning for their implementation and sequencing, as well as to identify limits of adaptation strategies.

A complementary major political and scientific challenge is the assessment and evaluation of residual risk. As knowledge on the effectiveness and limitations of adaptation strategies in the ocean and cryosphere is sharpening, so too is the understanding of residual risks, especially in coastal, mountainous and polar settlements. This report, therefore, assesses these residual risks, as they appear today and in view of future climate changes.

1.6 Governance and Institutions

Climate governance is about how different actors mediate their interests, negotiate, and share their rights and responsibilities in pursuit of climate action (Forino et al., 2015). The government, the public sector, civil society, the private sector, academia and affected people all have important and different roles (Field et al., 2014). Institutions, defined for this report as formal and informal social rules that shape human behaviour (Roggero et al., 2017), have received increased attention since AR5 because they may both foster as well as hinder climate action. This report explores how the interlinkages between climate change, governance efforts and institutional change play out in the socio-ecological systems of the oceans, and cryosphere (Pahl-Wostl, 2006). For example, high mountain cryosphere is connected through hydrological processes between upstream and downstream areas of river basins (Nepal et al., 2014) including floodplains and deltaic regions (Kilroy, 2015). Some Small Island States, e.g., Kiribati, the Republic of the Marshall Islands and Tuvalu, face the possibility of losing their state, culture and voice in institutions including the United Nations (Gerrard and Wannier, 2013). Apart from the relevance of biophysical linkages within the river basin, the basin is also a political construct (Molle, 2009) that provides important ecosystem services in sustaining food, water, and energy security downstream (Rasul, 2014). Cryosphere and ocean changes caused by climate change may also result in regional to global-scale impacts (Section 1.4), highlighting the transboundary component of associated adaptation and mitigation responses.

Multiple organisations and institutions are involved in governing, using different frameworks, operating in varying capacities with their own strengths and weaknesses (Cross-Chapter Box 2). Limitations include boundaries in the spatial extent of governance structures, which may not allow governance actions to match the spatial extent of the pressures caused by ocean and cryosphere change (Delmas and Young, 2009; Young, 2009). The gaps in legal frameworks between affected countries also may limit the ability for nations to cooperate effectively (Winter, 2006; Kim, 2012) leading to poor responses to climate-related pressures (Eriksen et al., 2011). Therefore, there is an important place for local level adaptation, enabling communities to respond to climate change. This must work in addition to the global governance structures needed to provide an overarching policy framework for action. Such frameworks often provide the necessary resources (funding and infrastructure) needed to enable community responses. The main challenges for governance related to ocean and cryosphere change are: First, to ensure coordination of the top-down and bottom-up governance processes (Bond, 2006; Green et al., 2014; Bisaro and Hinkel, 2016) which are both critical for effective responses to climate change; Second, to mobilize adequate resources for empowering all relevant actors; and Third, to access and incorporate private sector, public sector and business sector capabilities to contribute to adaptive and mitigative responses in a polycentric governance perspective (Jordan et al., 2015).

[INSERT CROSS-CHAPTER BOX 2 HERE]

1.7 Knowledge Systems for Understanding and Responding to Change

1.7.1 Ways of Knowing, Diversity of Knowledge Systems, and Why it is Important

Humans create, use and adapt knowledge systems to interact with their environment (Agrawal, 1995; Escobar, 2001) and to observe and respond to change (Huntington, 2000; Maldonado et al., 2016). Assessments of how climate change is interacting with the ocean and cryosphere, including all past IPCC assessments, are based largely on the scientific knowledge system. However, most people use an Indigenous or Local Knowledge (ILK) system to understand and interact with their environment and to function on a daily basis (Sillitoe, 2007; Yeh, 2016). For instance, research in Papua New Guinea shows how local communities use resources based upon how local ecosystems are imbued with sentient beings (Ericksen and Woodley, 2005). Although efforts have been made to bridge knowledge systems in global environmental assessments (Berkes et al., 2006; Thaman et al., 2013), most assessments still fail to incorporate 'the plurality and heterogeneity of worldviews' (Obermeister, 2017) resulting 'in a partial understanding of core issues that limits the potential for locally and culturally appropriate adaptation responses' (Ford et al., 2016b).

Overall, scientific knowledge often can be characterized as reductionist, objective and generalizable, whereas ILK is holistic, subjective and context-specific (Mistry and Berardi, 2016). Table 1.1 presents an amalgamation of understandings.

Table 1.1: Comparison of the main attributes of indigenous and local knowledge and scientific knowledge (Berneshawi, 1997; Riedlinger and Berkes, 2001; Chilisa, 2011).

	Indigenous and local knowledge	Scientific knowledge
Dominant mode of thinking	Intuitive, holistic, general	Analytical, segmented, and specialized
Characteristics	Holistic, subjective and spiritual	Objective, tangible, often reductionist
Effectiveness:		
Data creation	- slow and inclusive	-fast and more selective
Prediction	- cyclical	-linear
Explanation	- Spiritual, includes the inexplicable	-scientific hypothesis, theory and laws
Classification	Ecological and interconnected	Genetic and hierarchical
Reason for doing the research	To reconstruct a body of knowledge to enrich mainstream thinking	To discover generalizable laws that govern the universe

Ontological assumptions	Multiple realities shaped by the diversity of human connections to the world	One reality, knowable within probability
Place of values in research process	Guided by relational accountability	Value free
Nature of knowledge	Relational	Objective
What counts as truth	The set of multiple relations with the universe	Replicable observation and measurement, verifiable hypotheses
Type of information	Mainly qualitative with some quantitative for resource use	Predominantly quantitative
Consistency	Through the cross-referencing within and between communities of cumulative observations over time	Data can be fragmented, missing variables, isolated station readings with some consistency via global observing and sustained time series
Reliability	Subjective, validated through land use, history, triangulation and local expertise	Objective but difficult to extrapolate across physical and cultural expanses
Ease of information transfer	Difficult to integrate with scientific approaches, requires community collaboration	Relatively easy
Accessibility	Time- and labor- intensive requiring community partnerships and participation	Depending on data type, can be relatively inexpensive (instrumental data from weather stations) in money, time and labor or expensive (satellite images, proxy data, in-situ observational programmes)
Kinds of questions that can be addressed	Indicators; rates of change; impact of wildlife, short-term natural variability; extremes; human adaptation to change	Amounts, highs and lows, means, difference from normal, pre-history, natural variability compared to unprecedented change, extremes, trends in global and regional weather and climate

1.7.2 Characteristics of Scientific Knowledge

Scientific knowledge is based upon principles of formal reasoning, including experimentation, scientific inference, hypothesis testing and replication, which foster both reductionist inquiry and the generalization of results (Pumaccahua et al., 2017; Table 1.1).

Scientific knowledge of the ocean and cryosphere has developed greatly during the last century. In situ observations of the ocean surface and for glaciers have increased in number and spatial coverage, and international programs have been established for systematic monitoring and archiving of data e.g., (Boyer et al., 2013; WGMS, 2017). New instrumentation (e.g., Argo ocean floats) and approaches (e.g., instrumentation on marine mammals) have enabled expansion of scientific data into parts of the ocean previously inaccessible to routine monitoring. Remote sensing from satellite missions during recent decades has provided near globally-complete information on the ocean and cryosphere surface (Dowell et al., 2013), including continuous monitoring in the remote polar regions which had little or no data prior to this development. Paleoclimate records have been developed and compiled into databases (PAGES2k Consortium, 2017) that can now provide regional-scale syntheses of ocean (McGregor et al., 2015; Tierney et al., 2015) and cryosphere (PAGES2k Consortium, 2013; Stenni et al., 2017) conditions prior to instrumental observations and before anthropogenic climate change (Jones et al., 2016). Systematic of climate model experiments (Taylor et al., 2012) have allowed for international cooperation in the production and assessment of climate model output, including experiments of future climate change scenarios where models provide the only available data source. Advances across these scientific knowledge systems have enabled detection of a range of ocean and cryosphere changes attributable to anthropogenic climate change (Section 1.3). Yet some key areas of the ocean and cryosphere are still unsampled or undersampled, and many ocean and cryosphere datasets are still short relative to the time-scales of natural variability and anthropogenic climate change (Jones and O'Neill, 2016), including the key time-scales used in this assessment report (Section 1.8.2; Figure 1.4).

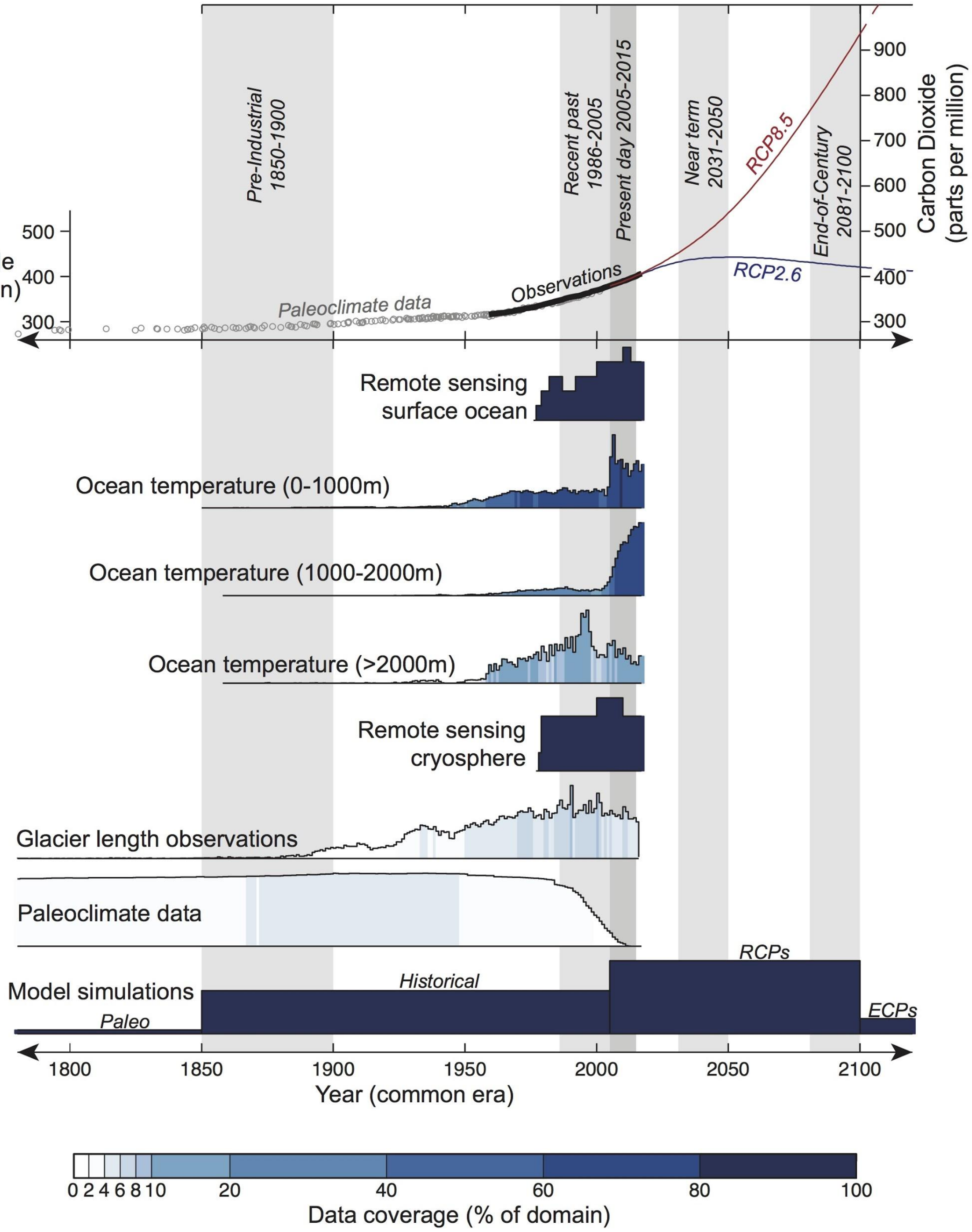


Figure 1.4: Major time periods covered in this Special Report and examples of ocean and cryosphere data coverage over these times. Upper panel displays observed (Keeling et al., 1976) and reconstructed (Bereiter et al., 2015) atmospheric carbon dioxide concentrations, as well as low (RCP2.6) and high (RCP8.5) future projections (Van Vuuren et al., 2011; Section 1.8.2.3). Lower panel gives examples of available data for the ocean and cryosphere (Boyer et al., 2013; Dowell et al., 2013; PAGES2k Consortium, 2017; Section 1.7.2; WGMS, 2017) . Heights depict the number of observations, parameters or simulations available through time expressed relative to the maximum data availability, and

colour scale depicts spatial coverage of data across the relevant domain. See Appendix 1.A: Supplementary Material text for further details. Observational data for ocean temperature, glacier length and paleotemperature represent some of the best monitored parameters for the ocean and cryosphere, and datasets of biogeochemical and ecological parameters are typically shorter and sparser than the examples shown in Figure 1.4. Shaded bars across both panels depict the key time periods referred to throughout this Special Report (Section 1.8.2.2), including pre-industrial (1850–1900), recent past (1986–2005), present day (2005–2105), near-term (2031–2050) and end-of-century (2081–2100). [PLACEHOLDER FOR SECOND ORDER DRAFT: incorporation of ILK and ecological data examples in this figure to be considered].

1.7.2.1 Ocean and Cryosphere Observations

Strong international coordination exists for standardising and maintaining ocean observations, for example through the Global Climate Observing System (GCOS, 2016). In situ platforms for ocean measurements include ocean buoys (moored and drifting), expendable bathythermographs (Cheng et al., 2016), subsurface floats as part of the Argo array (Riser et al., 2016), full-depth moorings (Cronin et al., 2012), shipboard measurements (Talley et al., 2016), tide gauges (IOC, 1997), and marine mammals equipped with scientific instruments (Roquet et al., 2017). In situ observations of temperature and salinity in the upper 2000 m of the ocean have reached near-global coverage through the Argo array, complemented by station and ship-based observations (Abraham et al., 2013). Ship-based measurements are crucial for delivering deep ocean observations below 2000 m (Purkey and Johnson, 2010; Desbruyères et al., 2016), and are indispensable for validating Argo measurements including the new capability (since 2014) for deep Argo floats that autonomously sample the ocean to 6000 m depth.

Ocean biogeochemical and biological data tends to be less extensive than physical parameters. Ship-based programs along repeated lines (e.g., Talley et al., 2016)) provide full-depth observations for biogeochemical parameters including carbon, oxygen, and nutrients. Autonomous biogeochemical platforms are also being developed (Johnson and Claustre, 2016). Systematic sampling for key biological variables, including zooplankton and fish stocks, and other higher trophic organisms, lags substantially behind the monitoring achieved for the physical and biogeochemical ocean observing systems. Thus, assessments of long-term ocean ecosystem changes are feasible only for a limited subset of variables and often restricted to a regional basis (Miloslavich et al., 2018).

Maintenance of the current global ocean observing system, and extension into currently undersampled regions (the deep ocean, shelf areas, marginal seas, and the subpolar and polar oceans) and realms (e.g., biological data), is key for improved climate change studies (Von Schuckmann et al., 2016). Purposely designed observational arrays and highly resolved ship-based hydrographic lines are also essential for monitoring climatically critical ocean regions. Examples include the recently established sampling of deep ocean circulation in the North Atlantic (McCarthy et al., 2017) and South Atlantic (Meinen et al., 2017; Meinen et al., 2018), and continuation of long-term monitoring arrays in the tropical Pacific where El Niño-Southern Oscillation (ENSO) variability originates (McPhaden et al., 2010).

In situ observations of the cryosphere in high mountains in some cases extend across multiple centuries. The Global Terrestrial Network for Glaciers (GTN-G) is the framework for the internationally coordinated monitoring of glaciers and ice caps. The network is jointly run by the World Glacier Monitoring Service (WGMS), the National Snow and Ice Data Center (NSIDC), and the Global Land Ice Measurements from Space initiative (GLIMS). WGMS collects standardized observations on changes in the mass, volume, area and length of glaciers with time (WGMS, 2017). Permafrost observation still relies on ground station networks and lacks global coverage. The Global Terrestrial Network for Permafrost (GTN-P) is the primary international programme concerned with monitoring permafrost to obtain a comprehensive view of the spatial structure, trends and variability in active layer thickness and permafrost temperature. Monitoring of the Greenland and Antarctic ice sheets, and the sea ice coverage across the polar oceans, is almost entirely based upon satellite observations. However, dedicated aircraft missions (e.g., IceBridge, AGAP, IceCap) are also yielding new observational data for the polar cryosphere, including ice sheet and sea ice thickness, sea ice concentration, ice sheet velocity.

Satellite remote sensing has provided a revolutionary capability for monitoring the surface ocean and the cryosphere (Parkinson and DiGirolamo, 2016; Visbeck, 2018). Satellite data for the ocean and cryosphere typically begins after the late 1970s (Dowell et al., 2013). In some cases these records are now long enough to robustly identify climate change trends (Henson et al., 2016), but in other locations such as the Southern Ocean and Antarctica the large magnitude of natural variability still hinders the characterisation of climate change-related trends from short satellite-based records (Jones et al., 2016). Ocean and cryosphere parameters that can be determined from satellite monitoring include sea level, sea surface temperature, salinity, ocean mass, ocean surface productivity, sea ice extent, ice sheet and glacier height and area, and snow cover.

1.7.2.2 Paleoclimate Evidence

Direct observations of the ocean and cryosphere tend to be short and scarce prior to the development of global monitoring systems in the latter part of the 20th century (Figure 1.4). This necessitates the use of indirect methods for establishing the nature of earlier ocean and cryosphere changes (Masson-Delmotte et al., 2013), including times prior to anthropogenic climate change (Jones et al., 2016). Paleoclimate records utilise the accumulation of physical or chemical properties within a natural archive that can be related to properties of the climate at the time when the archive formed. Commonly used paleoclimate evidence for ocean and cryosphere change come from marine sediments, ice layers, tree growth rings, past shorelines and shallow reef deposits. Paleoclimate records provide a long-term context for assessing if recent observed changes are unusual and attributable to anthropogenic climate change (e.g., Chapter 3; Abram et al., 2014), and provide evidence for what ocean and cryosphere changes are possible within the Earth system including abrupt climate change events (e.g., Chapter 6) and the responses to past climates that were regionally or globally warmer than present (e.g., Chapter 4; Hansen et al., 2016; Fischer et al., in review). Paleoclimate data is also important in assessing the performance of climate models across a wider-range of climate states than is possible using recent observational data alone (Flato et al., 2013).

1.7.2.3 Modelling Data

Climate models are a critical tool for testing the processes associated with past, recent and future climate change. Recent progress in model development has seen improvements in model resolution that allow fine scale processes such as ocean eddies to be resolved, and the incorporation of more elements of the Earth system. For example, ice sheets and marine ecosystems have been included in some Earth System Models since 2010. Phase 5 of the Coupled Model Intercomparison Project (CMIP5), involved 62 atmosphere-ocean general circulation models from 29 groups worldwide which ran a systematic set of experiments (Taylor et al., 2012) used in AR5 and in this report (Section 1.8.2). Climate models are idealised representations and are affected by biases due to errors in model formulation, specification of initial states and forcing, and parameterization of physical processes (Deser et al., 2012; Bopp et al., 2013; Gupta et al., 2013; Lin et al., 2016). The use of results from a wide array of models, such as the CMIP5 ensembles, provides one way of addressing model errors by assessing the range of possible outcomes produced by different models. Testing models against observational and palaeoclimate data is also important for model evaluation (Bracegirdle et al., 2016). Climate models provide the only source of data on future ocean and cryosphere change, including providing information on the outcomes of different future emission and development pathways (Section 1.8.2).

1.7.2.4 Reanalysis Data

Reanalysis products are produced through the combination of numerical modelling with in-situ and satellite-derived climate observations. They use data assimilation methods to constrain models with observations and minimize model bias to produce physically consistent global products. Input of more observations into the models allows higher temporal and spatial resolution of reanalysis products to produce a more realistic climate state. Due to the community effort on the intercomparison of ocean reanalyses and related cross-validation at an international level (Balmaseda et al., 2015), strengths and weaknesses for specific ocean reanalysis characteristics can be assessed. For example, the reanalysis skill for steric sea level and ocean heat content show considerable improvement for the upper 2000 m of the ocean where the assimilated data density is high compared to the deeper ocean (Chevallier et al., 2017; Palmer et al., 2017). Multi-analysis ensemble approaches can also be used to minimize the impact of structural uncertainty in each individual product (Chevallier et al., 2017; Palmer et al., 2017; Xue et al., 2017), and to initialize seasonal (Zhu et al., 2013) and decadal (Pohlmann et al., 2013) climate predictions.

1.7.3 Characteristics of Indigenous and Local Knowledge

Indigenous and Local knowledge (ILK) provides necessary knowledge to interact effectively with changing conditions, and to problem-solve individually and collectively. ILK is used in research and policy efforts to understand local cultural predilections and to engage affected communities and resource users (Bielawski, 1995; Crate and Nuttall, 2009; Crate and Nuttall, 2016). Increasingly, ILK is integrated into projects to facilitate site-specific understandings of, and responses to, the local effects of climate change (Barnes et al., 2013; Orlove et al., 2014), and has become integrated in global assessment reports (Beck et al., 2014; Diaz et al., 2015). ILK's diverse ways of knowing contribute richly to climate resilient development pathways. Examples of ILK related to ocean and cryosphere change are explored in each chapter of this Special Report, and in Cross Chapter Box 4.

Efforts to integrate ILK in local/regional studies and in global assessments have had advances (Obermeister, 2017), though ILK remains incompletely examined and incorporated (Ford et al., 2016b). Keyword references to Indigenous knowledge increased 60% from AR4 to AR5 (Ford et al., 2016b). Indigenous knowledge aided AR4 and AR5 in assessing the increased sensitivity of indigenous people to climate change impacts related to poverty, dependence on resource-based livelihoods, and concentration in specific geographic areas. Fuller recognition of Indigenous knowledge provides not merely a set of observations, but explanatory accounts that can guide responses and inform policy. International science-policy assessments that parallel IPCC, such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) further highlight the importance of ILK (Thaman et al., 2013). ILK complements scientific data with chronological and landscape-specific precision and detail that is critical for building scenarios and models for biodiversity and ecosystem services at broader spatial and temporal scales (Brotons et al., 2016).

A major strength of ILK is providing site and context-specific information, but this also creates challenges in extrapolating it to regional scales, or generalizing ILK beyond its origin. Regarding climate change, ILK can be difficult to apply 'to the scales and kinds of disturbance that contemporary society is exerting on natural systems' (Wohling, 2009). Moreover, there are limitations in the ability to accurately, effectively and authentically collect ILK in a manner acceptable for IPCC assessments. Researchers' efforts to translate ILK into categorical data mutes the multidimensional, dynamic and nuanced features that provide meaning and power to ILK (DeWalt, 1994; Goldman and Lovell, 2017). This can result in critical gaps due to an insufficient approach to appropriate documentation (e.g., peer-reviewed literature), and not due to the validity of the knowledge system itself (Section 1.7.4). Systematically assessing published ILK in parallel with peer-reviewed scientific knowledge provides benefits of incorporating the multiple ways of knowing to better address impacts of climatic change in the ocean and cryosphere.

[INSERT CROSS-CHAPTER BOX 3 HERE]

1.7.4 Integrating Indigenous and Local Knowledge and Scientific Knowledge

Policy formulation and environmental governance for the ocean and cryosphere in a changing climate is informed by the integration of ILK and science (Mistry and Berardi, 2016); the question is where do the two meet? Research efforts to integrate ILK have resulted in demonstrably powerful exercises that show how a community is perceiving, understanding and responding to change (Orlove et al., 2010; Crate, 2011; Marino, 2015), and the complementary addition their knowledge brings to assessments (Hou et al., 2017; Mekonnen et al., 2017). Scientific knowledge and ILK complement each other methodologically via the integration of qualitative and quantitative information, and by engaging both large climate data and people's observations and responses, to produce a more holistic understanding of ocean and cryosphere change (Huntington, 2000). There are a number of conceptual frameworks to guide meaningful and rigorous integration of ILK and scientific knowledge systems, all of which are highly context-and culture specific (Cross-Chapter Box 3).

Bridging ILK and scientific knowledge systems (Table 1.1) requires interdisciplinary or transdisciplinary approaches (Klenk and Meehan, 2015). Interdisciplinarity involves working across multiple disciplines to address complex issues. It requires large investments of both time and resources, along with researchers' willingness to engage with those outside their discipline to find common language and work towards solutions. The interdisciplinary process is especially challenging when working across quantitative and qualitative information systems, since each possesses a distinct path to scientific rigor (Strang, 2009). Transdisciplinarity goes beyond the settings of research institutions to engage relevant stakeholders, including affected communities, local and regional representatives, policy makers and managers, organisations, etc (Burnham et al., 2016). This approach faces the additional hurdle of challenging distributions of power in the use of research results that tend to favour the use of scientific assessments by an educated and economically advantaged elite (Castree et al., 2014). Transdisciplinarity can effectively integrate knowledge systems in the context of knowledge governance, a process that analytically and politically scales assessments based on locality (Obermeister, 2017).

One recent attempt to successfully create synergies across knowledge systems in global environmental assessments argues for viewing contrasting ways of knowing as dualistic (complementary) rather than as dichotomous (conflictual). This renders a Multiple Evidence Based approach that acknowledges all systems of knowledge as valid, useful and complementary (Tengö et al., 2014). Another suggests a moving away from the focus on the 'integration imperative' of necessarily integrating all knowledge inherent to a context, and towards experimenting with triangulation of knowledge systems to compose a common world. This can include using the Multiple Evidence Based approach described above, or engaging in scenario building across stakeholder groups to appreciate the multiple ways of perceiving the environment and acting within it (Klenk and Meehan, 2015).

1.8 Approach Taken in this Special Report

This report assesses literature on ocean and cryosphere change and associated impacts and responses, focusing on advances in knowledge since AR5. The literature used is primarily published, peer-reviewed scientific and social science works, although in some cases other literature sources (for example, technical reports from institutions) are used. A particular effort is made in this Special Report to incorporate sources of Indigenous and Local Knowledge (Cross-Chapter Box 3).

This Special Report does not attempt to assess all aspects of ocean and cryosphere change. A full assessment of knowledge on the physical changes in the climate system and their impacts will be undertaken in the IPCC Sixth Assessment Report (AR6). Examples of research themes that will be covered in the Sixth Assessment Report and not this Special Report include assessments of ocean and cryosphere changes in the Sixth Coupled Model Intercomparison Project (CMIP6) experiments, and a thorough assessment of mitigation options for responding to ocean and cryosphere change.

1.8.1 Methodologies Relevant to this Report

This Special Report draws, where possible, upon established methodologies and/or frameworks from across the physical and social sciences. Cross-Chapter Boxes address methodologies used for assessing risk, including cascading risks (Cross-Chapter Box 1), for examining governance options relevant to a problem or region (Cross-Chapter Box 2), and for incorporating Indigenous and Local Knowledge sources (Cross-Chapter Box 3).

Detection and Attribution assesses evidence for past and future changes in the ocean and cryosphere, relative to normal conditions (*detection*), and the extent to which these changes have been caused by anthropogenic climate change or by other factors (*attribution*) (Bindoff et al., 2013; Cramer et al., 2014). Reliable detection and attribution of changes in climate, and their effects, is fundamental to our understanding of the scientific basis of climate change and in enabling decision makers to manage climate-related risk (Hegerl et al., 2010). Statistical approaches for detection and attribution have been developed for use in the physical sciences, but confident attribution remains challenging where there are multiple or confounding factors that influence the state of the ocean and/or cryosphere (Hegerl et al., 2010). Qualitative and quantitative approaches for detection and attribution using social science data, including indigenous and local knowledge, can also provide critical information when assessing detection and attribution (Rosenzweig and Neofotis, 2013).

Ecosystem Services Framework. The Millennium Ecosystem Assessment (MEA, 2005) established a framework highlighting that natural systems provide vital life-support services to humans and the planet, including direct material services (e.g., food, timber), non-material services (e.g., cultural continuity, mental health), and many services that regulate environmental status (e,g, soil formation, water purification). This framework provides an approach that quantifies benefits for valuation and trade-off analyses that support decision-making. The ecosystem services framework has been challenged as monetizing the relationships of people with nature, and undervaluing small-scale livelihoods, cultural values and other considerations that contribute little to global commerce (Díaz et al., 2018). More recent frameworks, such as Nature's Contributions to People (NCP) (Díaz et al., 2018) used in the Intergovernmental Platform on Biodiversity and Ecosystem Services assessments, aim to better encompass the non-commercial ways that nature contributes to human quality of life . Both ecosystem services and NCP frameworks are used within the chapters of this Special Report to assess the impacts of changes in the ocean and cryosphere on humans both directly, and through changes to the ecosystems that support human life and civilisation.

Economic Methods are important for developing responses to the challenges arising from the ocean and cryosphere under a changing climate. In this Special Report, we draw mainly upon two types of economic methods:
The first type comprises economic valuation methods that attach monetary value to non-market goods. From an economic viewpoint, biodiversity is seen as part of our natural capital essential for our welfare. In order to estimate the natural capital, the Total Economic Value includes direct and indirect values, existence and non use values in order to link ecosystem valuation to human well-being. To assess the ecosystem services and the people affected, the services are categorized into provisioning services, regulating and supporting services, and cultural and recreational services. When marine ecosystems change, human economies and societies are affected. The paradigm of sustainable development with its three pillars – social, economic and environmental – and the linkages between climate impacts on ecosystem services and the consequences on sustainable development goals, such as food security or poverty eradication.

The second type of economic methods are the formal decision-analytical methods used to identify options that perform best or reasonably well given some criteria. Decision analytical methods that are widely applied for adaptation and mitigation include cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis and robust decision making. Such formal methods are specifically relevant for appraising long-term investment decisions as occurring in the context of coastal adaptation (e.g., section 4.4.5.3).

Assessing Vulnerability. This report examines vulnerability following the conceptual definition and logic presented in Section 1.4.1 and Cross-Chapter Box 1. Vulnerability is treated in relative, rather than absolute terms, and focus is given to the differential vulnerability that results from social, political, cultural, economic, institutional, geographical, and demographic factors, including social exclusion, inequalities, and differential access to and control over social, financial, and environmental resources that are required for adaptation and transformation.

Individuals, groups, and populations of humans, other species, and ecosystems are differentially vulnerable to climate change: women and girls, children and the elderly, Indigenous populations, migrants, small island states, and other groups are often more vulnerable to pressures and impacts from ocean and cryosphere change compared to more economically or socially advantaged groups (Oppenheimer et al., 2014). Socially and culturally constructed structures and institutions, e.g., gender roles, age, ethnicity, discrimination, and economic marginalization, can increase climate change vulnerability and reduce adaptive capacity (Oppenheimer et al., 2014). For instance, Indigenous populations often experience greater climate change risks due existing social inequities and reliance upon oceans and cryosphere for subsistence, cultural identity and spiritual sustenance (Whyte, 2014; Ford et al., 2016b; Brugnach et al., 2017). Importantly, vulnerability is not static or homogeneously experienced individual, group, and population vulnerability to climate change is dynamic and diverse, and reflects changing societal and environmental conditions.

1.8.2 Scenarios, Baselines, and Time Frames Considered

1.8.2.1 Temporal and Spatial Scales

The time scales of ocean and cryosphere change vary from daily to decadal, from centuries to many millennia. This report assesses past ocean and cryosphere changes mainly on decades to century scales, but also documents daily to interannual changes in the context of climate extremes and natural hazards. Projections of future climate change are derived from climate models on timescales from hours to centuries, and at both global and regional scales. The spatial scales relevant to ocean and cryosphere change may range from local (less than 100,000 km^2), through regional (100,000 to 10 million km^2) to continental (10 to 100 million km^2) and global. In the context of climate model outputs, regional generally refers to a high-resolution model that is embedded within a discrete spatial area of a lower-resolution global climate model in order to investigate specific climate processes and changes relevant to local to continental-scale climate conditions.

1.8.2.2 Baselines and Time Periods

Baseline indicates a reference period relative to which changes are calculated. In the context of anthropogenic climate change, the baseline should ideally approximate 'pre-industrial' conditions before human influences on the climate became significant. The period 1850–1900 was used as a 'pre-industrial' baseline in AR5 and SR1.5 [PLACEHOLDER FOR SR1.5] for assessing historical and future climate change. This period includes several major volcanic eruptions and greenhouse gas concentrations and surface temperatures had already started to rise during this interval (Jones et al., 2016; Hawkins et al., 2017). However, the scarcity of reliable ocean and cryosphere observations for earlier periods represents a major challenge for quantifying earlier ideal pre-industrial states (Figure 1.4). This report uses, wherever possible, the 1850–1990 pre-industrial baseline period for consistency with other IPCC reports.

A 'present-day' reference is critical to assessments of current climate conditions in order to avoid conflating uncertainty in past and future changes (e.g., Millar et al., 2017). In this report, the 1986–2005 interval (used in AR5) is referred to as the 'recent-past' reference period, while a 2005–2015 period is used for 'present-day'. The 2005–2015 reference interval incorporates near-global ocean and cryosphere data coverage (section 1.7.2), and it aligns this report with a more current reference than the 1986–2005 reference adopted by AR5. The caveat is that the 11-year 'present-day' period is short and may be modulated by natural climate variability: for instance, the 2005–2015 interval sits during the negative phase of the Pacific Decadal Oscillation (PDO) which resulted in a temporarily reduced rate of global atmospheric warming (England et al., 2014).

This report commonly provides future change assessments for two key intervals: A 'near-term' interval of 2031-2050 is used to represent a policy-relevant timeframe that is important, for example, to the Sustainable Development Goals. An 'end-of-century' interval of 2081–2100 represents the average climate conditions reached at the conclusion of the standard CMIP5 RCP simulations (1.8.2.3). In some cases, such as the assessment of future sea level rise where changes may be committed or irreversible over multi-century timescales, this report also considers model evidence for 'long-term' changes beyond the end of the current century (Figure 1.4).

In this Special Report, timeframes are also relevant for the assessment of the significance and rates of ocean and cryosphere change. The inhomogeneity and often short observational records of the ocean and cryosphere represent a challenge for applying consistent methods and time intervals in trend assessments across the chapters of this report, although more consistency in approach is possible for assessments based on model output. Also relevant is the concept of 'Time of Emergence', which requires decisions on the baseline interval, the method of characterising the range of natural variability during that baseline interval, and the method for determining the long-term climate state. In the chapters of this Special Report, assessments of trends and the Time of Emergence provide details of these methodological choices as they are relevant to a particular case of ocean and/or cryosphere change.

1.8.2.3 Scenarios and Pathways

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Climate model simulations of the future use a set of plausible radiative forcing pathways based on assumptions about demographic and socioeconomic development and technological change. Representative Concentration Pathways (RCP) are time series of future greenhouse gas concentrations, aerosols and chemically active gases, as well as land use changes (Moss et al., 2008). RCPs usually refer to the portion of the concentration pathway extending up to 2100, while extended by Extended Concentration Pathways (ECPs) continue from 2100 to 2500. There are four pathways, identified by their approximate total radiative forcing in 2100 (relative to 1750): 2.6 W m^{-2} (RCP2.6), 4.5 W m^{-2} (RCP4.5), 6.0 W m^{-2} (RCP6.0), and 8.5 W m^{-2} (RCP8.5). For RCP2.6 radiative forcing peaks and declines during the 21st century and this is the pathway considered most compatible with the Paris Agreement goals of limiting global warming to well below 2°C (Rogelj et al., 2018); For RCP4.5 radiative forcing stabilizes by 2100; and for RCP6.0 and RCP8.5, radiative forcing does not peak by year 2100. The RCPs were used as input for the CMIP5 future climate experiments (Taylor et al., 2012) used to assess future climate change in AR5.

Within this Special Report, assessments of future change are based on results from RCP-based experiments wherever possible. In some cases, however, assessments will rely upon the earlier Special Report on Emission Scenarios (SRES) scenarios (Nakicenovic and Swart, 2000) used in AR3 and AR4. With respect to the radiative forcing, RCP4.5 is close to SRES B1, RCP6 is close to SRES A1B, and RCP8.5 is somewhat higher than A2 and close to the SRES A1FI scenario. RCP2.6 is lower than any of the SRES scenarios (Cubasch et al., 2013; Stocker et al., 2013).

The RCPs are complemented by the Shared Socio-economic Pathways (SSPs), which allow future scenarios to be structured according to varying socio-economic challenges to adaptation and mitigation. The SSPs describe alternative socio-economic futures comprising: sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fuelled development (SSP5) (Kriegler et al., 2016; Riahi et al., 2017). Socioeconomic drivers, comprising population and education, economic growth, and urbanisation, are quantified for all SSPs.

1.8.3 Communication of Certainty in Assessment Findings

This Special Report aims to use a common, calibrated language for the treatment of certainty in the assessment process. This follows practices developed in previous IPCC assessments for evaluating and communicating the degree of certainty in expert judgements (Mastrandrea et al., 2010b). The calibrated language is designed to reflect uncertainties that arise from incomplete knowledge due to a lack of information, or from disagreement about what is known or even knowable. Uncertainty may have many types of sources, from imprecision in the data, to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. The IPCC calibrated language conveys certainty levels that can be based on quantitative expressions of the likelihood of a finding, or qualitative expressions of confidence based on the amount, consistency and robustness of evidence for a finding.

Quantitative expressions (likelihood scale) are used where findings can be attributed with a probabilistic estimate. In the scientific literature, a finding is often said to be significant if it has a likelihood exceeding 95% confidence; that is, there is a less than 5% probability of the result occurring by chance. Using calibrated IPCC language, this level of statistical certainty would use the term *extremely likely*. Language to describe probabilistic likelihoods is provided in Table 1.2a. Findings with a quantified likelihood of less than 5% are also considered significant, but represent findings that are *extremely unlikely*. Where a range of estimates is produced, for example in assessing results from a large ensemble of climate model simulations, a 5-95% confidence interval is commonly used to report the range of likely outcomes.

Qualitative expressions (*confidence scale*) are used to describe the validity of a finding based on the type, amount, quality and consistency of evidence, and the degree of agreement between different lines of evidence. Table 1.2b defines the IPCC calibrated language scale used to describe confidence. *Very high* and *high* confidence findings are those that are supported by multiple lines of robust evidence with high agreement. *Low* or *very low* confidence describe findings for which there is limited to medium evidence and low to medium agreement among different lines of evidence, and are only presented in this Special Report if they address a major topic of concern.

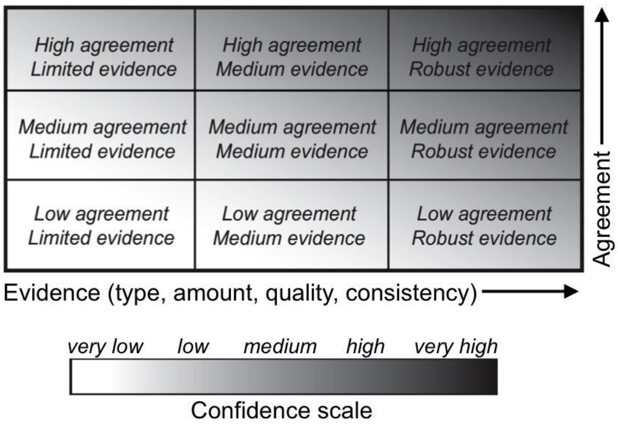
In some cases, *deep uncertainty* may exist in the current scientific assessment of the rate, timing and scale of future changes in the ocean and cryosphere in a changing climate. Nevertheless, comprehensive risk assessment that informs adaptation planning would also address such highly uncertain changes that could have catastrophic consequences (Cross-Chapter Box 4).

Table 1.2: IPCC uncertainty language for a) likelihood and b) confidence after (Mastrandrea et al., 2010b). In b, confidence increases towards the top-right corner as suggested by the increasing strength of shading.

a. Likelihood

Uncertainty language	Statistical likelihood
Virtually certain	99–100% (>99%)
Extremely likely	95–100% (>95%)
Very likely	90–100% (>90%)
Likely	66–100% (>66%)
More likely than not	50–100% (>50%)
About as likely as not	33–66% (33–66%)
Unlikely	0–33% (<33%)
Very unlikely	0–10% (<10%)
Extremely unlikely	0–5% (<5%)
Exceptionally unlikely	0–1% (<1%)

b. Confidence



High agreement *Limited evidence*	*High agreement* *Medium evidence*	*High agreement* *Robust evidence*
Medium agreement *Limited evidence*	*Medium agreement* *Medium evidence*	*Medium agreement* *Robust evidence*
Low agreement *Limited evidence*	*Low agreement* *Medium evidence*	*Low agreement* *Robust evidence*

[INSERT CROSS-CHAPTER BOX 4 HERE]

1.9 Integrated Storyline of this Special Report

This IPCC Special Report assesses current knowledge on the Ocean and Cryosphere in a Changing Climate. Each chapter presents an integrated storyline that brings together knowledge on why the ocean and cryosphere are important; how and why they are changing; what, where and for whom this brings risks and opportunities; and what the response options and outcomes of our choices could be.

The chapters that follow in this Special Report are framed around geographic or climatic aspects where the oceans and/or cryosphere are particularly important for ecosystems and human systems. Chapter 2 assesses *High Mountain Areas*, where the cryosphere represents a life-giving freshwater resource as well as a source of hazards to mountain and downstream populations. Chapter 3 moves to the *Polar Regions* of the northern and southern high latitudes, which are characterised by vast stores of frozen water in ice sheets, glaciers, ice shelves, sea ice and permafrost, and by the interaction of these cryosphere elements and the polar oceans with the ecosystems and people that depend on them. Chapter 4 brings together elements of ocean and cryosphere change relevant to the local, regional and global impacts of *Sea Level Rise on Low-Lying Regions, Coasts and Communities*. Integrative Cross-Chapter Box 5 is further dedicated to *Low-Lying Islands and Coasts* and highlights the multitude of ways in which these regions are vulnerable to the impacts of ocean and cryosphere change, along with resilience and adaptation strategies, opportunities and governance options specific to these settings. Chapter 5 focuses on the *Changing Ocean*, with a particular focus on how climate change impacts on the ocean are altering *Marine Ecosystems* and affecting *Dependent Communities*. Chapter 6 is dedicated to assessing *Extremes* and *Abrupt Events*, and reflects the potential for rapid and possibly irreversible changes as climate change alters Earth's oceans and cryosphere and the challenges this brings to *Managing Risk*.

[START CROSS-CHAPTER BOX 1 HERE]

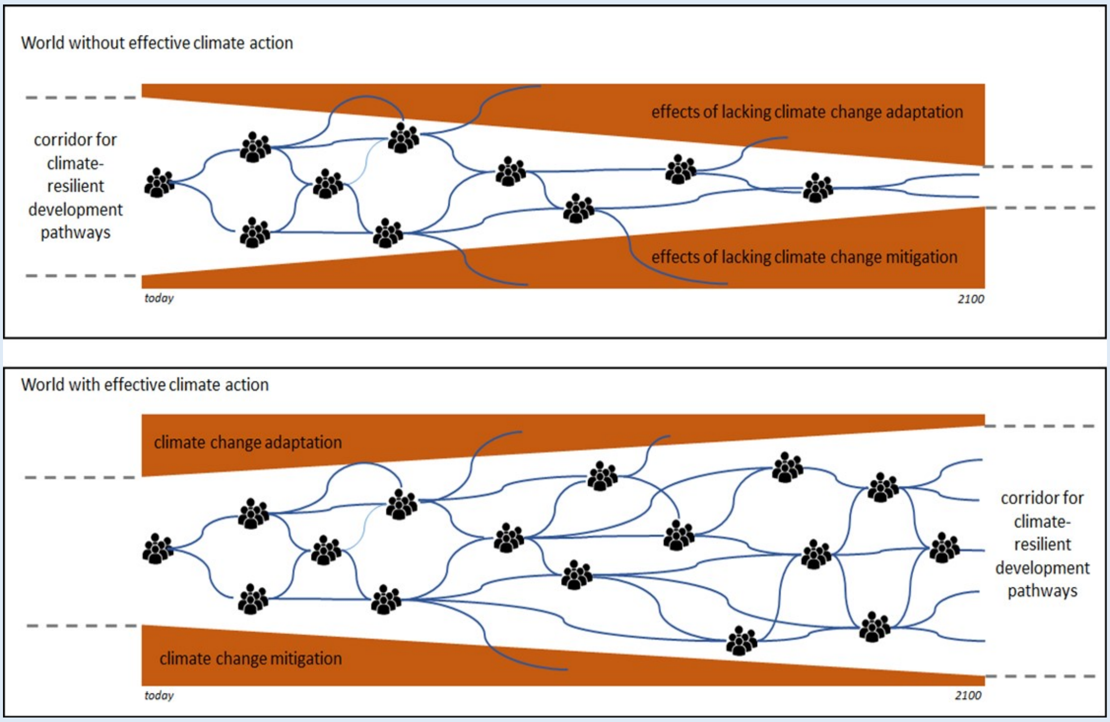
Cross-Chapter Box 1: IPCC Conceptual Risk and Resilience Framework

Authors: Matthias Garschagen (Germany), Susie Crate (USA), Hélène Descombe (Fiji/France), Bruce Glavovic (New Zealand/South Africa), Sherilee Harper (Canada), Elisabeth Holland (Fiji/USA), Gary Kofinas (USA), Sean O'Donoghue (South Africa), Ben Orlove (USA), Zita Sebesvari (Germany/Hungary), Martin Sommerkorn (Norway/Germany)

Climate change-related effects on the ocean and cryosphere add stress and shocks to ecosystems and humans, hence, highlighting the importance of resilience as an analytical and normative concept to understand and guide the trajectories of social-ecological systems. Resilience is understood here as the capacity of social, economic and environmental systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain the system's essential function, identity and structure (Agard et al., 2014). The literature on resilience offers many perspectives on the concept. It is often defined as a positive attribute of systems and an aspirational goal (Steiner, 2015), which helps to explain the concept's recent popularity in science, policy and practice and its capacity to bridge between disciplines and convene actors (Davoudi, 2012). From this perspective, resilience is beneficial when it maintains the capacity for adaptation, learning and transformation (Walker et al., 2004). Others define it descriptively as a system property that is neither good nor bad (Weichselgartner and Kelman, 2014). Following this definition, a system can also be highly resilient in keeping its unfavoured attributes such as poverty or social exclusion.

There have been critiques of the concept and its applications to social systems, for example, arguing that endeavors for resilience-building often tend to shift responsibility onto the shoulders of vulnerable and resource-poor populations (e.g., Chandler, 2013; Reid, 2013; Rigg and Oven, 2015; Tierney, 2015; Olsson et al., 2017). However, despite these concerns, 'resilience thinking' invites an emphasis on system dynamics, often not captured in conventional risk and vulnerability analyses, such as tipping points, regime shifts, the role of fast and slow variables, feedbacks, cross-scale interactions, system complexity, uncertainty and emergence, surprise, and the potential of human agency in transforming a social-ecological systems and their trajectories. Resilience thinking further urges scientists, risk practitioners and decision makers to accept that climate-change related shocks, crises and risks oftentimes cannot be fully mitigated or avoided despite adaptation action, especially in at the low-lying coast, in high mountains and polar regions. Resilience thinking, therefore, stresses the need to build and maintain systems' capacity to navigate such shocks, crises and risks (Varma et al., 2014; Sud et al., 2015).

The term climate resilient development pathways is gaining prominence as a forward-looking perspective for scientific assessments and policy trajectories. A relatively new concept, it describes sustainable development pathways that combine adaptation and mitigation to reduce climate change and its impacts, including an iterative process to ensure effective risk management today and in the future [PLACEHOLDER FOR SECOND ORDER DRAFT: SR1.5]. It builds on the related concept of adaptation pathways which has been used to map critical future decision points, their respective options for policy and action, as well as potential trajectories for each option (Haasnoot et al., 2013; Wise et al., 2014; Fazey et al., 2016) (Cross-Chapter Box 1, Figure 1). This approach also provides an opportunity to consider cultural, social, and ecosystem factors that can influence the decision-making process in any multi-stakeholder governance setting and the sustainability of adaptation measures. The concept of climate resilient development pathways stresses the implications of climate action and its timing for development options, corridors and outcomes. As illustrated in Cross-Chapter Box 1, Figure 1, the lack of adequate climate change mitigation and adaptation over time will limit the options for resilience-building and the space for sustainable development pathways. This pathways approach has been successfully used at local levels, including with remote and disadvantaged communities, also showcasing the potential to counter maladaptative choices (e.g., Barnett et al., 2014; Butler et al., 2014; Maru et al., 2014). Furthermore, this approach provides a narrative of hope and opportunity that can extend beyond risk reduction and coping (Amundsen et al., 2018). Although climate change impacts on oceans and cryosphere elicit many emotions—including fear, anger, despair and apathy (Cunsolo Willox et al., 2013; Cunsolo and Landman, 2017; Cunsolo and Ellis, 2018)—narratives of hope are critical in provoking motivation, creative thinking and behavioural changes in response to climate change (Myers et al., 2012; Prescott and Logan, 2018). For instance, research has demonstrated that eliciting hope significantly increases climate policy support and activism (Smith and Leiserowitz, 2014; Feldman and Hart, 2016; Feldman and Hart, 2018); as such, hope is considered an asset in climate resilient development pathways.

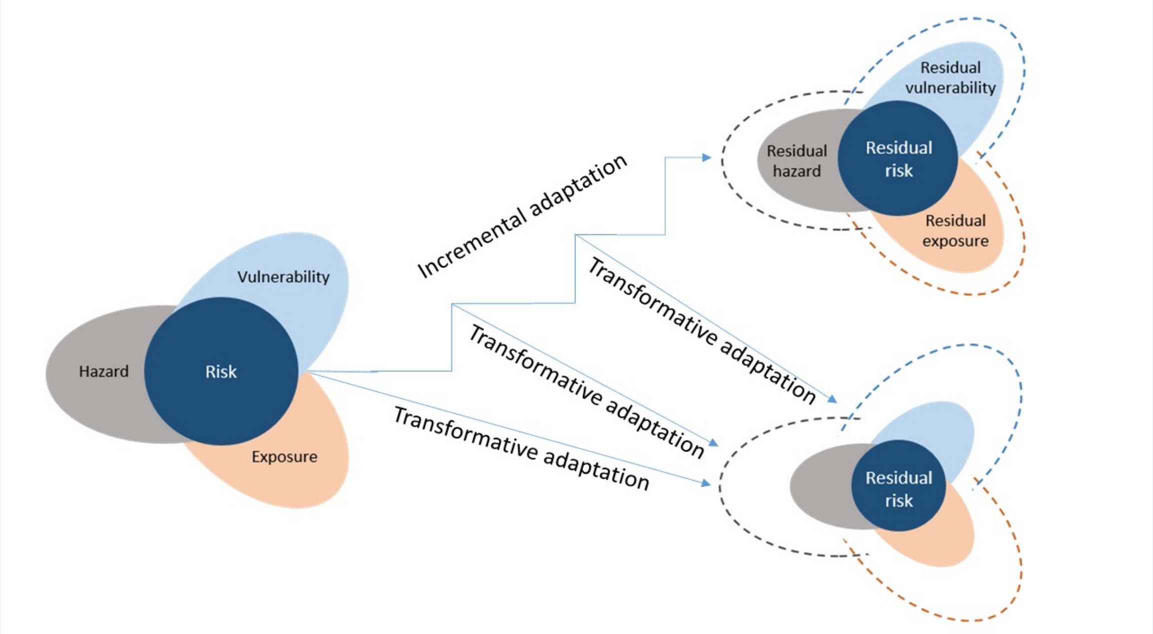


Cross-Chapter Box 1, Figure 1: The concept of climate resilient development pathways.

Pursuing climate resilient development pathways implies action for climate risk reduction and climate change adaptation. Both spheres are causally linked since climate risk can be reduced through adaptation although residual risks usually remain (Cross-Chapter Box 1, Figure 2). Adaptation, in the context of this report, is a process in which the exposure and vulnerability of human and natural systems is reduced to the hazards emerging from climate change-driven changes in the ocean and cryosphere. It can happen in response to observed or anticipated hazards, yet the precautionary type in many contexts allows for better planning and more effective reduction of risks and mitigation of potential losses (Grothmann and Reusswig, 2006). It focuses particular attention on processes of adjustment that seek opportunities to reduce harm and realise beneficial opportunities, including building capacity to cope with climate impacts. In some cases, risk reduction can also be achieved through direct influence on the hazard (e.g., by reducing urban flooding through flood retention areas), in addition to long-term climate change hazard mitigation through emission reductions (Chapter 4). In ecological systems, especially in managed ecosystems, human intervention can serve to enable ecological adaptation with concomitant human benefits (Chapter 4).

Despite adaptation, residual risks with respect to the effects of climate change-related hazards in the ocean and cryosphere are likely to remain (*high confidence, high agreement*). Their type, level and timing will continue to depend on the inertia in the climate, ocean and cryosphere system, the level of future anthropogenic climate change forcing and the level of effectiveness of adaptation across geographical scales and time. In the policy field, these residual risks have increasingly been linked to the emerging debate on loss and damage (Huq et al., 2013; Warner and van der Geest, 2013).

Much of the literature published since AR5 has in this context emphasized the need for societal transformations in relation to climate change, not only for enabling climate change mitigation (most notably to decarbonize the economy) but also for adaptation (e.g., Pelling et al., 2015; Few et al., 2017). Transformative adaptation is therein understood to imply fundamental changes in the attributes and configurations of a system or process (O'Brien, 2012; Pelling et al., 2015), e.g., a legal system or cultural convention for coastal development planning and risk reduction (Solecki et al., 2017). It becomes necessary when incremental adaptation through limited gradual adjustments and the retching-up of existing adaptation practices cannot reduce risks and impacts to an acceptable level. Transformative adaptation therefore commonly involves fundamental modifications of policies, policy-making processes and cultural values (Pelling et al., 2015; Solecki et al., 2017). Examples related to changes in the ocean and cryosphere include, shifting from protection paradigm to living with (salt)water as a response to (coastal) flooding (Renaud et al., 2015) or fundamental risk management changes in coastal megacities, including retreat (Solecki et al., 2017). Transdisciplinary research, in collaboration of actors from science, policy, practice, civil society and the public, has been instrumental in examining how positive transformation can be fostered in different governance contexts (Padmanabhan, 2017) (Cross-Chapter Box 2). However, this field of research is still young and many questions still remain unresolved, particularly when viewing at the persisting gap between an increasing body of knowledge on climate change and its (potential) impacts and the inertia in action towards transformation.



Cross-Chapter Box 1, Figure 2: Linkages between risk reduction, adaptation, transformation and residual risk.

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[END CROSS-CHAPTER BOX 1 HERE]

[START CROSS-CHAPTER BOX 2 HERE]

Cross-Chapter Box 2: Governance of the Ocean, Coasts and the Cryosphere under Climate Change

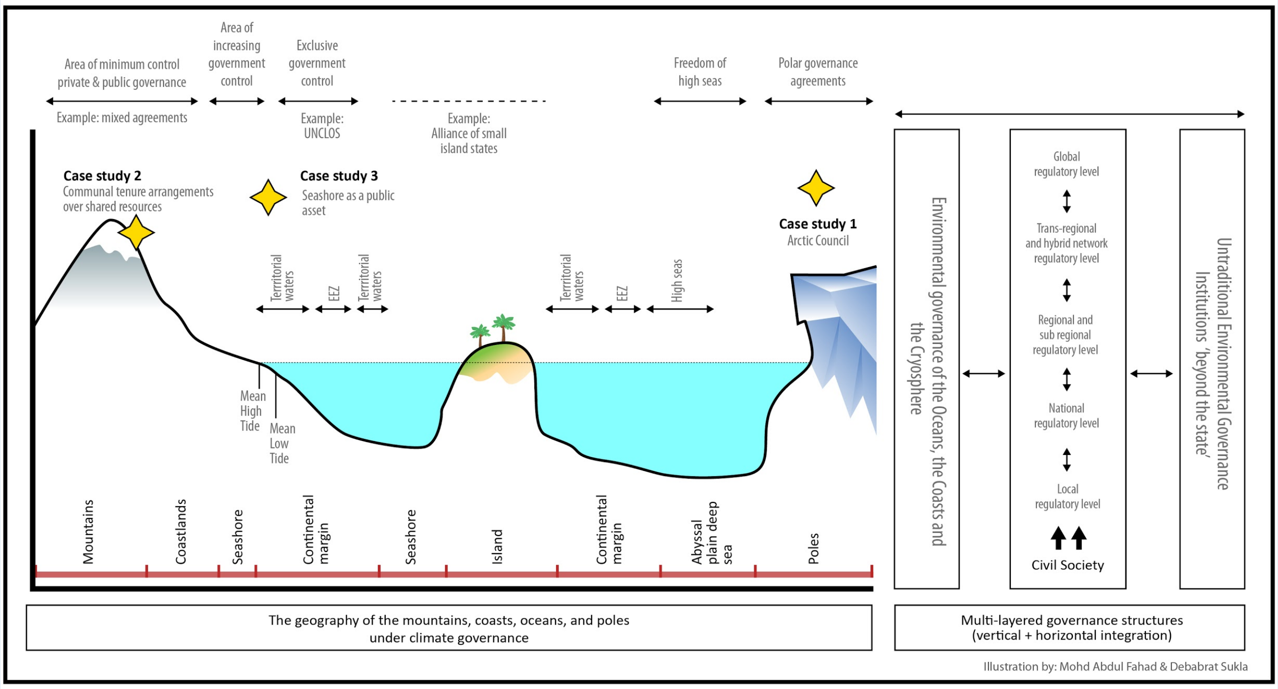
Authors: Anjal Prakash (Nepal/India), Sandra Cassotta (Denmark/Italy), Bruce Glavovic (New Zealand/South Africa), Jochen Hinkel (Germany), Saiful Karim (Australia), Ben Orlove (USA), Beate Ratter (Germany), Jake Rice (Canada), Evelia Rivera-Arriaga (Mexico), Catherine Sutherland (South Africa)

This cross chapter box defines environmental governance concepts and illustrates governance challenges and emerging solutions for the ocean, coasts and the cryosphere under a changing climate, drawing upon three diverse case studies of - the international law of the sea; mountain governance in Gilgit-Baltistan, Pakistan; and coastal governance in Cape Town, South Africa. The box concludes by exploring ways of moving forward to a more resilient and sustainable future for the ocean, coasts and the cryosphere.

Environmental Governance under a Changing Climate

Governance is a broad concept used in a variety of research fields with different meanings. In SROCC, environmental governance is used to refer to the efforts of establishing, applying and modifying governance structures and institutions that help in regulatory processes, mitigate conflicts and realizing mutual gains associated with environmental resources, sinks and risks (Williamson, 2000; Paavola, 2007; Lockwood et al., 2010). Governance may be an exclusive act of governments (e.g., a government passing formal regulation or facilitating actors to respond more effectively to climate change), or a collaborative effort amongst local actors governing themselves through customary law, or a multi-level effort involving actors from governments, the private sector and the civil society (Paavola, 2007). Institutions are formal and informal social ‘rules’ that influence and partially shape individual behaviour and social interactions (North, 1990; Ostrom, 2005; Hodgson, 2006). Formal institutions include constitutions, laws, policies, contracts, etc. and informal ones include customs, taboos and social norms. Already existing and newly emerging governance structures and institutions, shape roles and responsibilities of actors in the face of climate change. They inform how decisions are made and who can exercise power within governance processes (Graham et al., 2003).

In the face of changing climate, two specific challenges arise for the governance of the Coast, the Ocean and the Cryosphere. First, climate change has introduced transboundary and global conflicts between users of atmospheric sinks and those affected by climate change impacts. Addressing this challenge requires cooperation and institutions across national borders, which are more difficult to establish than within national borders, because in the former case there is no sovereign, state-like entity which could foster, monitor and enforce the implementation of solutions (Kaul et al., 1999; Barrett, 2005; Walker et al., 2009). Second, climate impacts progressively alter existing, or introduce new environmental and social challenges, changing relationships between actors, which in turn requires continuous efforts to adapt governance structures and institutions (Bisaro and Hinkel, 2016; Roggero et al., 2018). These challenges and emerging solutions are illustrated in the following three case studies. Cross-Chapter Box 2, Figure 1 shows the complexities of governance challenges in this context.



Cross-Chapter Box 2, Figure 1: The complexity of governance of the ocean, coasts and the cryosphere.

Case Study 1 — Multi-level Regulatory Interactions and Informal Actors for the Ocean and Cryosphere: Sea level rise (SLR) and ice-melting change the low-water line of coastal states, hence reducing their maritime territory and resources, as well as their coastal rights, or even leading to complete loss of them [PLACEHOLDER FOR SECOND ORDER DRAFT: reference needed for International Law Association, 2012]. These challenges have not been addressed by major legal frameworks for oceans, such as the United Nation Convention on the Law of the Sea (UNCLOS) (Rayfuse and Scott, 2012; Andreone, 2017; De Lucia, 2017; Grip, 2017). A challenge reducing the effectiveness of existing governance structures, is the lack of precision in the formulation of the 'law of the sea' provisions, enforcement, compliance, monitoring and dispute settlement mechanisms (Vidas, 2000; Louka, 2006; Karim, 2009; Karim, 2015; De Lucia, 2017). There is *medium agreement* that these challenges are in the process of being addressed by shifting from traditional international law to multi-level and informal governance structures involving not only states, but also informal civil society actors (including indigenous people) (Vidas, 2000; Cassotta, 2012; Young, 2012; Shadian, 2014; Young, 2016; Andreone, 2017). Evidence of this shift taking place is found in the Arctic Council (AC), a hybrid governance structure blending new forms of formal and informal multilevel regional cooperation for climate mitigation and adaptation in the Arctic, employing mainly soft law mechanisms that draw upon best available practices and standards (Cassotta and Mazza, 2015; Pincus and Ali, 2015). The AC is too small to deal with global and transnational impacts of climate change (Young, 2016) but has amplified the voice of Arctic people affected by the impacts of climate change i.e., by producing the Arctic Climate Impact Assessment and disseminating its findings (Cassotta et al., 2016; Koivurova, 2016).

Case Study 2 — Mountain Governance in Gilgit-Baltistan, Pakistan: Gilgit-Baltistan is an arid administrative territory in a mountainous region of northern Pakistan. Streams fed by snow and glacier meltwater supply irrigation water for rural livelihoods (Nüsser and Schmidt, 2017). The labour-intensive work of constructing and maintaining gravity-fed irrigation canals has largely been carried out by traditional community associations known as *jirga*. As glaciers retreat with climate change, water sources located at the edge of glacier, have dried up, reducing the availability of irrigation water. To cope with water scarcity, villagers constructed new channels from streams, located at some distance across rugged terrain to irrigate croplands, pastures and woodlots (Parveen et al., 2015). To carry out this substantial task, a new kind of cross-scale governance structure emerged. Villages received financial, logistical and organizational support from an international donor, the Aga Khan Development Network (AKDN). This network was established to alleviate poverty, and has developed deep connections with the communities, drawing on local residents for staff (Walter, 2014). This structure benefited the communities by giving them resources, training and networks. It benefited the donor as well, since it was seeking to broaden its base of communities and projects. Nevertheless, the coalition faces three current and potential threats. Firstly, some newly built canals have been damaged by landslides which may be increasing due to incessant rains due to changing climate. Secondly, the local streams flow into the Indus River, which is governed by the Indus Water Treaty (1960) between India and Pakistan. A breakdown of this relatively stable agreement, possibly stimulated by decreasing water supplies caused by glacier retreat across South Asia, could have cascading impacts on water management throughout the entire Indus watershed, including in Gilgit-Baltistan (Uprety and Salman, 2011). Further, the expansion of Pakistan's hydropower may lead to inundation and displacement of the villages (Shaikh et al., 2015).

Case Study 3 — Coastal Governance in the City of Cape Town, South Africa: Rising sea level and coastal flooding form the focus of the City of Cape Town's coastal climate adaptation efforts. The Milnerton coastline experiences significant coastal erosion due to climate change. The High Water Mark is moving landwards, intersecting with private property boundaries and producing a governance dilemma. The dune cordon will be lost if no remedial action is taken. Private property and municipal infrastructure will be flooded and damaged in storm conditions (Brundrit, 2016). The city risks losing a racially and socio-economically diverse, transformative public space, the Milnerton Beach (Sowman et al., 2016). Private property owners have employed a mixture of informal and illegal hard and soft measures to protect their assets. These ad hoc interventions are cumulatively creating additional erosion impacts on the coastline. Legally the City of Cape Town is not responsible for remediating private land as a result of coastal erosion, but its officials feel compelled to take action for the common good (Smith et al., 2016; Whittal, 2016). City officials, through their progressive approach to climate adaptation, are pioneering a participatory approach for addressing the impacts of climate change in Milnerton. This represents a shift away from a legalistic, hierarchical, state-centric, technical and compliance approach to coastal management (Cartwright et al., 2012; Colenbrander et al., 2015). Multiple stakeholders are being included in a participatory process, which is mindful of international frameworks on climate change and responsive to national and provincial legislation and policy, so as to open up ongoing dialogue and co-construct knowledge to jointly find workable solutions to reduce the 'transfer of risk'. A major challenge will be navigating the politics which will be triggered by this consultative process

Ways Forward

The three cases illustrate that governance solutions are emerging in response to new challenges arising in the face of climate change. Specifically, the cases show the emergence of innovative participatory (i.e., South Africa) and network governance structures (i.e., the Arctic Council and the coalition between Aga Khan Development Network and the community of Gilgit-Baltistan). They all reflect the formation of informal and flexible networks and hybrid governance structures amongst state, private and civil society actors, which are recognized as promising solutions specifically for environmental governance challenges (Newig and Fritsch, 2009).

Despite these new approaches, a range of challenges remain within the cases and beyond, and it is unclear how governance structures and institutions will develop as climate change progressively introduces more severe environmental conflicts. To address such deeply uncertain future changes, the environmental governance literature has proposed governance designs such as adaptive governance (Folke et al., 2005) and transformative governance (Chaffin et al., 2016). These designs combine a range of principles that have either been empirically observed to be effective in specific cases (e.g., multi-level governance) or derived from ethical considerations. The latter include good governance (Reed et al., 2010; Zurba et al., 2012) and deliberative governance (Dryzek, 2012; Glavovic, 2016), postulating that governance processes should be inclusive, fair, deliberative, support learning and be respectful of ethical pluralism. Comparison across case studies have, however, found limited generalizable evidence on the environmental performance of these design principles. In the governance literature there is strong agreement that solutions are generally context specific. More empirical research is needed to determine which of these principles have broader transformative value for effective climate change governance (Ostrom, 2007; Young et al., 2008; Newig and Fritsch, 2009).

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[END CROSS-CHAPTER BOX 2 HERE]

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Cross-Chapter Box 3: Indigenous and Local Knowledge

Authors: Susie Crate (USA), William Cheung (Canada), Sherilee Harper (Canada), Hélène Jacot Des Combes (Fiji/France), Ben Orlove (USA), Anjal Prakash (Nepal/India), Martin Sommerkorn (Norway/Germany)

Introduction

Indigenous and local knowledge (ILK) is a critical component of understanding the ocean and cryosphere and of assessing and responding to impacts of climate change on these systems. ILK is recognized by a number of international organizations, including the United Nations Environment Programme (UNEP), United Nations Development Programme (UNDP), United Nations Educational, Scientific and Cultural Organisation (UNESCO), Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES) and the World Bank. Though discussed in AR4 and AR5, among other global assessments, ILK remains incompletely examined and incorporated (Ford et al., 2016a; Obermeister, 2017). The SROCC Section 1.7 discusses ILK and compares it to scientific knowledge in Table 1.1 and Chapters 2 to 6 demonstrate the relevance of ILK in case contexts.

Scientific recognition of ILK developed simultaneously with early exploration and colonialism (Achan et al., 2011), but the need to engage ILK in environmental and climate management is relatively recent. For example, Alaskan Inuit, who rely on bowhead whales for subsistence, formed the Alaska Eskimo Whaling Commission in response to a scientific report that erroneously estimated the bowhead whale population in decline. This commission facilitated a recount using the visual, sonic and aerial observations of Indigenous knowledge, delivering an accurate population estimate indicating a stable population (Huntington, 2000: 1272). Additionally, in some cases, ILK holders integrate systems. Mi'kmaw Elders' concept of Two Eyed Seeing, is 'learning to see from one eye with the strengths of Indigenous knowledges, and from the other eye with the strengths of Western [scientific] knowledge, and using both these eyes together for the benefit of all' (Bartlett et al., 2012). This allows 'a weaving back and forth' between diverse ways of knowing that preserves the distinctiveness of each, while allowing for fuller understandings and actions (Bartlett et al., 2012).

Observations, Responses, and Governance

Observations, responses and governance are ILK's three important contributions to the understanding of climate change in the ocean and cryosphere, and to the planning, implementation, evaluation and modification of activities to respond and adapt to climate change risks and impacts.

Observations: ILK observations of ocean and cryosphere systems include glacier extents, sea ice, permafrost dynamics, coastal processes, etc. (Section 1.2), and how these processes interact with social factors and other drivers of change (West and Hovelsrud, 2010; Cruikshank, 2012). While Indigenous peoples and local populations have observed climate changes continuously, researchers are increasingly documenting ILK observations in the last decades (Crate et al., 2008; Marino, 2015) (Sections 2.3.1.1, 2.4.1.1).

Responses: ILK informs responses in many settings, such as changing irrigation techniques, foraging at altered seasonal times, developing alternative modes of transport (Section 2.4.1.4.1), resting largely on ILK, (Yager, 2015; Dangi et al., 2017), and sometimes integrated with scientific knowledge (Nüsser and Schmidt, 2017). This knowledge system integration depends upon the continued development, accumulation and transmission of local and/or indigenous knowledge (Pearce et al., 2015) on one hand and the availability of scientific knowledge, brought into a people's specific ecological and cultural context (Crate and Fedorov, 2013) on the other. For example, using place-based [local] knowledge for successful adaptation in coastal communities (O'Neill and Graham, 2016), ILK facilitates the incorporation of local priorities into adaptation initiatives (Section 2.4.7).

Governance: ILK supports the incorporation of Indigenous and local institutions, which have developed and maintained ILK, into decision-making and policy-making about climate issues (Karlsson and Hovelsrud, 2015). Examples include the involvement of Indigenous communities in planning for disaster risk reduction in response to cryosphere hazards (Carey et al., 2015). As researchers using indigenous (decolonized) methods have shown, collaborative engagement of communities and stakeholders supports the inclusion of multiple knowledge systems towards solutions (Smith, 1999; Chilisa, 2011; Sections 2.4.1.3.1, 2.4.3.3, 5.4.2).

ILK Trajectories in a Changing Climate

A broad sweep of the literature shows how a variety of forces, often historically-grounded in colonial regimes, many of which continue today (Simpson, 2004; Alfred and Corntassel, 2005), affect the use and continued perpetuation of ILK, both within management frameworks and in the social context of communities (Spoon, 2011). Although many research efforts find ILK use flourishing (Thornton and Scheer, 2012), there also exist contexts where it is in decline. In Nepal's glacial-fed Kailash Sacred Landscape researchers documented 56 types of LK practices on decline due to the influx of knowledge from outside the area, a decrease of plant resource availability and agricultural intensification (Atreya et al., 2018). In Aymara communities in two highland districts in Bolivia, a team including an Aymara researcher, found reductions in ILK compared to previous generations, particularly in households with higher levels of education, outmigration and adoption of mechanized agriculture (Gilles et al., 2013). The case of yak herding in the high-altitude Himalayas shows ILK in decline due to youth out migration from rural areas (Ning et al., 2016).

Other cases show ILK as increasingly vital and dynamic. In a high mountain glacial area in Yunnan, China, instead of adopting Genetically Modified Organisms, Yi farmers continue to raise tartary buckwheat (*Fagopyrum tataricum*) because of its adaptability to high mountain conditions, its use as a cover crop and its good performance in poor years. In addition to historical use for consumption and rituals, contemporary Yi also market it, particularly as a health food (Saunders Bulan et al., 2017). In a central Andean region of Peru, which has undergone an increase in commercial production in agriculture, pastoralism and forestry, a team of scientists and members of Indigenous local Non-Governmental Organization (NGO), compared a variety of types of land use, including intensive cultivation and indigenous agropastoral systems of crop rotation; the latter showed higher levels of soil fertility and biodiversity of soil macrofauna, even controlling for elevation (De Valença et al., 2017).

Three Examples Linking Across the Chapters

Indigenous Knowledge and Coastal Management in the Pacific: Pacific communities depend on coastal marine resources for essential protein (Pratchett et al., 2011). Historically, local management systems, tenured by a community, clan or family, determined access to and spatial and temporal closure of fishing grounds to respect the death of prominent community members, the protection of sacred sites and the preparation of customary feasts. Today, a hybrid system, Locally Managed Marine Protected Areas (LMMAs) proliferate in the Pacific, integrating customary or local governance with interventions of co-management partners, generally NGOs or government agencies (Aswani and Ruddle, 2013; Jupiter et al., 2014). LMMAs' main objectives are to: increase long-term sustainability of fisheries and efficiency of short time harvest; maintain/restore biodiversity and ecosystem functions, including breeding populations; enhance livelihoods and, adaptation to climate change; reinforce customary rights; assert access rights; and empower communities (Jupiter et al., 2014). Despite the multiplicity of drivers of change and the consequent difficulty to precisely assess LMMAs' impact (Rohe et al., 2017), LMMAs are used in other world areas (Rocliffe et al., 2014) because such co-management systems protect vegetation and fisheries through conservation habitats, eliminate overfishing and overall reduce the risk of climate change impacts on marine biodiversity and ecosystem services (Section 5.4).

Indigenous Knowledge and the North Water Polynya: Pikialasorsuaq (North Water Polynya), in Baffin Bay between Greenland and Canada, is one of the world's largest polynyas and one of the most biologically productive regions in the Arctic (Barber et al., 2001). Adjacent Inuit communities depend on the polynya's biological productivity for their subsistence economy (Hastrup et al., 2018), relying on Inuit Qaujimajatuqangit, meaning 'that which has long been known by Inuit', a knowledge system that informs daily and seasonal activities, embracing past, present and future understandings, experience and values of Inuit society (ICC, 2017). In recent years, the sea-ice bridge north of the Pikialasorsuaq has not formed as reliably as in the past due to climate change, resulting in a polynya that is geographically and seasonally less defined (Ryan and Münchow, 2017). In response, the Inuit Circumpolar Council initiated the Inuit-led Pikialasorsuaq Commission to consult adjacent communities to capture and incorporate Indigenous knowledge for safeguarding, monitoring and managing the Pikialasorsuaq. These consultations documented the Inuit Qaujimajatuqangit related to the intimate and interdependent relationship people have with the polynya and included discussion of how climate change was affecting food security, economic development and governance. This resulted in the Pikialasorsuaq Commission's recommendations for an Inuit-led management authority to oversee monitoring and research to: (1) promote the conservation of the polynya's living resources and related well-being of the communities; (2) identify an Indigenous Protected Area, inclusive of the polynya and adjacent dependent communities; and (3) establish a free travel zone for Inuit across the Pikialasorsuaq region (ICC, 2017).

Local Knowledge to Manage Flooding in the Himalayas: The glacier fed Gandaki river basin, a transboundary basin in the central Himalayan region of China, Nepal and India, is home to nearly 40 million people. Climate change is increasing glacial and water-induced disasters (Shrestha and Aryal, 2011; Siderius et al., 2013; Lutz et al., 2014). Local communities across this region are observing and adapting to climate change and these disasters in variety of ways (Vedwan and Rhoades, 2001; Manandhar and Rasul, 2009; Orsatti, 2010; Nadeem et al., 2012). Rains upstream of Gandaki flood in downstream areas of Bihar, India, and local communities' knowledge of forecasting floods, which has evolved over time through the complexities of caste, class, gender and ecological flux, is critical to flood forecasting and disaster risk reduction. Local communities use sophisticated knowledge indicators including phenomenological, ecological, riverine meteorological, official informational and/ or some combination of them (Acharya and Poddar, 2016). The phenomenological indicator Halla (noise) occurs as water from the river starts to rise and approach the nearest house, signaling residents to shout- 'get your things, the flood is coming.'' The ecological indicator of large numbers of red ants emerging with eggs in their mouths warns that flood water is rising. Local communities often match these indicators with meteorological and official information. If river water changes color and has more silt and debris, people sense incessant rainfall and triangulate it with official and/or social network information. These examples show how local knowledge systems compliment and bolster scientific information and how the integration of knowledge systems strengthens response and adaptation (Acharya and Poddar, 2016).

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[END CROSS-CHAPTER BOX 3 HERE]

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Cross Chapter Box 4: Confidence and Deep Uncertainty

Authors: Carolina Adler (Switzerland/Australia), Michael Oppenheimer (USA), Nerilie Abram (Australia) Kathleen McInnes (Australia)

Definition and Context

Complex decision-making contexts ensue from assessing and managing the risks of climate change. Responses to reduce impacts and minimise losses demand a dynamic interaction with the system. Risk assessment and management includes characterizing uncertainty. Deep Uncertainty arises when parties to a decision cannot identify risks (e.g., unknown unknowns) or cannot agree on the conceptual framing or quantification of risk and uncertainty (intractable ‘disagreements’). Deep uncertainty manifests in situations where parties do not know or cannot agree on: (1) appropriate conceptual models that describe relationships among key driving forces in a system; (2) the probability distributions used to represent uncertainty about key variables and parameters as representations of these conceptual models, and/or; (3) how to value the desirability of alternative outcomes (Lempert et al., 2003). Other terms such as ‘great uncertainty’ (e.g., Hansson and Hirsch Hadorn, 2017) are also present in the literature to refer to the multiple components of uncertainty that need to be accounted for in uncertainty evaluation for decision making.

The IPCC assessment process can illuminate areas where deep uncertainty exists. For example, in assessing confidence and agreement of the scientific evidence for anthropogenic climate change, and its influence on the Earth system in the past and future, the IPCC assessment process can identify areas where a large range of possibilities exist in the scientific literature or where knowledge of the underlying processes and responses is lacking. The development of guidelines to ensure consistent treatment of uncertainties by IPCC author teams (Mastrandrea et al., 2010a, Section 1.8.3) may not be sufficient to ensure the desired consistency and guide robust findings when conditions of deep uncertainty are present (Adler and Hirsch Hadorn, 2014).

The purpose of this Cross-Chapter Box is to highlight experiences with deep uncertainty relevant to the ocean and cryosphere. This includes presenting examples of cases discussed in more detail within the chapters of this Special Report, where deep uncertainty has been addressed to advance assessment and risk management. … [PLACEHOLDER FOR SECOND ORDER DRAFT: additional detail on ‘confidence’].

How has the IPCC and other Literature Dealt with Deep Uncertainty?

The IPCC and earlier assessments encountered deep uncertainty when evaluating numerous aspects of the climate change problem, shedding light on various approaches to quantifying and reducing deep uncertainty. An assessment report of the US National Academy of Sciences (Charney et al., 1979; commonly referred to as the Charney Report) provides a classic example: Evaluating climate sensitivity to a doubling of carbon dioxide concentration was challenging because only two 3-D climate models and a handful of model variants and realizations were available. The panel invoked three strategies: (1) Use of multiple lines of evidence to complement the limited model results; (2) estimation of the consequences of poor or absent model representations of certain physical processes, particularly cumulus convection, high-altitude cloud formation, and non-cloud entrainment; and, (3) evaluating mismatches between model results and observations to assess reliability among the range of available realizations. This triage yielded ‘probable bounds’ of 2°C – 3.5°C on what we now call climate sensitivity. The panel then invoked expert judgment to broaden the range to 3°C ± 1.5°C, with 3°C referred to as the ‘most probable value’. However, the panel did not report any indication of its confidence in these judgments.

The numerical value of the sensitivity range has proved to be robust, which could be misinterpreted as indicating that little improvement has occurred in characterizing climate sensitivity. However, the literature has expanded greatly allowing successive IPCC assessments to expand and refine the approach taken in the Charney report. By AR5, four lines of evidence (from instrumental records, paleoclimate data, model inter-comparison of sensitivity, and model-climatology comparisons) led to quantification of the 3°C ± 1.5°C range as *likely* (i.e., 17–83% probability) with *high confidence*. The Charney report began the process of convergence of opinion around a single distribution, at least for sensitivity arising from fast feedbacks (Hansen et al., 2007), while the subsequent assessments eliminated deep uncertainty about this part of the sensitivity problem.

Dynamical ice loss from Antarctica provides an example of newly emergent deep uncertainty and its evolving treatment across IPCC assessment cycles. AR3 evaluated the total Antarctic contribution to sea level rise by 2100 as –0.17 to 0.02 m, stating, 'It is now widely agreed that major loss of grounded ice and accelerated sea level rise are very unlikely during the 21st century', based largely on a small number of process-based models (IPCC, 2001: 642). A spate of new observations disagreeing with decade-scale predictions of these models (Lemke et al., 2007) led to the inability of AR4 to estimate the dynamical sea level contribution of either the Greenland or Antarctic ice sheet due to a lack of knowledge - a state of deep uncertainty. Based on subsequent literature, AR5 (Church et al., 2013) used multiple lines of evidence including a statistical model with limited process descriptions to derive a likely range of –0.05 to 0.14 m, for the Antarctic ice sheet contribution to sea level by 2100. AR5 also used expert judgment to re-characterize the *very likely* (595%) range of the model estimates as the *likely* (17–83%) range, and to characterize the contribution of the tail of the sea level rise distribution above the likely range as follows: 'literature suggests (with *medium confidence*) that its potential magnitude is several tenths of a metre.' (Church et al., 2013: 1173). Similar to the climate sensitivity case, uncertainty was narrowed using both quantitative and qualitative approaches. In the cases below and elsewhere in this Special Report (e.g., Section 4.4.5.3) other frameworks for reducing deep uncertainty, including expert elicitation and development of plausible sea level scenarios, are discussed in the context of coastal risk.

Cases of Deep Uncertainty from SROCC

Case A — Greenhouse Gas emissions from permafrost: [PLACEHOLDER FOR SECOND ORDER DRAFT: content yet to be written/elaborated] Case study content may include: Biogeochemical models are currently lacking key landscape-level mechanisms that are known to abruptly thaw permafrost and expose organic carbon to decomposition. The release of greenhouse gases from the Arctic affects the emission caps allowable from human activity in order to avoid dangerous climate change. Decision makers need to be able to account for additional Arctic carbon emissions when negotiating emission reductions but will need to do this while confronting the deep uncertainty of Arctic carbon dioxide and methane rate of release. Various expert judgement tools have been applied to this problem and these examples could be used as a road map for other issues involving deep uncertainty].

Case B — Antarctic sea ice: Antarctic sea ice is an example where deep uncertainty is known to currently exist through the divergence of observations and climate model output (Section 3.3.1). Climate models produce long-term declines in sea ice around Antarctica as a response to anthropogenic climate change, yet observational records of Antarctic sea ice change since the availability of continuous satellite data in 1979 document a small but significant increase in Antarctic sea ice (Jones et al., 2016) that was assessed as very likely in AR5 (Vaughan et al., 2013). Proposed explanations for the expansion of Antarctic sea ice include a dynamical response to strengthening and southward migration of the Southern Ocean westerly winds (Holland and Kwok, 2012), teleconnections with mid-latitudes (Purich et al., 2016) or ocean freshening from Antarctic land ice loss (Bintanja et al., 2013), with the pattern of Southern Ocean overturning circulation delaying the development of anthropogenic warming in the Southern Ocean (Armour et al., 2016). Large year-to-year variability combined with short observational records may also be masking the detection of anthropogenic trends in Antarctic sea ice extent (Jones et al., 2016). Rapid retreat of Antarctic sea ice during 2016 and 2017 was not predicted and it is unclear yet if these record minima mark the emergence of expected Antarctic sea ice decline or are the result of extreme natural variability (Stuecker et al., 2017; Turner et al., 2017). This is the focus of much ongoing research, yet any future Antarctic sea ice change will have implications for the management of Southern Ocean fisheries and marine living resources and for ship operations including tourism and research station resupply within the Antarctic sea ice zone. Currently these management decisions must be undertaken with the knowledge that deep uncertainty exists in our understanding of the processes and future trajectory of Antarctic sea ice change. In response to this and other uncertainties, the Commission for the Conservation of Antarctic Marine Living Resources uses the 'precautionary approach' to managing Southern Ocean fisheries, where lower catches are allowed when uncertainty exists and should only increase when there is improved information that reduces uncertainty (Constable, 2011).

Case C — Antarctic ice sheet and sea level rise: Antarctica's contribution to sea level rise is an example where deep uncertainty has changed across subsequent IPCC assessment reports as scientific knowledge has developed (see above: How has the IPCC and other literature dealt with deep uncertainty?). Research since AR5 has continued to develop new theories for the processes that affect Antarctic ice sheet stability (DeConto and Pollard, 2016), the extent to which the ice sheet is projected to change (Golledge et al., 2015; DeConto and Pollard, 2016), and whether further eventual ice loss in the Amundsen Sea region equivalent to ~1m sea level rise is now inevitable (Joughin et al., 2014; Rignot et al., 2014). SROCC assessment of recent estimates of the Antarctic contribution by 2100 under a high emission pathway (RCP8.5) leads to a GMSL rise of 82-133cm (likely range) compared to 1986-2005. The long-term commitment to additional rise beyond 2100 is still considered to be deeply uncertain (Section 4.2.3). Sea level change has implications for low-lying coasts and communities that require policy makers, city planners and governments to develop infrastructure and resettlement plans for multi-decadal time horizons that are resilient to the worst-case sea level rise estimates, at the same time that new scientific understanding of those estimates is emerging (Chapters 3 and 4). For example, extreme sea levels (e.g., the local 'hundred-year flood') now occurring during storms that are historically rare are projected to become annual events by 2100 at many low-lying coastal areas (4.4.3). Coastal cities are working with scientific experts to understand the implications of new estimates of very large increases in flood frequencies by the end of this century (Chapter 4). Antarctica's contribution to sea level rise represents a situation where deep uncertainty in scientific knowledge persists for outcomes with probability outside the likely range and for outcomes beyond the 21st century. The commitment to a large sea level rise and costly societal impacts in the future also depends on the climate change pathway followed, bringing another element of deep uncertainty for coastal planning. Formal and informal elicitation of expert judgment is often used to characterize sea level rise, including part or all of its deeply uncertain Antarctic contribution (Horton et al., 2014; de Vries and van de Wal, 2015; Ritz et al., 2015; Bamber et al., 2016; de Vries and van de Wal, 2016; Bakker et al., 2017; Kopp et al., 2017). Frameworks for managing this combination of deep uncertainty in the context of time lags between emissions mitigation and resulting changes in ice sheet response, and between coastal adaptation planning and implementation are currently emerging in the literature (Haasnoot et al., 2013; Ranger et al., 2013; New Zealand Government, 2017), (see Case D below).

Case D — Multi-risks and compound events: Multi-risk and cascading impacts (see Figure 6.1) arise from the interaction of hazards with exposure and vulnerability (Cross-Chapter Box 1). Hazards in the context of multi-risk include single events, rendered more extreme by climate change and those comprised of multiple events that coincide or occur in sequence (i.e., compound events). Similarly, a severe or compound event can increase exposure and vulnerability through multiple pathways and through time.

Evaluating likelihoods of rare compound events in the present climate is challenging given the limited observations available to evaluate robust statistical estimates. Multi-risk is characterised by deep uncertainty, brought about by the combined uncertainties of hazards in a changing climate and incomplete information on exposure and vulnerability. Inability to evaluate, in a statistical sense, the likelihood of compound events occurring does not preclude the need to develop robust strategies to reduce multi-risk. Knowing that an event can occur in a region rather than knowing when it will occur can lead to effective risk reduction strategies (Dessai et al., 2009), such strategies typically being well-hedged against a variety of different futures and adjustable through time in response to emerging information (Lempert et al., 2010).

Future hazards under a changing climate may be currently so rare that they lie outside historical experience and thus many of their characteristics, including effective coping and adaptation responses, are deeply uncertain. Even envisaging the types of compound events and multi-risk that may arise in the future is challenging. The role of case studies that document regional examples of compound events can reduce deep uncertainty, provide valuable learnings for decision makers in the form of analogues (McLeman and Hunter, 2010), and be used to devise scenarios to stress test systems in other regions. Box 6.1 provides an example of multi-risks and cascading impacts experienced across the Australian state of Tasmania in 2015/2016. It highlights how climate change was detected in the severity of several climate events that played out over approximately a six-month period. The climate events included a drought that led to low dam water levels for irrigation and hydroelectricity production together with a subsequent, unrelated failure of the electric cable link to the mainland that led to energy shortages. The dry prevailing conditions and a lightning storm caused severe bushfires in world heritage forests, and a flooding event due to an extra-tropical storm in the state's northeast later in the summer, stretched the state's emergency services that were simultaneously responding to both events. Meanwhile an unprecedented marine heatwave off the east coast had a significant impact on the state's east coast aquaculture industry. The combined effects of these climate events on food, energy and manufacturing sectors reduced the anticipated growth in Tasmania's gross state product by approximately half.

[PLACEHOLDER FOR SECOND ORDER DRAFT: inclusion of additional policy lesson on DU multi-risk case study, if available, to be considered]

What can we learn from Cases on Addressing Confidence and Deep Uncertainty?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

Recommendations

[PLACEHOLDER FOR SECOND ORDER DRAFT]

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[END CROSS CHAPTER BOX 4 HERE]

[START FAQ1.1 HERE]

FAQ 1.1: Why are the ocean and the cryosphere so significant for climate change?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

[END FAQ1.1 HERE]

[START FAQ1.2 HERE]

FAQ 1.2: How are the ocean and cryosphere significant for people?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

[END FAQ1.2 HERE]

[START FAQ1.3 HERE]

FAQ 1.3: What kind of information do scientists use to understand the impacts of climate change on the ocean and cryosphere?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

[END FAQ1.3 HERE]

[START FAQ1.4 HERE]

FAQ 1.4: How can governance at various levels address the effects of climate change in coastal, polar and mountain communities?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

[END FAQ1.4 HERE]

[START FAQ1.5 HERE]

FAQ 1.5: How can societies address changes in the ocean and cryosphere and at the same time pursue sustainable development?

[PLACEHOLDER FOR SECOND ORDER DRAFT]

[END FAQ1.5 HERE]

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Appendix 1.A: Supplementary Material

Appendix 1.A, Table 1: Chapters of this report addressing the efficiency, readiness, benefits, and/or disbenefits of the measures to respond to climate change shown in Figure 1.3 and discussed in Section 1.5.

	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Cross-Chapter Box LLIC
Addressing the causes						
Renewable energy	X	-	-	X	-	-
Increase energy efficiency	-	-	-	-	-	-
Carbon capture and storage	-	-	-	X	-	-
Direct air capture and storage	-	-	-	X	-	-
Bioenergy with carbon capture and storage	-	-	-	-	-	-
Biochar and soil carbon	-	-	-	-	-	-
Afforestation and reforestation	-	-	-	X	-	-
Enhance open-ocean productivity	-	-	-	X	-	-
Enhanced weathering and alkalinization	-	-	-	X	-	-
Supporting biological and ecological adaptation						
Pollution reduction	-	-	-	X	X	-
Biodiversity preservation	-	X	X	X	X	-
Assisted evolution	-	-	-	X	-	-
Restoration and enhancement of habitats	-	-	-	X	-	-
Enhancing societal adaptation						
Community-based adaptation	X	X	X	X	X	X
Infrastructure-based adaptation	X	X	X	X	X	X
Relocate and diversify economic activities	X	-	X	X	X	X
Relocate people	X	X	X	-	X	X
Change practices and policies		X	X	X	X	X
Managing solar radiation						
Cloud brightening	-	-	-	-	-	-
Space-based methods	-	-	-	-	-	-
Surface albedo enhancement	-	-	-	-	-	-
Aerosol-based methods	-	-	-	-	-	-

Appendix 1.A, Table 2: Summary of impacts and responses of natural systems to ocean and cryosphere change (after Tables 18.7 and 18.8 of Cramer et al. (2014). Where confidence of attribution presents multiple options, the original tables reported different levels of confidence in different continents or seas. The evaluation of patchiness of impacts and responses is based on information cited in the original tables. Extensive = many cases reviewed and magnitude and/or nature of impacts/responses were affected by many factors so local information essential for explanation; Moderate = many cases reviewed and impacts/responses showed some variation among cases, but often similarities within regions or biomes; Some = a fairly small number of cases were reviewed, but evidence of heterogeneity was present among them; Fairly consistent = at least several different cases were reviewed, and generally similar patterns of impact / response seemed to be present; Limited information = too small a number of cases were reviewed to be able to draw inferences about the generality of the patterns.

Aspect of ocean or cryosphere change producing the pressure	Change in natural system as impacts or responses to impacts	Confidence of attribution to the specific pressure	Spatial or taxonomic patchiness of impact or response
Ocean warming *Cryosphere loss caused by atmospheric warming*	Decline in coral reefs – bleaching, disease	High/medium	Some
	Extension of coral reefs poleward	Medium	Limited information
	Poleward shifts in marine plankton, macroinvertebrates, and fish	High / medium	Extensive
	Depth changes in marine fishes	High / medium	Extensive
	Range changes in marine reptiles, seabirds, marine mammals	High	Extensive
	Changes in maximum body size and predator-prey interactions of marine fish communities (ch 5)	Medium	Extensive
	Changes in migration timing of fish (esp salmon), seabirds	High /Medium / low	Moderate
	Population declines in polar seabirds and marine mammals	Medium	Moderate
	Phenology changes in plankton	Medium	Moderate
	‘Invasions’ of new (warm-water) species	Medium	Moderate
	Species replacements of key trophic species	Low	Extensive
	Changing migration patterns and phenology of seabirds	Medium / Low	Limited information
	Upward shift in montane tree line	Medium / Low	Some
	Northward shift of shrubs and treeline into tundra	High / medium	Fairly Consistent
	Increases in wildfires in tundra and boreal systems	Medium	Some
	Loss of snow-bed ecosystem and tussock structure	High	Limited information
	Range changes in polar plant and animal species	High	Extensive
	Changes in migration timing, routes and breeding areas of polar species	Medium	Extensive
	Changes in phenology and productivity of polar lacustrine communities	High	Limited Information
Changes in sea ice, permafrost, and in related ocean conditions	Increased coastal erosion	Medium / Low	Fairly Consistent
	Population declines in migratory polar species	High	Moderate
	Changes in phenology and productivity of polar seabirds	Medium	Limited information
	Declines in zooplankton productivity in polar seas	Medium	Limited information
Sea level rise and related changes in ocean conditions	Degradation of mangroves	Low	Some
	Degradation of other coastal vegetation	Medium / Low	Some
	Increasing flooding and erosion	Low	Extensive
	Saline intrusion into groundwater and	Low	Limited information
Ocean acidification	Reduced thickness of calcareous shells of marine organisms, and of calcareous structures built by bio-engineers	High	Extensive

	Reduced productivity of organisms with calcareous shells	High / Medium	Extensive
Storm surges from extreme weather	Coastal Flooding, inundation of estuaries and deltas	High	Extensive
	Destruction of kelp and seagrass beds and other coastal macrophytes	Medium	Extensive
Expansion of hypoxic zones	Decrease in biodiversity and productivity	Low (in link to climate)	Extensive

Supplementary Material for Figure 1.4

The lower panel of Figure 1.4 gives examples of available data for the ocean and cryosphere (Section 1.7.2). Heights depict the number of observations, parameters or simulations available through time expressed relative to the maximum data availability, and colour scale depicts spatial coverage of data across the relevant domain. Details and data sources are:

- Remote sensing (surface ocean) shows the availability through time of five surface ocean parameters; sea surface salinity, ocean wind, surface level, surface temperature and ocean colour (Dowell et al., 2013).
- Ocean temperature observations are from the World Ocean Database (Boyer et al., 2013). The data in Figure 1.4 shows the number of observations in the database through time for three depth layers, relative to maximum annual values of 650,552 for the 0-1000m layer, 127,281 for the 1000–2000 m layer, and 5,624 for observations deeper than 2000m. Spatial coverage is calculated as the percentage of 3° x 3° ocean grid cells that have observations. Database: https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html
- Remote sensing (cryosphere) shows the availability through time of four cryosphere parameters; ice area, ice elevation, sea ice and snow cover (Dowell et al., 2013).
- Glacier length observations are from the World Glacier Monitoring Service (WGMS) (WGMS, 2017). Data amalgamate the glacier front variation and glacier reconstructed front variation databases and show the number of glacier length observations through time relative to a maximum annual value of 837. The percentage coverage is based on the number of glaciers with length observations relative to the total number of glacier identification codes in the WGMS database (8490). Database doi: 10.5904/wgms-fog-2017-10
- Paleoclimate data uses an example from the PAGES2k version 2.0.0 database (PAGES2k Consortium, 2017) of temperature sensitive records, which include temperature proxies over ice sheets (from ice cores) and in the ocean (from corals and marine sediments). Figure 1.4 shows the number of paleoclimate records available through time, relative to an annual maximum of 649. Spatial coverage is calculated as the percentage of 3° x 3° surface grid cells across the globe that have paleoclimate data. Database doi: 10.6084/m9.figshare.c.3285353
- Model simulations data in Figure 1.4 is based on search results for CMIP5 simulations (Taylor et al., 2012) in the Earth System Grid Federation database (http://esgf.llnl.gov/), using the search criteria of last millennium (p1000; 850–1850 CE), historical (1851–2005 CE), RCP (2005–2100 CE), and RCP-extended (2100 CE onwards) experiments with monthly resolution output for the ocean. Data availability is shown relative to the maximum number of datasets meeting these search criteria (508 for RCP experiments).