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), Susan 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), Phillip Williamson (UK)

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

Chapter Scientist: Avash Pandey (Nepal)

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Executive Summary

This special report assesses the ocean and cryosphere (the frozen parts of our planet) in a changing climate. The report covers new knowledge since the IPCC Fifth Assessment Report (AR5) on how the ocean and cryosphere have and are expected to respond to ongoing climate-related changes, how this alters the services that the ocean and cryosphere provide to people and nature and the factors that affect their resilience and vulnerability to change, and adaptation options and governance frameworks for reducing future risks.

Ocean and cryosphere elements span from the top of Earth's highest mountains to the depths of the seas, and all people depend directly or indirectly on the multitude of ecosystem services they provide. Coasts are the most densely populated areas on Earth, home to approximately 27% of the global population including over half of the world's megacities. Almost 13% of the global population lives in Arctic or high mountain regions. All people on Earth rely on the ocean and cryosphere for the climate regulation, rainfall, food and water supplies, renewable energy, and trade and transport they support. Worsening climate change impacts on the ocean and cryosphere put sustainable development pathways at risk (*high agreement, medium evidence*[1]), and present particular challenges to communities living in close connection to polar, mountain and coastal environments, and to cities, states and nations whose territorial boundaries are being transformed by ongoing sea level rise. {1.1, 1.2, 1.5}

The characteristics and impacts of ocean and cryosphere change place urgency on limiting climate warming in accordance with the temperature targets of the Paris Agreement. Marine, coastal, high mountain and Arctic systems are expected to be at *high* to *very high* risk of dangerous impacts as global temperatures approach or exceed 1.5°C to 2°C above pre-industrial (*high confidence*). Many ocean and cryosphere changes are irreversible on timescales relevant to human societies (decades to centuries), and include feedback processes expected to further amplify anthropogenic climate change. {1.1, 1.2, 1.3}

Unequivocal climate warming, that AR5 assessed as *extremely likely*[2] attributable to human-induced greenhouse gas emissions, has so far resulted in global average warming of 1°C ± 0.2°C since the pre-industrial (*likely*) and been accompanied by ongoing and accelerating changes in the ocean and cryosphere. The IPCC has assessed knowledge on climate change and its impacts since 1988. Many projections of earlier assessments have since been confirmed, or continue to develop at the upper, more extreme end of past projections. Ocean and cryosphere changes that have continued unabated since AR5 include warming, acidification and deoxygenation of the ocean, and Arctic sea ice and permafrost decline. Worldwide retreat of mountain glaciers, reductions in the Greenland and Antarctic ice sheets, as well as ongoing warming of the global ocean, are resulting in continued sea level rise with century to millennial-scale commitments to future change. {1.1, 1.3, 1.4, 1.8, Cross-Chapter Box 4}

Climate change-related impacts on the ocean and cryosphere compound the risks related to climatic and other environmental hazards already faced by many human and natural systems, particularly in coastal, polar, and mountain areas. Adaptation efforts reduce risk by reducing hazards, exposures and/or vulnerabilities. The vulnerability of people to ocean and cryosphere change, and their adaptive capacity, is shaped by social, political, cultural, economic, institutional, geographical, and demographic factors. Sustainable development can be supported by charting climate resilient development pathways, which combine efforts for climate change mitigation and adaptation and include profound economic and institutional transformations (*high confidence*). {1.5; Cross-Chapter Box 1}

[1] FOOTNOTE: In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Section 1.9.3 and Figure 1.4 for more details).

[2] FOOTNOTE: In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Section 1.9.3 and Figure 1.4 for more details).

Committed ocean and cryosphere changes necessitate the use of adaptation measures to reduce impacts on human and natural systems, alongside urgent efforts to reduce greenhouse gas emissions. Ocean and cryosphere-related mitigation and adaptation measures include options that address the causes of climate change, support biological and ecological adaptation and enhance societal adaptation. Ocean-based CO_2 removal at a global scale has potentially large trade offs (*high confidence*). Most mitigation and adaptation measures implemented at the local scale have co-benefits and few trade offs, but do not present global-scale solutions to climate change mitigation (*high confidence*). Limits to adaptation mean that urgent efforts to minimise anthropogenic climate change are necessary to give unavoidable adaptation measures the best chance of success. {1.6}

Existing and forthcoming challenges brought about by climate change can be addressed by international and trans-boundary cooperation in the governance of the ocean, coasts, and cryosphere (*high confidence*). Ocean and cryosphere changes are interconnected across geographies that extend over a range of socio-ecological and legal frameworks, governance structures, and institutions. In addition to national to global-level governance and institutional options, local-adaptation provides space for communities to respond to climate change. Adaptive and transformative governance allow actors and networks to learn from experience, and to develop context-relevant governance arrangements that can be adjusted to address worsening climate change impacts. {1.7; Cross-Chapter Box 2}

Diverse knowledge sources provide the foundation for assessing past, current, and plausible future changes in the ocean and cryosphere, and for developing governance and response options. Continued development of scientific knowledge is crucial to close knowledge gaps in poorly sampled or unsampled areas of the ocean and cryosphere, to detect and quantify the emergence of anthropogenically forced changes beyond the range of large natural variability, and to assess future ocean and cryosphere changes under plausible greenhouse gas emission and socio-economic growth and development scenarios. Indigenous knowledge and local knowledge are complementary with scientific knowledge, to provide comprehensive understandings that aid the development of effective, context-specific responses and policies. {1.3, 1.8, 1.9; Cross-Chapter Box 3}

Comprehensive risk assessments that inform adaptation planning can address future ocean and cryosphere changes, even where future changes remain deeply uncertain. Certainty evolves in assessments of ocean and cryosphere change as the availability of data and knowledge of physical and ecological processes develops. New knowledge since AR5 has reduced uncertainties in some projected future changes, including permafrost decline and the Antarctic contribution to sea level rise. However, other aspects of the rate, timing, magnitude, and cascading elements of ocean and cryosphere change remain deeply uncertain, including low confidence or low likelihood changes that would have catastrophic consequences if realised without effective adaptation planning. {1.8.1, 1.9.3; Cross-Chapter Box 4}

1.1 Why this Special Report?

Earth's ocean and cryosphere (Box 1.1) are on the frontline of impacts attributed to human-induced climate change. These impacts are projected to substantially worsen if urgent action to limit climate change is not taken, putting sustainable development pathways at risk.

All people depend either directly or indirectly on the services provided by the ocean and the cryosphere (FAQ 1.1). Coasts are the most densely populated areas on Earth. As of 2010, 27% of the global population (1.9 billion people) were living in areas less than 100 km from the coastline and less than 100 m above sea level, including over half (17 out of 30) of the world's megacities which are each home to more than 5 million people (Kummu et al., 2016). This coastal zone is projected to be inhabited by over 2.4 billion people by 2050, with 80% living in cities (Kummu et al., 2016), and more than one billion living on land less than 10 m above sea level (Jones and O'Neill, 2016; Merkens et al., 2016). Approximately 4 million people live in the Arctic (Heleniak, 2014) and 890 million in high mountain regions (Chapter 2). For people living in close contact with the ocean and cryosphere, these provide essential livelihoods, food security, well-being and cultural identity, but are also a source of hazards. Even people living far from the ocean or cryosphere are dependent on these systems. For example, the Hindu Kush Himalaya distributes freshwater for more than 1.9 billion people living in downstream river basins (Sharma et al., in press). The ocean and cryosphere also regulate global climate and weather, and the ocean is the primary source of rainfall needed to sustain life on land. The ocean's biosphere is responsible for about half of the primary production on Earth, and 17% of the non-grain protein in human diets is derived from the ocean (FAO, 2018). The ocean and cryosphere further support (or hinder) transport and economic trade on local to global scales. The 2030 Sustainable Development Goals (SDGs) (UN, 2015) highlight climate change (SDG 13), the ocean (SDG 14) and water security (SDG 6) as focal concerns for development pathways that are environmentally sustainable and advance peace, equity and justice globally (FAQ 1.2). Moreover, the ocean and cryosphere are essential for achievement of many of the other SDGs (e.g., life in land, eradicating poverty and hunger, health and well-being, clean energy, economic growth, infrastructure, and cities), underscoring the importance of protecting the ocean and cryosphere, and their dependent ecosystems and communities, from climate change impacts (LeBlanc et al., 2017; Visbeck, 2018).

The IPCC Fifth Assessment Report (AR5) concluded that, '*Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased*' (IPCC, 2013). Subsequently, the Paris Agreement committed governments worldwide to '*holding the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C*' (UNFCCC, 2015). These temperature thresholds reflect growing scientific evidence for the risk of dangerous climate change impacts, many of which involve ocean and/or cryosphere changes. At current levels of global warming (1 ± 0.2°C above pre-industrial (*likely*); (Allen et al., in press-a)) anthropogenic climate change impacts on natural systems are already detected, and are expected to worsen. Coral reefs are expected to decline by a further 70–90% at 1.5°C (*high confidence*, and there is risk of irreversible loss of many marine and coastal ecosystems with warming of 2°C or more (*high confidence*) (Allen et al., in press-a). Arctic and mountain systems are also expected to be at high risk of dangerous climate change impacts as global temperatures approach or exceed 1.5°C to 2°C above pre-industrial (O'Neill et al., 2017; Allen et al., in press-a). Once initiated, climate change impacts on the ocean and/or cryosphere (including ocean acidification and deoxygenation, and losses of the Greenland and Antarctic ice sheets, mountain glaciers, and permafrost) may be irreversible on timescales relevant to human societies (Lenton et al., 2008; Cai et al., 2016; Kopp et al., 2016). Furthermore, changes in the ocean and cryosphere have the potential to worsen anthropogenic climate change; for example, by reinforcing greenhouse gas emissions through permafrost thaw, or by increasing the absorption of solar energy through ice loss (AMAP, 2017; Steffen et al., 2018). The irreversible and amplifying nature of ocean and cryosphere changes, and the susceptibility of these systems to even modest levels of continued warming, places urgency on reducing and avoiding the risks of large-scale ocean and cryosphere change. Transformative adaptation strategies of people, economies and institutions will be needed, presenting special challenges to the adaptative capacities of cultures who maintain centuries to millennia-old relationships to the planet's polar, mountain, and coastal environments, and to cities, states and nations whose territorial boundaries are being transformed by ongoing sea level rise (Gerrard and Wannier, 2013).

This Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) has been developed in response to requests from a number of governments for improved information on the interconnected ways in which the ocean and cryosphere are expected to change in a warming climate, and the risks that this will bring. SROCC assesses new knowledge that has emerged since AR5 (2013–2014) and provides 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. It represents one of three special reports being produced by the IPCC during its Sixth Assessment Cycle (in addition to the assessment reports). The recent IPCC Special Report on Global Warming of 1.5°C (SR1.5) highlights the urgency of the Paris Agreement targets by concluding that human-induced warming will reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (*high confidence*) (Allen et al., in press-a). The concurrent IPCC Special Report on Climate Change and Land (SRCCL; due October 2019) links to SROCC where terrestrial environments and their habitability interact closely with the ocean or cryosphere, such as in high mountain, Arctic, and coastal regions.

SROCC reaches from the top of Earth's highest mountains to the depths of its ocean: it assesses ocean and cryosphere changes in high mountains (Chapter 2) and polar regions (Chapter 3), and their impacts on sea level and coasts (Chapter 4), ocean ecosystems and dependent communities (Chapter 5), and on abrupt and extreme events (Chapter 6). Chapter 1 presents the background context and framework required for the subsequent chapters of SROCC, including descriptions of the ocean and cryosphere (Box 1.1); how they operate and are changing (Sections 1.2, 1.3 and 1.4); the opportunities and hazards this brings (Section 1.5); the risk and resilience framework used in SROCC (Cross-Chapter Box 1); adaptation and governance response options (Sections 1.6 and 1.7, Cross-Chapter Box 2); knowledge systems (Section 1.8, Cross-Chapter Box 3); and the methodological approaches and storyline of SROCC (Sections 1.9 and 1.10, 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 is an interconnected body of saline water that encompasses polar to equatorial climate zones and covers 71% of the Earth surface. It includes the Arctic, Pacific, Atlantic, Indian, and Southern oceans, as well as marginal seas. The ocean contains about 97% of the Earth's water, and provides roughly half of the primary production on Earth.

Coasts are where ocean and land processes interact, and includes coastal cities, deltas, and estuaries. Densely-populated low elevation coastal zones (<10 m above sea level) are particularly exposed to climate change impacts (Chapter 4, Chapter 5, Cross-Chapter Box 7). Beyond coastlines, the continental shelf marks the shallow ocean areas (depth <200 m) that surround islands and continents, before descending at the continental slope into the deep abyssal plains which lie below the open ocean. Ocean depth and distance from the coast determine the governance that applies to ocean areas (Cross-Chapter Box 2).

The average depth of the global ocean is about 3700 m, with a maximum depth of more than 10,000 m. The ocean is normally stratified with less dense water sitting above more dense layers, determined by the seawater temperature, salinity and pressure. The surface of the ocean is in direct contact with the atmosphere, with the exception of sea ice covered regions. Sunlight penetrates into the water column and supports primary production (by phytoplankton) down to 50 to 200 m depth (epipelagic zone). Atmospheric-driven mixing occurs from the sea surface and into the mesopelagic zone (200 to 1000 m). The distinction between the upper ocean and deep ocean depends on the processes being considered. From a biological perspective, the deep ocean is below 200 m (Chapter 5); from a physical perspective, the deep ocean is below 1000 m depth (Chapter 3).

The ocean is a fundamental climate regulator on seasonal to millennial time scales. Seawater has a heat capacity four times larger than air and holds vast quantities of dissolved and particulate carbon. Heat, water, and biogeochemical substances (e.g., carbon, nitrogen) exchange at the air-sea interface, and ocean currents and mixing caused by winds, tides, density differences, and turbulence redistribute these throughout the global ocean (Box 1.1, Figure 1).

Cryosphere

The cryosphere refers to components of the Earth system that contain frozen water. This includes mountain glaciers, the ice sheets of Greenland and Antarctica, ice shelves, sea ice, permafrost, and snow. Presently, 10% of Earth's land area is covered with glaciers or ice sheets, which in total hold about two-thirds of Earth's freshwater. Cryosphere is common in polar regions (Chapter 3) and high mountains (Chapter 2), and changes in the cryosphere can have far-reaching and even global impacts (Chapters 4-6, Cross-Chapter Box 7).

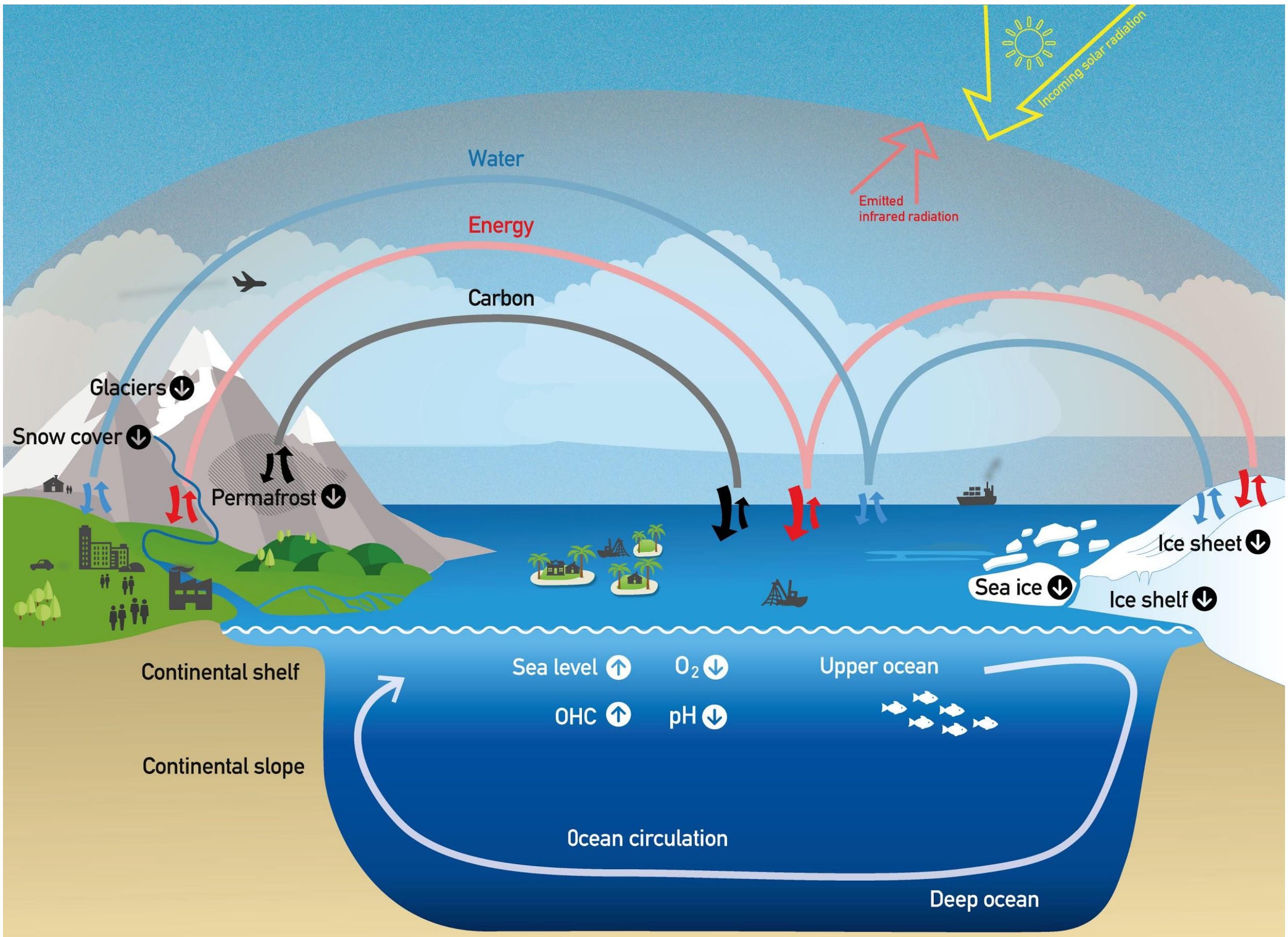
The largest ice bodies on Earth are the Greenland and Antarctic ice sheets (Box 1.1, Figure 1). Ice sheets are built up by accumulating snowfall on their surface. They flow outward from a high central ice plateau and at their margins ice and/or meltwater is discharged into the ocean. Marine-based ice sheets (e.g., West Antarctic Ice Sheet) sit upon bedrock that largely lies below sea level and are more vulnerable to rapid and irreversible ice loss.

Glaciers are land-based ice maintained by snowfall in high mountains and polar regions, or by ice flow at the margins of ice sheets. Ice sheets and glaciers that lose more ice than they accumulate contribute to global sea level rise. Glaciers and seasonal snow in high mountains are also a critical source of freshwater and energy resources for downstream communities.

Ice shelves are extensions of ice sheets and glaciers that float in the surrounding polar ocean. The transition between the grounded part of an ice sheet and a floating ice shelf is called the grounding line. Changes in ice-shelf size do not directly contribute to sea level rise, but laterally confined ice shelves restrict the flow of land-based ice into the ocean.

Sea ice forms by the freezing of seawater at the ocean surface, and is further thickened by snow accumulation. 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 to climate, populations, and ecosystems: it provides essential habitat for polar species and supports the livelihoods of people in the Arctic; regulates climate by reflecting solar energy (albedo); inhibits ocean-atmosphere exchange of heat, momentum, and gases (including carbon dioxide; CO_2); drives global deep ocean circulation via dense (cold and salty) water formation; and aids or hinders transportation and travel routes in the polar regions.

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 also offshore as submarine permafrost in the Arctic and Southern oceans. Its thickness ranges from less than 1 m to greater than 1000 m. Permafrost thaw can cause hazards, particularly in low-lying coastal regions in the Arctic vulnerable to coastal erosion. Overlying snow cover can act to thermally insulate permafrost from the atmosphere.



Box 1.1, Figure 1: Schematic illustration of key components and changes of the ocean and cryosphere, and their linkages through the movement of energy, water, and carbon (Section 1.2). Ongoing climate change-related effects in the ocean and cryosphere include sea level rise, increasing ocean heat content (OHC), ocean deoxygenation, ocean acidification, and global declines of sea ice, ice sheets, ice shelves, permafrost, glaciers, and snow cover (Section 1.4). For illustration purposes, a few human activities that directly interact with and impact the energy budget, and the water and biogeochemical cycles are shown.

[END BOX 1.1 HERE]

1.2 Role of the Ocean and Cryosphere in the Earth System

1.2.1 Ocean and Cryosphere in Earth's Energy, Water and Geochemical Cycles

The ocean and cryosphere are key regulators of Earth's climate. Powered by the sun, huge quantities of energy, water, and biogeochemical elements (predominately carbon, nitrogen, oxygen, and hydrogen) are exchanged between all components of the Earth system, including between the ocean and cryosphere (Box 1.1, Figure 1). During stable (equilibrium) climate states, the amount of incoming solar energy is balanced by an equal amount of outgoing radiation at the top of Earth's atmosphere (Hansen et al., 2011; Trenberth et al., 2014). At Earth's surface energy from the sun is transformed into various forms (heat, potential, latent, kinetic, and chemical), which evaporate water, drive weather systems in the atmosphere and currents in the ocean, fuel photosynthesis on land and in the ocean, and fundamentally determine the climate. The ocean has a large capacity to store and release heat from the atmosphere, and Earth's energy budget can be effectively monitored through the heat content of the ocean on time scales longer than one year (Palmer and McNeall, 2014; von Schuckmann et al., 2016; Cheng et al., 2018). The reflective properties of snow and ice also play an important role in regulating climate, via the albedo effect. Increased amounts of solar energy are absorbed when snow or ice are replaced by less reflective land or ocean surfaces, resulting in a climate change feedback.

About 97% of Earth's water is stored in the global ocean, and approximately 2% in the cryosphere. Driven by solar heating, water is exchanged between the ocean, the atmosphere, the land, and the cryosphere as part of the hydrological cycle (Box 1.1, Figure 1) (Trenberth et al., 2007; Lagerloef et al., 2010; Durack et al., 2016). Evaporation from the surface ocean is the main source of water in the atmosphere, which is moved back to the Earth's surface as precipitation (Gimeno et al., 2012). The hydrological cycle is closed by the eventual return of water to the ocean by rivers, streams, and groundwater flow, and through ice discharge and melting of ice sheets, ice caps and glaciers (Yu, 2018). Hydrological extremes related to the ocean and cryosphere include floods from extreme rainfall (including tropical cyclones) or meltwater discharge, or ocean circulation-related droughts (Li et al., 2016) (Sections 2.3, 3.4, 6.3, 6.5).

Ninety-two percent of the carbon on Earth that is not locked up in geological reservoirs resides in the ocean (Sarmiento and Gruber, 2002). Most of this is in the form of dissolved inorganic carbon that readily exchanges with the overlying atmosphere. This represents a major control on atmospheric CO_2 and makes the ocean and its carbon cycle one of the most important climate regulators in the Earth system (Berner and Kothavala, 2001). The ocean also contains as much organic carbon (mostly in the form of dissolved organic matter) as the total vegetation on land (Jiao et al., 2010; Hansell, 2013). Primary production in the ocean, which is as large as that on land (Field et al., 1998), fuels complex food-webs that provide essential food for people.

Ocean circulation and mixing redistribute heat and carbon over large distances and depths (Delworth et al., 2017). The ocean moves heat laterally from the tropics towards polar regions (Rhines et al., 2008). Vertical redistribution of heat and carbon occurs where warm, low-density surface ocean waters transform into high-density waters that sink to deeper layers of the ocean, taking high carbon concentrations with them (Talley, 2013). Driven by winds, ocean circulation also brings cold water up from deep layers (upwelling), allowing heat, oxygen and carbon exchange between the deep ocean and atmosphere (Marshall and Speer, 2012; Oschlies et al., 2018; Shi et al., 2018).

1.2.2 Interactions Between Ocean and Cryosphere

The ocean and cryosphere are interconnected in a multitude of ways (Box 1.1, Figure 1). Evaporation from the ocean provides snowfall that builds and sustains the ice sheets and glaciers that store large amounts of frozen water on land. Ocean volume changes as the ocean warms and expands, and as water stored on land (primarily as ice) is returned to the ocean, resulting in sea level rise (Section 4.2.1). The vast ice sheets in Antarctica and Greenland currently contain many tens of metres of potential global sea level rise (Fretwell et al., 2013; Frezzotti and Orombelli, 2014), although the majority is considered stable over long (century to millennial) time scales (Church et al., 2013). Ocean temperature and sea level affect ice-sheet stability in places where the base of ice sheets, glaciers, and ice shelves are in direct contact with ocean water (Section 3.3.1). The non-linear response of ice melt to temperature changes means that 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 of sea ice leads to the production of dense ocean water that drives deep ocean circulation (Abernathey et al., 2016; Haumann et al., 2016; Williams et al., 2016; Sévellec et al., 2017) (Section 3.2). Palaeoclimate evidence indicates that releases of large amounts of glacial meltwater into the surface ocean can disrupt deep overturning circulation of the ocean, resulting in rapid millennial-scale changes in global climate. Glacier and ice sheet loss in polar regions can also cause changes in surface ocean salinity and stratification that promote sea ice formation (Purich et al., 2018). The cryosphere and ocean further link through the exchange of biogeochemical nutrients. For example, iron accumulated in sea ice during winter 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). Nutrient-rich sediments delivered by glaciers further connect cryosphere processes to ocean productivity (Arrigo et al., 2017).

1.3 Timescales, Thresholds and Detection of Ocean and Cryosphere Change

It takes hundreds or more years for the entire deep ocean to turn over (Kuhlbrodt and Gregory, 2012; Buckley and Marshall, 2016), while renewal of the large ice sheets requires many thousands of years (Huybrechts and de Wolde, 1999). Long response times mean that the deep ocean and the large ice-sheets tend to lag behind in their response to the rapidly changing climate at Earth's surface, and that they will continue to evolve once climate stabilises (Figure 1.1a) (e.g., Golledge et al., 2015). Such a 'committed' change means that some ocean and cryosphere changes are essentially irreversible on timescales relevant to human societies (decades to centuries), even in the presence of urgent action to limit further global warming (Section 4.2.3.5).

Rapid and abrupt changes may occur in the ocean and cryosphere when critical thresholds are reached, even when the underlying forcing changes gradually (Figure 1.1a). Such tipping elements include the rapid disappearance of Arctic sea ice, the collapse of the meridional 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) (Section 6.2). Such non-linear systems may also exhibit hysteresis, where the future path taken by the system depends strongly on its past history. This leads to different pathways when climate warming is applied compared to when warming is stabilised and reversed (Figure 1.1a). Potential ocean and cryosphere tipping elements form part of the scientific evidence for limiting dangerous climate change (Allen et al., in press-a).

Anthropogenically forced change occurs against a backdrop of substantial natural variability. The anthropogenic signal is already detectable in global surface air temperature and several other climate variables (IPCC, 2014a), but short observational records and large year-to-year variability mean that this is not yet the case for many ocean and cryosphere changes (Jones et al., 2016). For some variables, these changes are expected to become detectable in the next few decades, for others it may take until the end of this century even under high emission scenarios (Collins et al., 2013; Keller et al., 2014; Rodgers et al., 2015). 'Time of Emergence' refers to the time when anthropogenic change signals emerge from the background noise of natural variability in a reference interval (Figure 1.1b; Section 1.9.1) (Hawkins and Sutton, 2012).

'Detection and Attribution' assesses evidence for past and future changes in the ocean and cryosphere, relative to normal/reference-interval 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; Knutson et al., 2017; Figure 1.1d). Reliable detection and attribution 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 attribution often involve using contrasting scenarios in climate model experiments to detect the forcing scenario that best explains an observed change (Figure 1.1d), but confident attribution remains challenging where there are multiple or confounding factors that influence the state of a system (Hegerl et al., 2010).

Extreme events (e.g., marine heat waves, storm surges) push a system to near or beyond the ends of its normally observed range (Figure 1.1b; IPCC, 2012). Extremes can be very costly in terms of loss of life, ecosystem destruction, and economic damage. In a system affected by climate change, the recurrence and intensity of these extreme events can change much faster, and have greater impacts, than changes of the average system state (Easterling et al., 2000; Parmesan et al., 2000; Hughes et al., 2018). Of particular concern are 'compound events', when there is a co-occurrence of more than one extreme event (Cross-Chapter Box 4; Sections 4.3.4, 6.8), such as when marine heatwaves co-occur with very low nutrient levels in the ocean resulting in extreme consequences. Compound events may occur by chance, but the interconnectedness of the ocean and cryosphere (Section 1.2.2) can also lead to cascading hazards where changes in one element trigger secondary changes in completely different but connected elements of the systems (Figure 1.1c). New methodologies for attributing extreme events, and the risks they bring, to climate change have emerged since AR5 (Stott et al., 2016; Kirchmeier-Young et al., 2017; Otto, 2017).

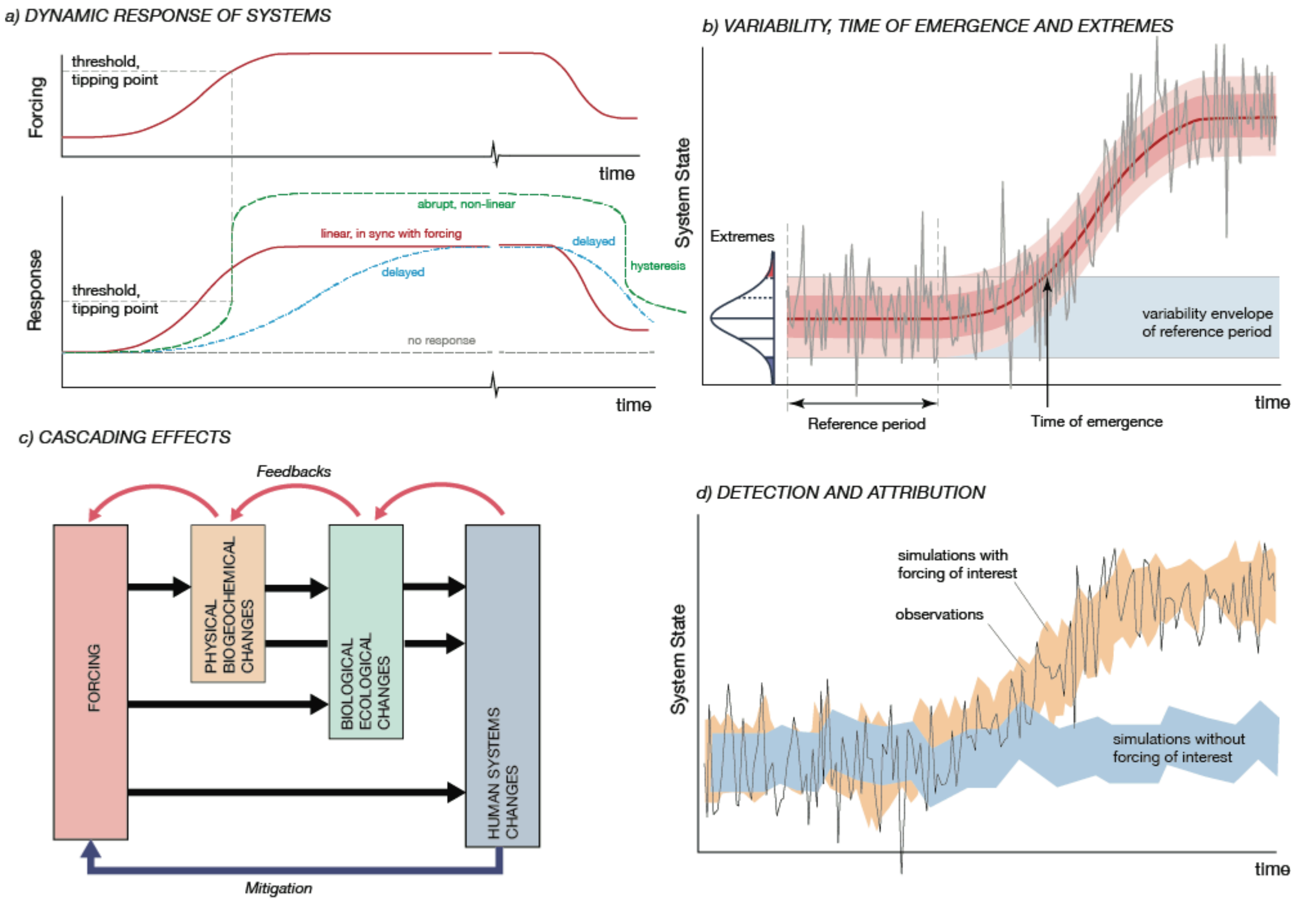


Figure 1.1: Schematic of key concepts associated with changes in the ocean and cryosphere. a) Differing responses of systems to gradual forcing (e.g., linear, delayed, abrupt, non-linear). Some non-linear systems have thresholds (often referred to as a tipping point), whose crossing results in an abrupt change for a small change in the forcing. (b) Evolution of a dynamical system in time, revealing both natural (unforced) variability and a response to a new (e.g., anthropogenic) forcing. Key concepts here are (i) the time of emergence, i.e., the point in time when the forcing pushes the system outside the noise of natural variability, defined as the variability during a reference period, and (ii) extreme events near or beyond the observed range of variability (often quantified in terms of the 1st and 99th percentiles). (c) Cascading effects, where changes in one part of a coupled system inevitably affect the state in another, and so forth, ultimately affecting the state of all subsystems. (d) Detection and attribution, i.e., the statistical framework used to determine whether a change occurs or not (detection), and whether this detected change is caused by a particular set of forcings (e.g., greenhouse gases). See Section 1.3 for details.

1.4 Changes in the Ocean and Cryosphere

Earth's climate varies across a wide range of timescales. This includes the seasonal waxing and waning of sea-ice, interannual to decadal ocean temperature changes of the El Niño-Southern Oscillation (ENSO) phenomenon that disrupt global rainfall patterns (Trenberth et al., 2002; Timmermann et al., 2018), and major shifts in ocean circulation, chemistry, and sea level associated with ice age cycles of the last million years and beyond (Sigman and Boyle, 2000; EPICA Consortium, 2004; Clark et al., 2009; Shakun et al., 2012; Rohling et al., 2014; Snyder, 2016). Some of this variability arises from internally generated (i.e., unforced) fluctuations in the climate system, such as ENSO variability that emerges from ocean and atmosphere interactions (Timmermann et al., 2018). Variability can also occur in response to external forcings, including volcanic eruptions, Earth's orbit around the sun, and oscillations in solar activity.

Since the onset of the industrial revolution, human activities have strongly enhanced the external forcings acting on Earth's climate (Myhre et al., 2013). These anthropogenic forcings include land use change (albedo), changes in atmospheric aerosols from the burning of biomass and fossil fuels, and most importantly the accumulation of greenhouse gases (including CO_2; Section 1.8.1) in the atmosphere as a result of the burning of fossil fuels, cement production, and land use change. In 2016, the global average atmospheric CO_2 concentration crossed 400 parts per million, a level not known for millions of years (Fischer et al., 2018). Earth's widespread, rapid and accelerating climate warming since 1850 is exceptional compared with natural changes in palaeoclimate records (PAGES2k Consortium, 2013; Fischer et al., 2018), and multiple lines of evidence indicate that it is *extremely likely* that climate warming since 1950 is attributed primarily to anthropogenic greenhouse gas emissions (IPCC, 2013).

The IPCC Fifth Assessment Report (AR5) provides ample evidence of profound changes in the ocean and the cryosphere (IPCC, 2014a). Now, nearly three decades since the first assessment report of the IPCC, many of the projections of previous assessments have proven true, and in some cases shown to err on the side of caution (Brysse et al., 2013). In response to the need to reframe policy-relevant assessments according to risk (Sections 1.5 and 1.9.3; Mach et al., 2016; Weaver et al., 2017; Sutton, 2018), an effort was made in AR5 to report on potential changes for which there is low scientific confidence or a low likelihood of occurrence (Section 1.9.3), but that would have large impacts if realised (Mach et al., 2017).

1.4.1 Observed and Projected Changes in the Ocean

There is *high confidence*[3] that the majority (more than 90%) of the extra thermal energy in Earth's climate system since 1970 (caused by greenhouse gas buildup in the atmosphere), is stored in the global ocean (IPCC, 2013). Mean ocean surface temperature has increased since the 1970s at 0.11 [0.09 to 0.13] °C per decade (*high confidence*), and forms part of a long-term warming of the surface ocean since the mid-19th century. In addition, the upper ocean (0-700 m, *virtually certain*) and intermediate ocean (700-2000 m, *likely*) have warmed since the 1970s, and during the 21st century heat will continue to penetrate from the surface to the deep ocean (IPCC, 2013). Ocean heat uptake has continued unabated since AR5 (Chapter 5), increasing the risk of marine heat waves and other extreme events (Section 6.4). Substantial changes in the regional distribution of sea surface salinity have also been observed, reflecting an acceleration of the Earth's water cycle (*high confidence*) which is expected to continue in the future (Sections 5.2.2, 6.3, 6.5).

Sea level rise since the mid-19th century has been greater than the mean rate of the previous two millennia (*high confidence)* (IPCC, 2013). Sea level rise continues as a result of ocean expansion due to warming (including heat uptake into deep ocean layers), freshwater added to the ocean by melting of glaciers and ice sheets , and changes to land-ocean water transport (Section 4.2.1), with a projected acceleration and century to millennial-scale commitments for ongoing rise (Section 4.2.3). SROCC reduces the large uncertainty range on projected 21st century sea level rise that existed at the time of AR5 (Section 4.2.3; Cross-Chapter Box 4).

By 2011, the ocean had taken up about 30% of the anthropogenic CO_2 that had been released to the atmosphere since the industrial revolution (*high confidence*) (IPCC, 2013). In response, ocean acidity increased by 26%, ocean pH decreased by 0.1 (*high confidence*), and oxygen concentrations decreased in many ocean regions (*medium confidence*). AR5 did not come to a final conclusion with regard to potential long-term changes in ocean productivity due to short observational records and divergent scientific evidence (Boyd et al., 2014; IPCC, 2014a). Ocean acidification and deoxygenation are projected to continue over the next century (Sections 3.2.2.3, 5.2.2).

1.4.2 Observed and Projected Changes in the Cryosphere

Many changes in the cryosphere were documented in AR5, including the widespread retreat of mountain glaciers, declining Arctic sea ice, thinning Antarctic ice shelves, and the loss of Greenland and Antarctic ice sheet mass (Vaughan et al., 2013).

A particularly rapid change in Earth's cryosphere has been the decrease in Arctic sea-ice extent in all seasons (Section 3.2.1.1). The annual mean decrease since 1979 was *very likely* in the range of 0.45–0.51 million km^2 per decade (0.73–1.07 million km^2 per decade for the summer minimum), and there is *medium confidence* that these declines are unprecedented in at least the last 1450 years (IPCC, 2013). AR5 assessed that there was *medium confidence* that a nearly-ice free summer Arctic Ocean is *likely* to occur before mid-century under a high emissions future (IPCC, 2013), while SR1.5 assessed that the risk of ice free summers could be

[3] FOOTNOTE: Confidence/likelihood statements in sections 1.4.1 and 1.4.2 derived from AR5, unless otherwise specified

limited to 1 per 100 years by keeping global warming below 1.5°C above pre-industrial (Allen et al., in press-a). At the time of AR5, increases in Antarctic sea ice extent were observed since 1979, but with *high confidence* of strong regional differences in sea ice change around Antarctica, and *low confidence* of projected Antarctic sea ice decline by the end of the 21st century (IPCC, 2013).

The Greenland and Antarctic ice sheets are continuing to lose mass under ongoing climate warming (Section 3.3). AR5 assessed that the annual mean loss from the Greenland ice sheet *very likely* substantially increased from 34 (± 40) Gt yr^{-1} (billion tonnes per year) over the period 1992 to 2001, to 215 (± 59) Gt yr^{-1} over the period 2002 to 2011 (IPCC, 2013). The average rate of ice loss from the Antarctic ice sheet also *likely* increased from 30 (± 67) Gt yr^{-1} over the period 1992–2001 to 147 (± 74) Gt yr^{-1} over the period 2002 to 2011 (IPCC, 2013). There is *very high confidence* that these losses are mainly from the Antarctic Peninsula and the West Antarctic ice sheet. Confidence in the quantification of ice sheet mass changes has increased across IPCC reports due to development of remote sensing observational methods (Section 1.8.1).

Glaciers are continuing to lose mass worldwide (Section 2.2.3). According to AR5, the average rate of ice loss from glaciers around the world (excluding glaciers on the periphery of the ice sheets), was *very likely* 226 (91 to 361) Gt yr^{-1} over the period 1971 to 2009, and *very likely* 275 (140 to 410) Gt yr^{-1} over the period 1993 to 2009 (IPCC, 2013). AR5 assessed that permafrost temperatures have increased in most regions since the early 1980s (*high confidence*), although the rate of increase has varied regionally (IPCC, 2013).

SROCC provides updated assessments of sea ice, ice sheet and glacier decline, as well as observed and projected changes in permafrost, snow cover, and lake and river ice (Sections 2.2, 3.4)

1.5 Risk and Impacts Related to Ocean and Cryosphere Change

A major objective of SROCC is to assess the risk (i.e., the potential for adverse consequences) and impacts (i.e., manifested risk) resulting from climate-related changes in the ocean and cryosphere. Knowledge on risk is essential for conceiving and implementing adequate responses. Cross-Chapter Box 1 introduces key concepts of risk, adaptation, resilience, and transformation, and explains why and how they matter for this report. Section 1.5.1 explores the relevance of risk and impacts in natural systems, and Section 1.5.2 details risks and impacts for human systems.

[START CROSS-CHAPTER BOX 1 HERE]

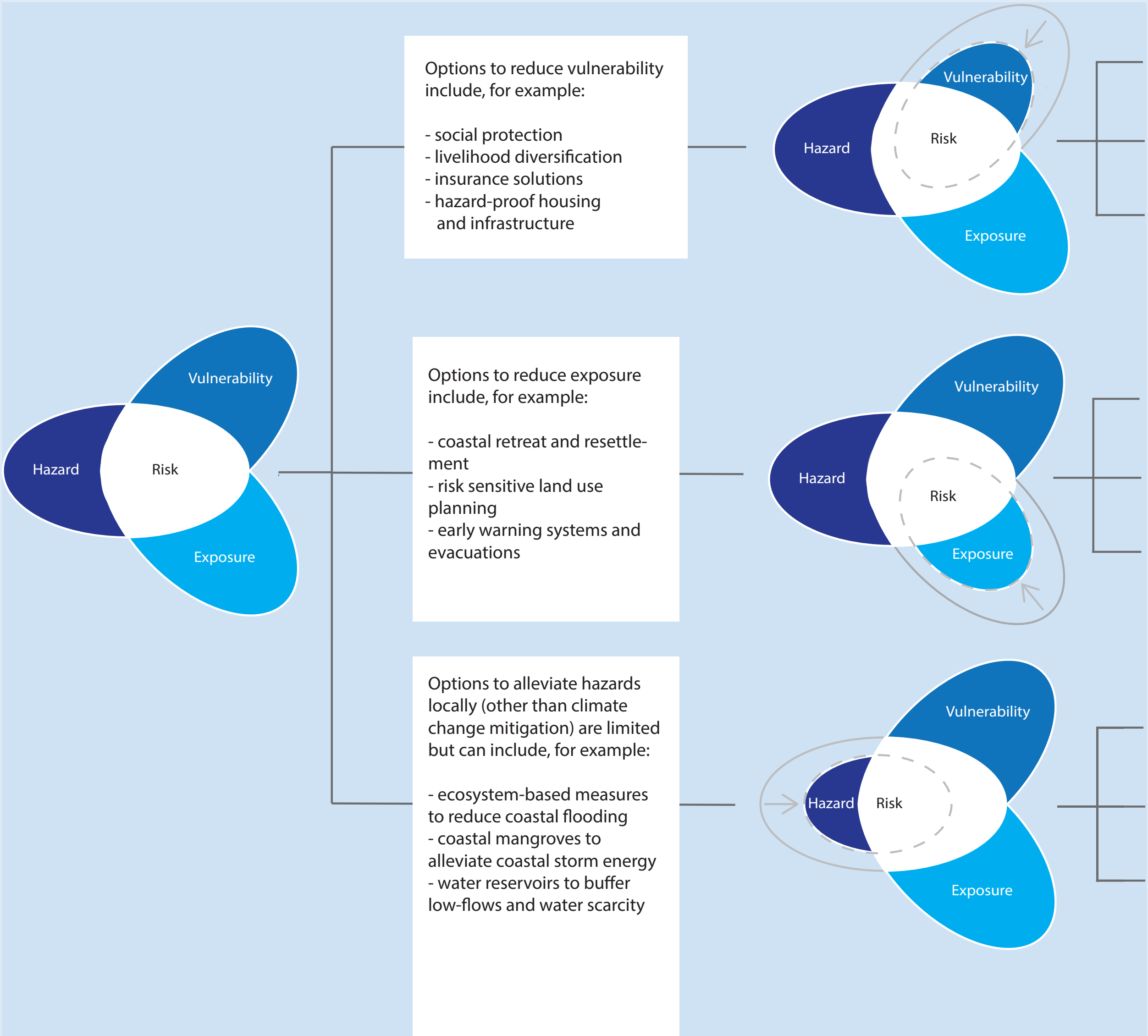
Cross-Chapter Box 1: Key Concepts of Risk, Adaptation, Resilience and Transformation

Authors: Matthias Garschagen (Germany), Carolina Adler (Switzerland), Susie Crate (USA), Hélène Jacot Des Combes (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 (Hungary), Martin Sommerkorn (Norway/Germany)

Cross-Chapter Box 1 introduces key concepts used in SROCC in relation to risk, adaptation, resilience, and transformation. Building on an assessment of the current literature, this box provides a conceptual framing for the report and the assessments within its chapters. Full definitions of key terms are provided in SROCC Annex I: Glossary.

Risk and adaptation

SROCC considers risk from climate change-related effects on the ocean and cryosphere as the result of the interaction between: (1) environmental hazards triggered by climate change, (2) the exposure of humans, infrastructure and ecosystems to those hazards, and (3) the systems' vulnerabilities. While risk (see SROCC Annex I: Glossary) refers to the potential for adverse consequences, impacts refer to materialised risk (see SROCC Annex I: Glossary). Next to assessing risk and impacts specifically resulting from climate change-related effects on the ocean, coast, and cryosphere, SROCC is also concerned with what options exist to reduce climate-related risk. Beyond mitigation, adaptation (see SROCC Annex I: Glossary) is a central way to reduce risk and exploit new opportunities. Adaptation efforts link into the causal fabric of risk by reducing existing and preventing future vulnerability, exposure, and/or (where possible) hazards (Cross-Chapter Box 1, Figure 1). Addressing these different risk components involves assessing and selecting options for policy and action. Such decision-making involves an evaluation of the effectiveness, efficiency, efficacy, and acceptance of actions. Adaptation responses are more effective when they promote resilience to climate change, consider plausible futures and inevitable surprises, strengthen essential or desired characteristics as well as values of the responding system, and/or make adjustments to avoid unsustainable pathways (*high agreement*, *medium evidence*). (Sections 2.3.2.3; 2.3.4.1; Box 2.4; 4.4.4; 4.4.5)



Cross-Chapter Box 1, Figure 1: Options for risk reduction through adaptation. Adaptation can reduce risk by addressing one or more of the three risk factors: vulnerability, exposure, and hazard. The reduction of vulnerability, exposure, and hazard potential can be achieved through different policy and action choices over time.

Adaptation requires adaptive capacity, which for human systems includes assets (financial, physical and/or ecological), capital (social and institutional), and technological know-how (Klein et al., 2014). The extent of adaptive capacity determines adaptation potential, but does not necessarily translate into effective adaptation if awareness of the need to act, the willingness to act, or the cooperation needed to act is lacking (*high agreement*, *robust evidence*) (Sections 2.3.1.4.2; Box 2.4; 4.3.2.6.3; 5.5.2.4).

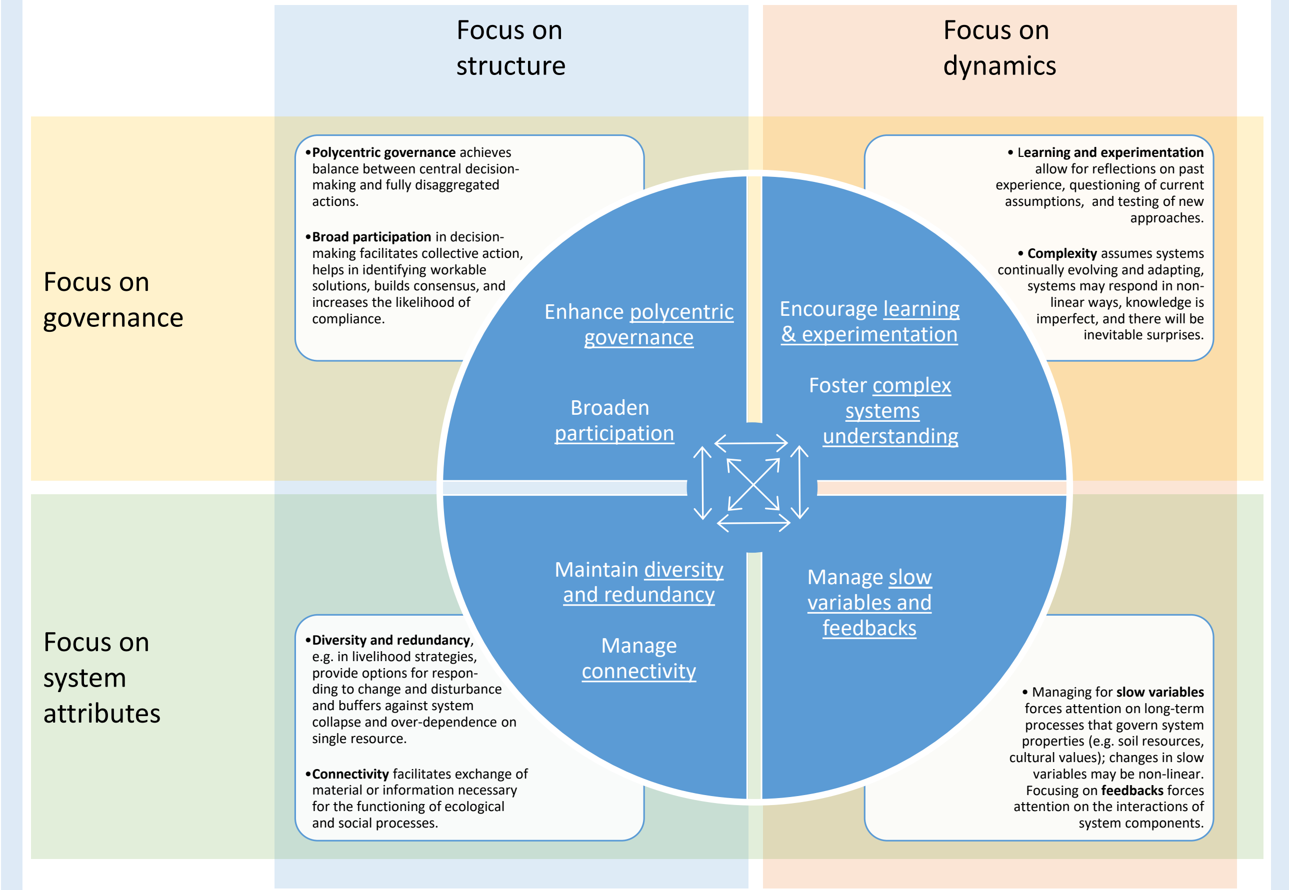
There are limits to adaptation, which can be physical, ecological, and/or socio-cultural (*high agreement*, *medium evidence*) (Dow et al., 2013; Klein et al., 2014). For example, the ability to adapt to sea level rise depends, in part, on the elevation of the low lying islands and coasts in question (Cross-Chapter Box 5). Limits to adaptation are different from barriers to adaptation. Barriers can in principle be overcome if adaptive capacity is available (e.g., where funding is made available), even though overcoming barriers is often hard in reality, particularly for resource-poor countries and communities (Section 4.4.5.5.2) (*high agreement*, *robust evidence*). Limits to adaptation are reached when adaptation does no longer allow an actor or ecosystem to secure valued objectives or key functions from intolerable risks (Section 4.3.4.2) (Dow et al., 2013). Defining tolerable risks and key system functions is therefore of central importance for the assessment of limits to adaptation.

Residual risks (the risk that endures following adaptation and risk reduction efforts) remain even where adaptation is possible (*high agreement*, *robust evidence*) (Chapters 2-6). In the policy arena, residual risks have bearing on the emerging debate about loss and damage (SROCC Annex I: Glossary; Huq et al., 2013; Warner and van der Geest, 2013; Boyd et al., 2017; Djalante et al., 2018; Mechler et al., 2018). Under the UNFCCC, the Warsaw International Mechanism for Loss and Damage has been established to address loss and damage associated with impacts of climate change in developing countries that are particularly vulnerable. It addresses loss and damage in relation to slow onset processes, e.g. ocean acidification (Chapter 5), sea level rise (Chapter 4), and glacier retreat (Chapter 2), as well as rapid onset hazards, e.g. storms (Chapter 6). It encompasses non-economic losses, including the impacts on intrinsic and spiritual attributes with which high mountain societies value their landscapes (Section 2.3.5); the interconnected relationship with, and reliance upon, the land, water, and ice for culture, livelihoods, and wellbeing in the Arctic (Chapter 3); and cultural heritage and displacement addressed in the Cross Chapter Box on Low lying Islands and Coasts (Burkett, 2016; Markham et al., 2016; Tschakert et al., 2017; Huggel et al., 2018). Since climate change risks cannot be fully avoided, resilience is necessary in human systems and ecosystems in order to deal with potential shocks and crises, and to avoid or minimise loss and damage (Sections 2.3.2.3; 2.4.2; Chapter 6) (*high agreement*, *medium evidence*).

Building resilience

Climate change-related impacts on the ocean and cryosphere can generate stresses and shocks to ecosystems and humans. This makes social-ecological resilience an important concept to understand and shape the trajectories of human and natural systems (Biggs et al., 2012). In SROCC, resilience is understood as the capacity of interconnected social, economic, and ecological systems to cope with disturbances, by reorganising in ways that maintain their essential function, structure, and identity (SROCC Annex I: Glossary; Walker et al., 2004; Agard et al., 2014). The literature on resilience offers many interpretations of the concept. Resilience may be considered as a positive attribute of systems and an aspirational goal (Steiner, 2015) when it helps to maintain the capacity for adaptation, learning, and/or transformation (Walker et al., 2004; Steiner, 2015). Alternately, resilience may be used descriptively as a system property that is neither good nor bad (Walker et al., 2004; Chapin et al., 2009; Weichselgartner and Kelman, 2014), for example, when a system is highly resilient in keeping its unfavoured attributes, such as poverty or social exclusion. Critics of the resilience concept warn that its application to social systems is problematic when the responsibility for resilience building is shifted 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).

“Resilience thinking” invites an emphasis on human and natural systems dynamics to cultivate the building and maintenance of a system’s capacity to navigate stress and shocks (Biggs et al., 2012; Varma et al., 2014; Sud et al., 2015). Seven general strategies for building social-ecological resilience have been recognized (Cross-Chapter Box 1, Figure 2) (Ostrom, 2010; Biggs et al., 2012; Quinlan et al., 2016). Resilience thinking allows scientists, risk practitioners, and decision makers to recognise how climate-change related risks often cannot be fully avoided or alleviated despite adaptation. For SROCC, this is especially relevant along low-lying coasts, in high mountain areas and in the polar regions (Chapters 2, 3, 4).

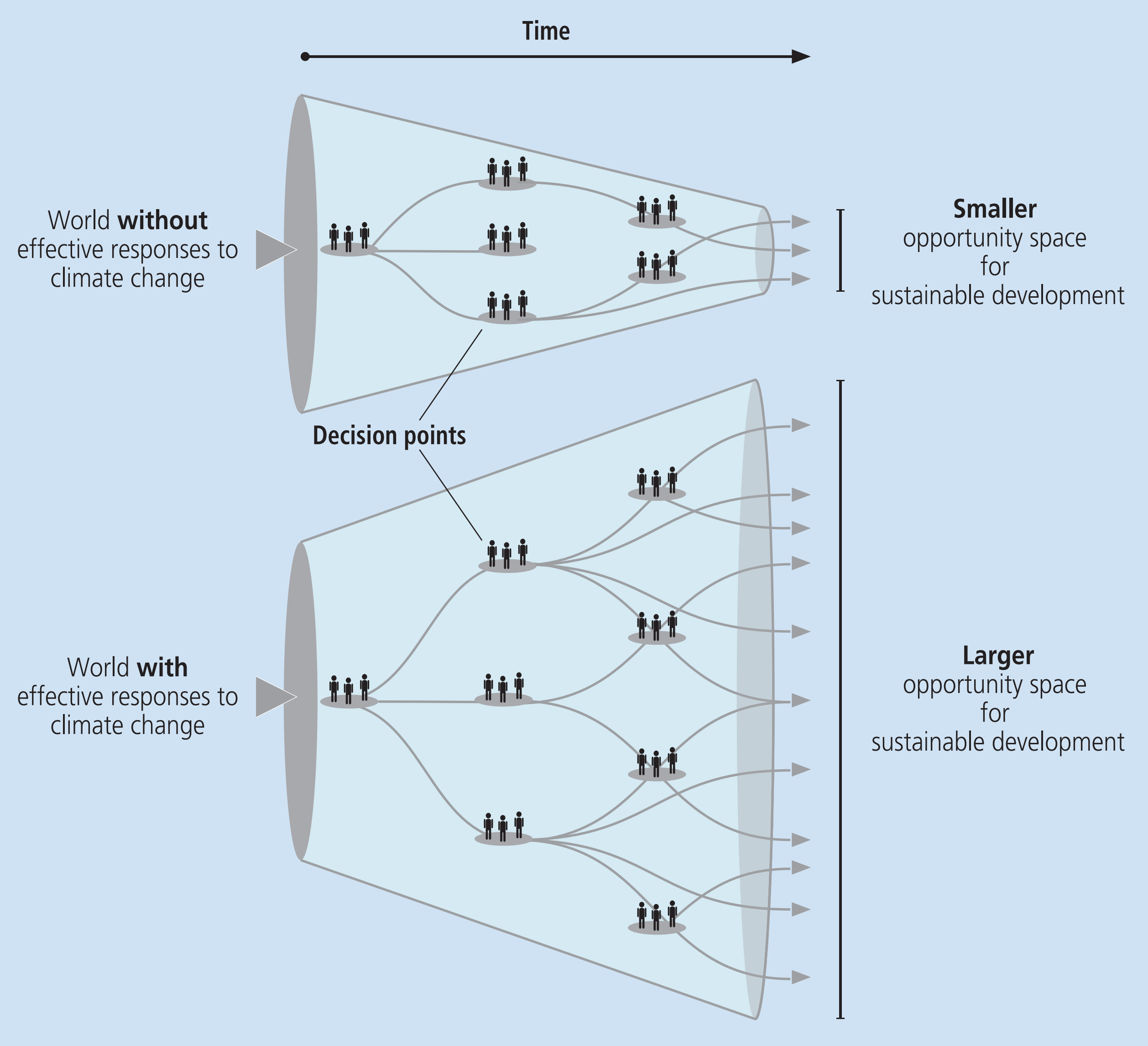


Cross-Chapter Box 1, Figure 2: General strategies for enhancing social-ecological resilience to support climate-resilient pathways. Seven identified strategies embody the key properties of social-ecological systems (centre circle). They group along two axes depending on whether they focus on system structure or dynamics, and whether they refer to the system's attributes or governance. The rationale for how each strategy enhances social-ecological resilience is summarised in the white boxes. The figure and text material are adapted from synthesis papers by Biggs et al. (2012) and Quinlan et al. (2016).

Many efforts are underway to apply resilience thinking in assessments, management practices, policy-making, and the day-to-day practices of affected communities. For example, leaders of the Pacific small island developing states (SIDS) use the Framework for Resilient Development in the Pacific, which integrates climate change and disaster risk management (Pacific Community et al., 2016; Cross-Chapter Box 5). In the Philippines, a new framework has been developed to conduct full inventories of actual and projected loss and damage due to climate change and associated disasters. Creating such an inventory is difficult due to the disconnect between tools for climate change assessment and those for post disaster assessment (Florano, 2018). In Arctic Alaska, evaluative frameworks are being applied to determine needs, responsibilities, and alternative sanctions associated with coastal village relocations (Bronen, 2015; Chapter 3). In all these initiatives, resilience is a key consideration for enabling climate resilient development pathways.

Climate resilient development pathways

Climate resilient development pathways (CRDPs) are a relatively new concept to describe pathways that combine the goals of climate change adaptation, mitigation, and sustainable development, through an iterative process for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change today and into the future (Kainuma et al., 2018; Roy et al., 2018). CRDPs are increasingly being explored as an approach for combining scientific assessments, stakeholder participation, and forward-looking development planning, acknowledging that pursuing CRDP is not only a technical challenge of risk management but also a social and political process (Roy et al., 2018). Adaptive decision-making over time is key to CRDPs (Haasnoot et al., 2013; Wise et al., 2014; Fazey et al., 2016; Cross-Chapter Box 1, Figure 3). CRDPs accommodate both the interacting cultural, social, and ecosystem factors that influence multi-stakeholder decision-making processes, and the overall sustainability of adaptation measures. As illustrated in Cross-Chapter Box 1, Figure 3, a lack of adequate climate change mitigation and adaptation can limit the opportunities for sustainable development pathways and the options for resilience-building. CRDPs involve series of adaptation choices over time, balancing short-term and long-term goals and accommodating newly available knowledge (Denton et al., 2014). The CRDPs approach has been successfully used, for example, in urban, remote, and disadvantaged communities, and can showcase the potential to counter maladaptative choices (e.g., Barnett et al., 2014; Butler et al., 2014; Maru et al., 2014). CRDPs aim to establish narratives of hope and opportunity that can extend beyond risk reduction and coping (Amundsen et al., 2018). Although climate change impacts on the ocean 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; Smith and Leiserowitz, 2014; Feldman and Hart, 2016; Feldman and Hart, 2018; Prescott and Logan, 2018).



Cross-Chapter Box 1, Figure 3: Climate change response and development pathways. The lack of effective mitigation and adaptation action over time limits the opportunity space for sustainable development and climate resilient pathways within that space. Adaptive decision-making over time helps to build climate-resilient development pathways and widens the opportunity space for sustainable development.

Much of the adaptation and resilience literature published since AR5 highlights the need for transformations (see SROCC Annex I: Glossary) that enable effective climate change mitigation (most notably, to decarbonise the economy) (Riahi et al., 2017), and support adaptation (e.g., Pelling et al., 2015; Few et al., 2017). Transformation becomes particularly relevant when existing mitigation and adaptation practices cannot reduce risks and impacts to an acceptable level. Transformative adaptation, therefore, involves fundamental modifications of policies, policy-making processes, institutions, human behaviour, and cultural values (Pelling et al., 2015; Solecki et al., 2017). Successful transformation requires attention to conditions that allow for such changes, including timing (i.e., windows of opportunity, social readiness (some level of willingness), and resources to act (trust, human skill and financial resources) (Kofinas et al., 2013; Moore et al., 2014). Examples related to SROCC include shifting from a protection paradigm reliant on seawalls, to a paradigm of living with saltwater as a response to coastal flooding (Renaud et al., 2015), or to one involving fundamental risk management changes in coastal megacities, including retreat (Solecki et al., 2017). Transdisciplinary approaches, that involve collaboration between actors in science, government, the private sector, civil society, and affected communities (Section 1.8.3 and Cross-Chapter Box 3), can foster transformation in different ocean and cryosphere contexts (Padmanabhan, 2017; Cross-Chapter Box 2).

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[END CROSS-CHAPTER BOX 1 HERE]

1.5.1 Natural Systems

In SROCC the term 'Natural System' is used to describe the biological and physical components of the environment, independent of human involvement but potentially affected by human activities. Additionally, 'Natural Systems' can also describe physical systems (e.g., an ocean upwelling system) without necessarily considering the organisms within that system. In neither usage does 'Natural System' imply a pristine system.

1.5.1.1 Hazards to Natural Systems

Hazards to marine ecosystems assessed in AR5 (IPCC, 2014b) included degradation of coral reefs (*high confidence*), oceanic deoxygenation (*medium confidence*), and ocean acidification (*high confidence*). Shifts in the ranges of plankton and fish were identified with *high confidence* regionally, but with uncertain trends globally. SROCC provides more evidence for global shifts in the distribution of marine organisms, and in how the phenology of animals is responding to ocean change (Sections 3.2.3, 5.2). The signature of climate change is now detected in almost all marine ecosystems, particularly in coral reef, sandy beach, pelagic surface, and seamount ecosystems (Section 5.2). Similar trends of changing habitat due to climate change are reported for the cryosphere (Sections 2.3.3, 3.4.3.2). It is noted that climate warming may lead to habitat expansion, e.g., into polar systems (Section 3.2.4), in addition to shifts in ecosystem/organism ranges and phenology.

Hazards faced by marine and coastal organisms, and the ecosystem services they provide, are dependent on future greenhouse gas emission pathways, with moderate risks of impacts under a low emission future, but high to very high risks of impacts under higher emission scenarios (Mora et al., 2013; Gattuso et al., 2015).

1.5.1.2 Exposure of Natural Systems

Exposure to risk in cryosphere systems can occur in the immediate vicinity of cryosphere components, or at regional to global scales where cryosphere changes link to other natural systems. For example, decreasing Arctic sea ice increases exposure for ecosystems that depend upon sea ice for habitat, but also has far-reaching impacts through the resulting direct albedo feedback and amplification of Arctic climate warming (e.g., Pistone et al., 2014) that then increases surface melting of the Greenland ice sheet (Liu et al., 2016; Stroeve et al., 2017). Ice loss from ice sheets and other sources is another example of cryosphere change causing the global-scale exposure of sea level rise, and more local effects to coastal ecosystems leading to modification and loss of habitat (Sections 3.2.3 and 4.3.3.5). 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 feedbacks from these interactions range from local impacts on topography, hydrology and biology, to complex influences on global scale biogeochemical cycling (e.g., methane release) and climate (Grosse et al., 2016; Phillips et al., 2017; Sections 2.2, 2.3, 3.4).

Exposure to climate change risk exists for virtually all coastal organisms and habitats (Section 5.2), through processes such as inundation and salinisation (Section 4.3). Coastal ecosystems may experience increases in harmful algal blooms and invasive species (Glibert et al., 2014; Gobler et al., 2017; Townhill et al., 2017; Box 5.3), while coral reef systems are under increasing pressure from both rising ocean temperature and acidification (Hoegh-Guldberg et al., 2017). Ocean acidification and deoxygenation further impact organisms (Sections 3.2.3, 5.2.3), and multi-driver impacts are dramatically altering ecosystem structure and function in the coastal and open ocean (Boyd et al., 2015; Deutsch et al., 2015).

Increasing exposure to climate change risk exposure in open ocean natural systems includes ocean acidification (O'Neill et al., 2017; Section 5.2.3), changes in ocean ventilation, deoxygenation (Shepherd et al., 2017; Section 5.2.2.4), and enhanced ocean-atmosphere coupling (Sections 6.3, 6.5). Heat content is rapidly changing throughout the ocean, with over one third of the industrial-era heat increase occurring below 700 m (Gleckler et al., 2016). Critically, global ocean models may severely underestimate the rate and range of rising heat content at regional scales (Saba et al., 2016).

1.5.1.3 Vulnerabilities in Natural Systems

Vulnerabilities to risk lead to direct and indirect impacts on natural systems; 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 range shifts for many species (Kleisner et al., 2017). Vulnerability may manifest where organisms or ecosystems are unable to migrate or evolve at the rate required to adapt to ocean and cryosphere changes. A wide range of non-climatic pressures also magnify the vulnerability of ocean and cryosphere ecosystems to climate-related changes. Examples include overfishing, coastal development, and pollution, including plastics pollution (Halpern et al., 2008; Halpern et al., 2015; IPBES, 2018a; IPBES, 2018d; IPBES, 2018b; IPBES, 2018c).

1.5.1.4 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 supports decision-making by quantifying benefits for valuation and trade-off analyses. The ecosystem services framework has been challenged as monetising 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 (IPBES), 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 SROCC to assess the impacts of changes in the ocean and cryosphere on humans directly, and through changes to the ecosystems that support human life and civilisations (Sections 2.3, 3.4.3.2, 4.3.3.5, 5.4, 6.4, 6.5, 6.8).

1.5.2 Human Systems

In SROCC, 'Human System' includes physiological, health, socio-cultural, belief, technological, economic, food, political, and legal systems, among others (Agard et al., 2014). Humans have depended upon the Earth's ocean (Kubiszewski et al., 2017) and cryosphere (Hovelsrud et al., 2011) for millennia (Redman, 1999). Contemporary human populations still depend directly on elements of the ocean and cryosphere, and the ecosystem services they provide, but at a much larger scale and with a proportionally greater environmental impact than in pre-industrial times (Inniss and Simcock, 2017).

1.5.2.1 Hazards and Opportunities for Human Systems

Changes in the ocean and cryosphere bring hazards that affect the wellbeing and security of populations in coastal, mountain, and polar environments (Allison, 2015; Shijin and Dahe, 2015; Pecl et al., 2017). Some impacts are direct, such as sea level rise or coastal erosion that can displace coastal residents (FitzGerald et al., 2008; McLeman and Brown, 2011; Collins et al., 2017; Otto et al., 2017). Other effects are indirect; for example, rising ocean temperatures have led to increases in maximum wind speed and rainfall rates in tropical cyclones (Stocker et al., 2013), creating hazards with severe consequences for natural and human systems (Chapters 4 and 6). The multiple category 4 and 5 Atlantic hurricanes in 2017 caused the loss of over 3300 lives and more than 350 billion US$ in economic damages (Andrade et al., 2018; Murakami et al., 2018; NOAA, 2018; Cross-Chapter Box 7). Some hazards related to ocean and cryosphere change involve nonlinear interactions, tipping points, and irreversible changes (Section 1.3), which generate additional and sometimes unpredictable risks (Chapter 6). For example, thawing permafrost and sea level rise has damaged Arctic infrastructure (e.g., buildings, roads) (AMAP, 2015). Permafrost thawing and extreme weather events have impacted reindeer husbandry livelihoods for Sami and other Arctic Indigenous peoples (Lavrillier and Gabyshev, 2017; Lavrillier and Gabyshev, 2018). Loss of coastal Arctic sea ice has impeded access to hunting grounds, other communities, and travel routes fundamental to the livelihoods, food security, and wellbeing of Inuit and other Northern cultures (AMAP, 2015; Watt-Cloutier, 2015). Here, the seemingly incremental loss of sea ice thickness and permafrost thawing has now reached a tipping point where adaptive practices can no longer work (Chapter 3).

Climate change impacts on the ocean and cryosphere also present opportunities, in at least the near and medium term. For example, in Nepal warming of high-mountain environments and accelerated melting of snow and ice have extended the growing season and crop yields for some local farmers (Gaire et al., 2015; Merrey et al., 2018; Section 2.3.1). In the Arctic, changing ice conditions could bring opportunities for new shipping routes and access to new mineral resources. Marine fishing opportunities are changing, with new fisheries opening and traditional ones being reduced as rising ocean temperatures cause a redistribution of marine fish (Bell et al., 2011; Fenichel et al., 2016; Section 5.4). To gain from new opportunities for improving the well-being of people, while also avoiding or mitigating new or increasing hazards, it is necessary to be informed of what may be coming in the future. Chapters 2 to 6 of SROCC provide the best knowledge available on possible ocean and cryosphere changes, and the enabling and limiting conditions for potential adaptation strategies.

1.5.2.2 Exposure of Human Systems

Those who live close to the ocean and/or cryosphere, or depend directly on their resources for livelihoods, are particularly exposed to climate change impacts (Barange et al., 2014; Romero-Lankao et al., 2014; AMAP, 2015). Exposure to some climate change hazards can result in infrastructure damage and failure; loss of habitability; changes in air quality; increased morbidity and mortality due to injury, infectious disease, heat stress, and mental health challenges; compromised food and water security; economic and non-economic impacts due to reduced production and social network system disruption; conflict; and widespread human migration (Oppenheimer et al., 2014; Van Ruijven et al., 2014; AMAP, 2015; Cunsolo and Ellis, 2018).

Chapters 2-6 document how people residing in coastal and cryosphere regions are already exposed to climate change hazards, and how many of these hazards are projected to increase in the future. For example, mountain communities have been exposed to increased snow and ice melt (Shrestha et al., 2017; You et al., 2017) that increase the risks of glacial lake outburst floods (Riaz et al., 2014; Gurung et al., 2017) and landslides (Huggel et al., 2012; Section 2.3.2). Exposure to hydrological system changes can 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). Exposure to declining glaciers can have socio-cultural impacts, as many glaciers hold sacred and symbolic meanings for mountain communities (Cruikshank, 2005; Allison, 2015; Shijin and Dahe, 2015; Section 2.3.4). In the Arctic, exposures to extreme warming, and to continued ice and permafrost loss are particularly challenging for Arctic Indigenous communities, due to the close interdependent relationships they hold with the sea ice for livelihoods, habitability, food security, transportation, culture, health and wellbeing (Larsen et al., 2014; Cunsolo Willox et al., 2015; Section 3.5).

People living in low elevation coastal zones (LECZ; land less than 10 m above sea level) are particularly exposed to future sea level rise. Population in the LECZ is projected to increase to more than one billion by 2050 (Jones and O'Neill, 2016; Merkens et al., 2016; Section 4.3.2.2). Coastal communities are also exposed to rising ocean temperatures (including marine heat waves; Section 6.4), enhanced coastal erosion, cyclones, and ocean acidification, with associated risks for the fisheries, tourism, trade, and food security these communities depend upon (Hoegh-Guldberg et al., 2014). Risks also include loss of life and damaged assets, and disruption of basic services including safe water supplies, sanitation, energy, and transportation networks (Chapters 4, 5, 6). Coastal shipping and industrial infrastructure are also exposed to risk from changes in sea level, wind, wave height, and storm intensity, with consequences for drinking water, energy, telecommunications, trade, and social service provision.

1.5.2.3 Vulnerabilities in Human Systems

Although communities may be exposed to various climate change-related hazards, their particular vulnerability to climate change risk is a function of social, political, cultural, economic, institutional, geographical, and/or demographic factors. These include social exclusion, inequalities, and differential access to and control over the social, financial, technological and environmental resources that are required for adaptation and transformation (Oppenheimer et al., 2014; AMAP, 2015), which can be shaped by factors such as gender, age, race, class, caste, indigeneity, disability, and other factors. Such disparities and inequities present a context of non-climatic challenges to health and wellbeing, economic development, and basic human rights, resulting in limited options for coping and adapting to change (Hijioka et al., 2014). It is also important to note that populations with greater wealth and privilege can also be vulnerable to some climate change risks (Cardona et al., 2012; Smith et al., 2014). For example, dependence upon established infrastructure that is poorly suited to ocean or cryosphere change can increase a population's vulnerability to climate change impacts.

Institutions and governance can shape vulnerability and adaptive capacity, and weak governance structures can be challenged to respond to extreme or persistent climate change hazards (Berrang-Ford et al., 2014; Hijioka et al., 2014). For example, the damage caused by the 2017 hurricane Maria in Puerto Rico illustrates how weak components within institutions and governance hindered effective responses to this extreme event (Alcorn, 2017; Vandermeer, 2017; Sections 6.4, 6.9). Furthermore, populations can be negatively impacted by inappropriate climate change policies, particularly ones that further marginalise their knowledge, culture, values, and livelihoods (Field et al., 2014; Cross-Chapter Box 2).

Vulnerability is not static or homogeneously experienced. The vulnerabilities of individuals, groups, and populations to climate change is dynamic and diverse, and reflects changing societal and environmental conditions. SROCC examines vulnerability following the conceptual definition presented in Cross-Chapter Box 1, and vulnerability in human systems is treated in relative, rather than absolute terms.

1.6 Addressing Consequences of Climate Change for the Ocean and Cryosphere

Effective and urgent mitigation of climate change is required to reach the goals of the Paris Agreement (UNFCCC, 2015), while adaptation to climate change effects on the ocean and cryosphere is necessary to enable climate resilient development pathways that keep residual risk as well as loss and damage to a minimum (Allen et al., in press-a; Cross-Chapter Box 1). *Mitigation* refers to human actions to limit climate change by reducing the emissions and enhancing the sinks of greenhouse gases, whereas *adaptation* is the process of adjustment to the actual, expected, and partly unavoidable impacts of climate change (Agard et al., 2014). Recognising the importance of the ocean in the climate system, the presidency of the 23rd Conference of the Parties (COP23) of UNFCCC introduced the oceans pathway into the climate solution space.

Mitigation and adaptation pathways to avoid dangerous climate change are considered in the IPCC Special Report on Global Warming of 1.5°C (SR1.5) (Allen et al., in press-a). SROCC assesses several ocean and cryosphere-specific measures for addressing the causes of climate change, supporting biological and ecological adaptation, and enhancing societal adaptation (Figure 1.2). Other mitigation options exist, including solar radiation management and several other forms of geoengineering, but are not addressed in SROCC as they are covered in other products of the IPCC Sixth Assessment Cycle (SR1.5 and AR6 Working Group III).

In-depth discussion of direct climate change mitigation is outside the scope of SROCC, but there are many indirect measures that involve the ocean and the cryosphere (Figure 1.2). These include supporting biological and ecological adaptation through pollution reduction (which moderates ocean acidification in eutrophied areas) and conservation (which preserves of biodiversity and habitats) in coastal regions.

Ocean-related mitigation measures have trade-offs. The consequences of approaches such as ocean-based CO_2 removal at the global scale is uncertain, with potentially large disbenefits (e.g., ocean fertilisation and alkalinisation). The greatest benefit is derived by combining global and local measures (Gattuso et al., 2018). Local measures, such as pollution reduction and conservation, provide significant co--benefits and few disbenefits. They can be rapidly scaled-up, but are less effective in addressing the global problem. Likewise, local efforts to decrease air pollution near mountain glaciers and other cryosphere components can bring health benefits while reducing snow and ice melting on regional scales (Shindell et al., 2012).

The adaptive capacity of natural systems to climate change can be further enhanced by human interventions. For example, manipulating an ecosystem's structural or functional properties (e.g., restoration of mangroves) may minimise climate change pressures, enhance natural resilience and/or re-direct ecosystem responses to reduce cascading risks on societies. In human systems, adaptation can involve both infrastructure (e.g., enhanced sea defences) and community-based action (e.g., changes in policies and practices). There are limits to effective adaptation, which mean that adaptation options to ongoing climate change need to be undertaken alongside climate change mitigation strategies.

Investment in reducing greenhouse gas emissions through mitigation creates opportunities for long term solutions which could reduce the need for adaptation strategies (IPCC, 2014a). Economic methods are important for decision making in the mitigation and adaptation space (Jones et al., 2014). In SROCC, two main economic approaches are used. The first comprises the Total Economic Value method to attach monetary value to non-market goods. From an economic viewpoint, biodiversity is seen as natural capital essential for human welfare, and has direct and indirect value, and existence and non-use value. Such ecosystem services are categorised into provisioning, regulating and supporting, as well as cultural and recreational. When marine and cryospheric ecosystems change, human economies and societies are affected (e.g., section 5.4). SROCC considers the paradigm of sustainable development, and the linkages between climate impacts on ecosystem services and the consequences on sustainable development goals including food security or poverty eradication. The second economic approach used in SROCC are the formal decision-analytical methods used to identify options that perform best, or reasonably well, given some criteria. These methods are widely applied for adaptation and mitigation and 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 in the context of coastal adaptation (e.g., Section 4.4.5.3).

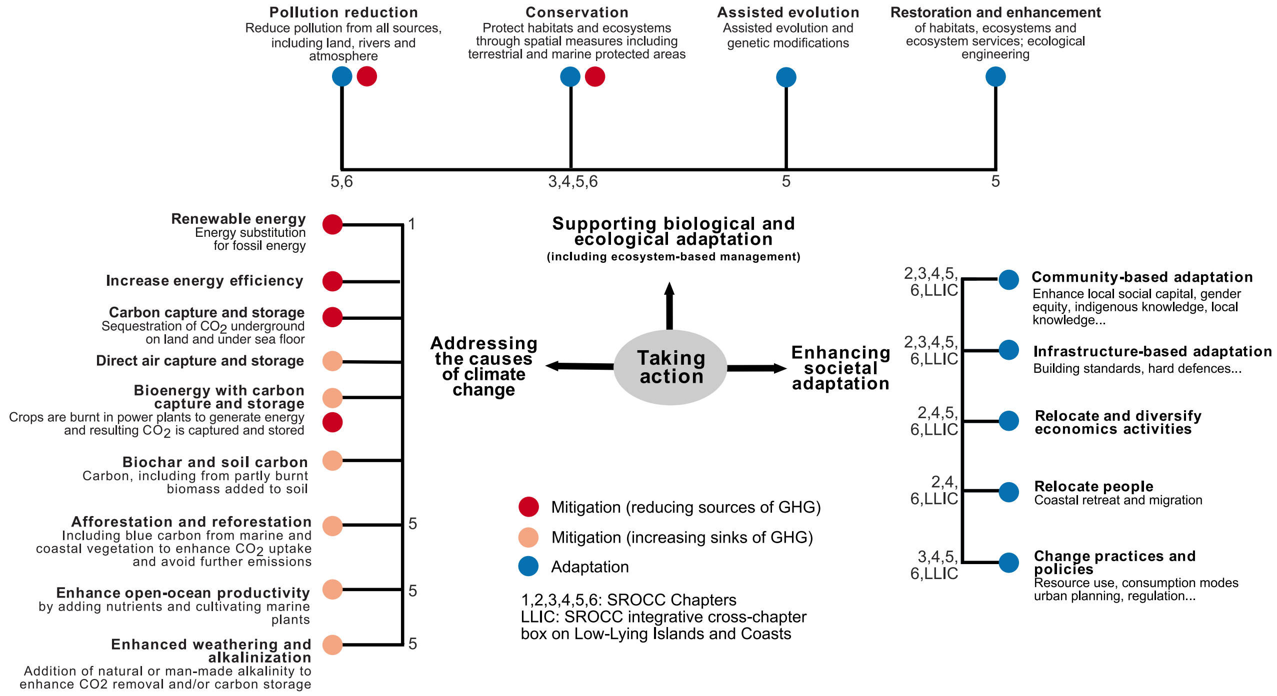


Figure 1.2: Overview of the main responses to observed and expected changes in the ocean and cryosphere in a changing climate including mitigation and adaptation measures. The numbers refer to the corresponding chapters of SROCC. Ecosystem-based management (covered in chapters 2-5) comprises activities to increase the resilience and reduce the vulnerability of people and the environment to climate change. Solar radiation management techniques are omitted because they are covered in other AR6 products (for example, SR1.5). Governance-based solutions (e.g., institutional arrangements) are not included in this figure but are covered in Cross-Chapter Box 2 and Chapters 2-6. Modified from Gattuso et al. (2018)

1.6.1 Adaptation in Natural Systems

In AR5, a range of changes in ocean and cryosphere natural systems were linked with *medium* to *high confidence* to pressures associated with climate change (Cramer et al., 2014). Climate change impacts on marine, coastal, coral reef, polar, and high altitude ecosystems are variable in both space and time. The multiplicity of pressures these natural systems experience make it hard to attribute population or ecosystem responses to a specific ocean and/or cryosphere change. The complex interconnectivity of populations with their ecosystems means that a single ‘adaptive response’ of a population, or the aggregate response of an ecosystem (comprising the adaptive responses of the interconnected populations), is influenced not just by the direct pressure of climate change, but occurs in concert with the adaptive responses of other species in the ecosystem.

Much effort has gone into resolving the mechanisms, interactions, and feedbacks of natural systems associated with the ocean and cryosphere since AR5. New knowledge is assessed in the chapters of SROCC and includes, for example, substantial new information that marine heat waves and large pools of anomalously warm water are occurring in many ocean settings (Oliver et al., 2018; Section 6.4). Chapters 4, 5, and 6 review the adaptive responses of wetlands, coral reefs, other coastal habitats, and the populations of marine organisms encountering these increasing ocean temperature extremes. Likewise, examples from Chapters 2 and 3 describe emerging knowledge on how ecosystems in high-mountain areas are adapting to glacial decline, and in the Arctic to diminishing sea ice.

Past IPCC assessments have begun to highlight the importance of evolutionary adaptation as a component of how populations adapt to climate change pressures. Acclimatisation (phenotypic plasticity) can result from changes in gene expression but does not involve any change in the underlying DNA sequence. Plastic responses can occur both within single generations and over several generations. In contrast, evolution requires changes in the genetic composition of a population over multiple generations; for example, by differential survival or fecundity of different genotypes (Sunday et al., 2014). Adaptive evolution is the subset of evolution that is attributable to natural selection. This type of evolution leads to populations becoming more fit in the environment where they are evolving (Sunday et al., 2014) and can extend the range of environments where populations persist (van Oppen et al., 2015). The efficacy of natural selection is affected by population size (Charlesworth, 2009), standing genetic variation, the ability of a population to generate novel genetic variation, migration rates, and the frequency of genetic recombination (Rice, 2002). Many studies have shown trait evolution within and across life-stages of populations (Pespeni et al., 2013; Hinners et al., 2017), but there are fewer studies on how evolutionary change can impact ecosystem or community function, and whether trait evolution is stable (Schaum and Collins, 2014). Although acclimatisation and evolutionary adaptation are separate processes, they influence each other, and both adaptive and maladaptive plasticity can facilitate evolution (Schaum and Collins, 2014; Ghalambor et al., 2015). Natural evolutionary adaptation may be challenged by the speed and magnitude of current ocean and cryosphere changes, but emerging data looks at ways in which human actions can assist evolutionary adaptation enhance the resilience of natural systems to climate change pressures (e.g., Chapter 5)

1.6.2 Adaptation in Human Systems

There are several key human adaptation options for climate change impacts on the ocean and cryosphere. Adaptive responses include nature-based approaches (Renaud et al., 2016), ecosystem-based approaches (Serpetti et al., 2017), and managed retreat, along with other forms of internal migration (Black et al., 2011; Hino et al., 2017). Building from AR5 insights (Wong et al., 2014), Chapter 4 describes four main modes of adaptation for sea level rise and storms in low-lying areas: protect, advance, accommodate, and retreat (Wong et al., 2014). Chapters 2-6 of SROCC demonstrate that all modes of adaptation include mixes of institutional, socio-cultural, engineering and/or ecosystem-based measures (e.g., Section 4.4.2).

As affected individuals, communities, and nations implement, test, and evaluate adaptive responses, researchers generate new evidence on processes and outcomes. There is emerging evidence about the effectiveness and performance of different adaptation options, and of their social acceptance, political feasibility, cost-efficiency, co-benefits, and trade-offs (Jones et al., 2012; Adger et al., 2013; Eriksen et al., 2015). Nevertheless, scientific evaluation of past adaptation successes and future adaptation options are complex and inadequately researched (Magnan and Ribera, 2016). In the end, the priorities for adaptation will depend on the risk attitudes of investment institutions (and the returns they may gain) (Lobell et al., 2008), along with access to finances, technology, capacity, and other resources (Berrang-Ford et al., 2014; Eisenack et al., 2014).

Since AR5, transformational adaptation (the need for fundamental changes in institutions and flexible decision-making processes to face climate change consequences) has been increasingly studied (Cross-Chapter Box 1). The recent literature documents how societies, institutions, and/or individuals increasingly assume a readiness to engage in transformative change, via their acceptance and promotion of fundamental alterations in natural or human systems (Klinsky et al., 2016). People living in and near coastal, mountain, and river environments often pioneer these types of transformations, since they are at the frontline of ocean and cryosphere change (e.g., Solecki et al., 2017). Similarly, the concepts of scenario planning and 'adaptation pathway' design have emerged since AR5, especially in the context of development planning for coastal and delta regions (Haasnoot et al., 2013; Wise et al., 2014; Maier et al., 2016; Flynn et al., 2018; Section 4.4, Cross-Chapter Box 7). Such approaches are helpful when choosing between different options, planning for their implementation and sequencing, and identifying limits to adaptation strategies and uncertainties.

As knowledge on the effectiveness and limitations of adaptation strategies in the ocean and cryosphere sharpens, so too does the major political and scientific challenge of assessment and evaluation of risk, and of loss and damage (Allen et al., in press-a; Cross-Chapter Box 1). SROCC assesses these risks, both as they exist now, and into the future.

1.7 Governance and Institutions

SROCC conceptualises governance as deciding, managing, implementing and monitoring policies in the context of ocean and cryosphere change. Institutions are defined as formal and informal social rules that shape human behaviour (Roggero et al., 2017). Governance guides how different actors negotiate, mediate their interests, and share their rights and responsibilities (Forino et al., 2015). (See SROCC Annex I: Glossary and Cross-Chapter Box 2 for definition).

SROCC considers the ocean and cryosphere as socio-ecological systems and explores how the interlinkages between climate change, governance efforts and institutional change unfold (Pahl-Wostl, 2006). Hydrological processes in the high mountain cryosphere connect through upstream and downstream areas of river basins (Nepal et al., 2014) including floodplains and deltaic regions (Kilroy, 2015) (Cross-Chapter Box 3). The river basin is also a cultural and a political construct, influencing human securities by determining how ecosystem services which sustain food, water, and energy are used and distributed (Warner et al., 2008; Molle, 2009; Rasul, 2014). Small Island States face rising seas that challenge habitability of their homeland and the possibility of losing their nation-state, cultural identity and consequently their voice in high level policy making organisations (Gerrard and Wannier, 2013; Cross-Chapter Box 7). Cryosphere and ocean changes result in local to global-scale impacts (Section 1.4), highlighting the need for transboundary components to governance.

Governance of the ocean and cryosphere in a changing climate requires working across multiple organisations and institutions, bringing varying capacities, frameworks and spatial extents (Cross-Chapter Box 2). Gaps in legal frameworks, and spatial mismatches among countries can impede the effectiveness of governance responses to climate-related pressures (Delmas and Young, 2009; Young, 2009; Eriksen et al., 2011) and limit the ability for nations to cooperate effectively (Winter, 2006; Kim, 2012). Local level adaptation to climate change, must work in harmony with the regional and global governance structures that provide an overarching policy framework for action and allocate necessary resources. Coordinating the top-down and bottom-up governance processes (Bond, 2006; Green et al., 2014; Bisaro and Hinkel, 2016) to ensure effective responses, mobilise adequate resources, distribute them equitably, and access private and public sector capabilities requires a polycentric governance perspective (Ostrom, 2010; Jordan et al., 2015).

SROCC, together with SR1.5 (Allen et al., in press-a), highlights the critical place of governance in determining the effectiveness of climate adaptation options. Chapter 2 explores local community institutions offering autonomous adaptation in the Alps, Andes, Himalayas and other mountain regions (Section 2.4). However, global climate adaptation and disaster risk reduction frameworks do not fully address the specificities of high mountain regions in their responses to climate change process. Transboundary cooperation to support water governance is recognised, but evidence of implementation and evaluation of their effectiveness to mitigate conflict risks has remained limited. Chapter 3 characterises polar governance systems as facilitating the building of resilient pathways, knowledge co-production, social learning, adaptation, and power-sharing with indigenous peoples at the regional level. Greater cooperation in new multi-level governance landscapes at the international level is explored as a means to strengthen responses supporting adaptation in the environmental and socio-cultural dimensions (Section 3.5.4). Chapter 4 shows how sea level rise (SLR) governance varies, from a lack of suitable governance arrangements to having established governance arrangements in place reflecting the experiences of local SLR. In most SLR contexts, equity concerns affect all governance processes and difficult trade-offs are inevitable (Section 4.4.3). Governance innovations will be needed to resolve escalating conflict as sea level rises (Section 4.4). Community-based approaches are important, but meaningful participation is hard to achieve. Chapter 5 addresses the issues of ocean warming, acidification and deoxygenation, including a comprehensive review of existing international legal regimes encompassing the changing ocean, its ecosystems and their impact of dependent communities. Making climate change issues a mainstream consideration in global, regional, environmental and fisheries governance structures can facilitate appropriate responses to ocean change (Sections 5.4, 5.5). Chapter 6 explores how selected management measures, including early warning systems, can address the uncertainty of extreme events and abrupt changes at global, regional and local levels. Further, it shows how to build the credibility, trust, and reliability essential for governance to respond appropriately to unexpected extremes and abrupt changes. Such prevention is costly and difficult to assess but costs significantly less than not having any measures in place (Section 6.9).

[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), 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 outlines governance concepts relevant to the ocean, coasts and cryosphere in a changing climate. Three case studies illustrate governance challenges and emerging solutions involving [1] multi-level interactions at a regional scale; [2] mountain governance; and [3] coastal risk governance.

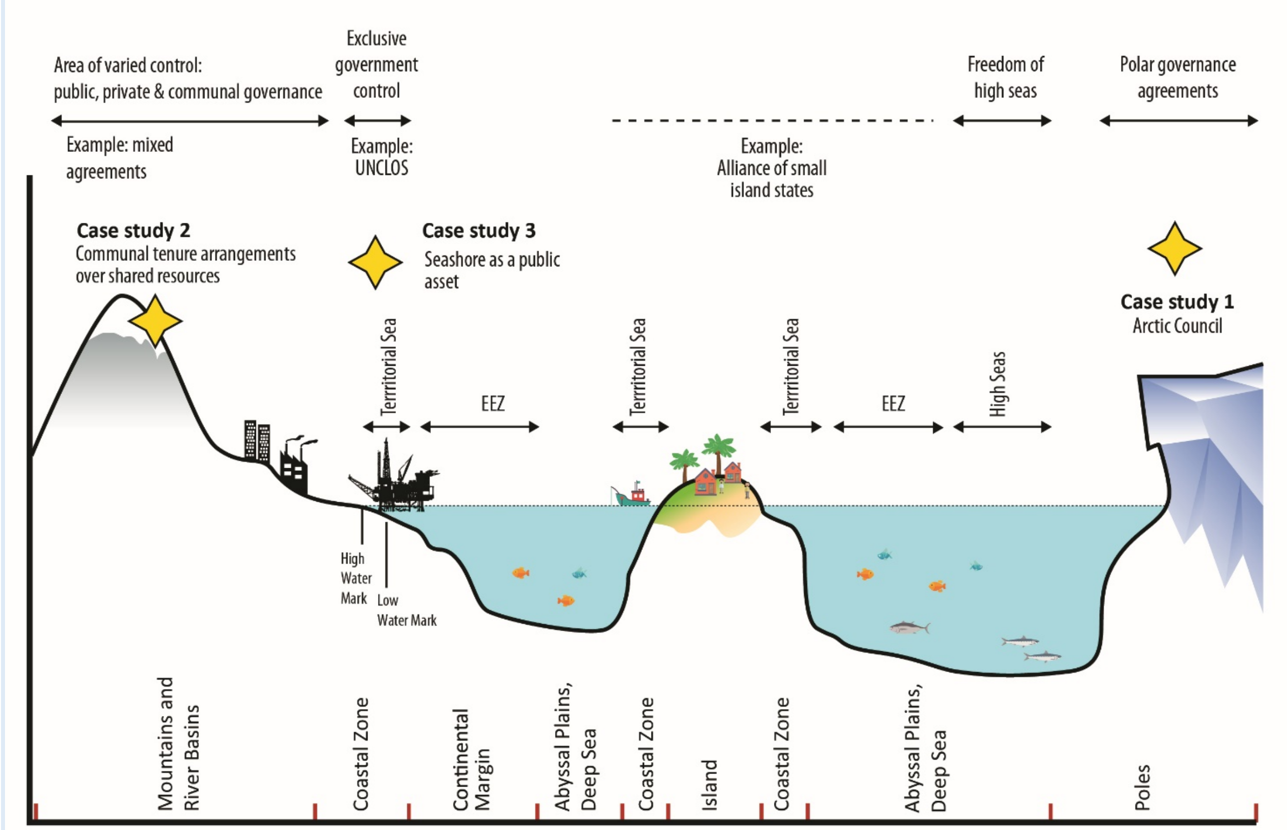
Understanding governance in a changing climate

In SROCC, governance refers to efforts to support, establish and modify institutional and organisational arrangements that help in regulatory processes, mitigating conflicts and realising mutual gains associated with resource management and related risks (Paavola, 2007; Lockwood et al., 2010). Governance may be an act of governments (e.g., passing laws or facilitating actors to respond more effectively to climate change); private sector actions (e.g., responses to market incentives such as insurance risk pricing); or a collaborative effort among local actors governing themselves through customary law (e.g., by establishing rules or norms regulating the common use of scarce resources). It can also be a multi-level effort involving actors from governments, the private sector and civil society (e.g., UNFCCC) or a multi-national effort (e.g., Antarctic Treaty). Institutions are formal and informal norms and rules that shape the roles, responsibilities and power relations of actors, and direct how individual and collective social choices are made (North, 1990; Ostrom, 2005). Formal institutions include constitutions, laws, policies, and contracts, while informal institutions include customs, social norms and taboos. Existing institutions define and constrain the roles and responsibilities of governance actors, with implications for how decisions are made, and who can exercise power and influence within governance processes (Graham et al., 2003).

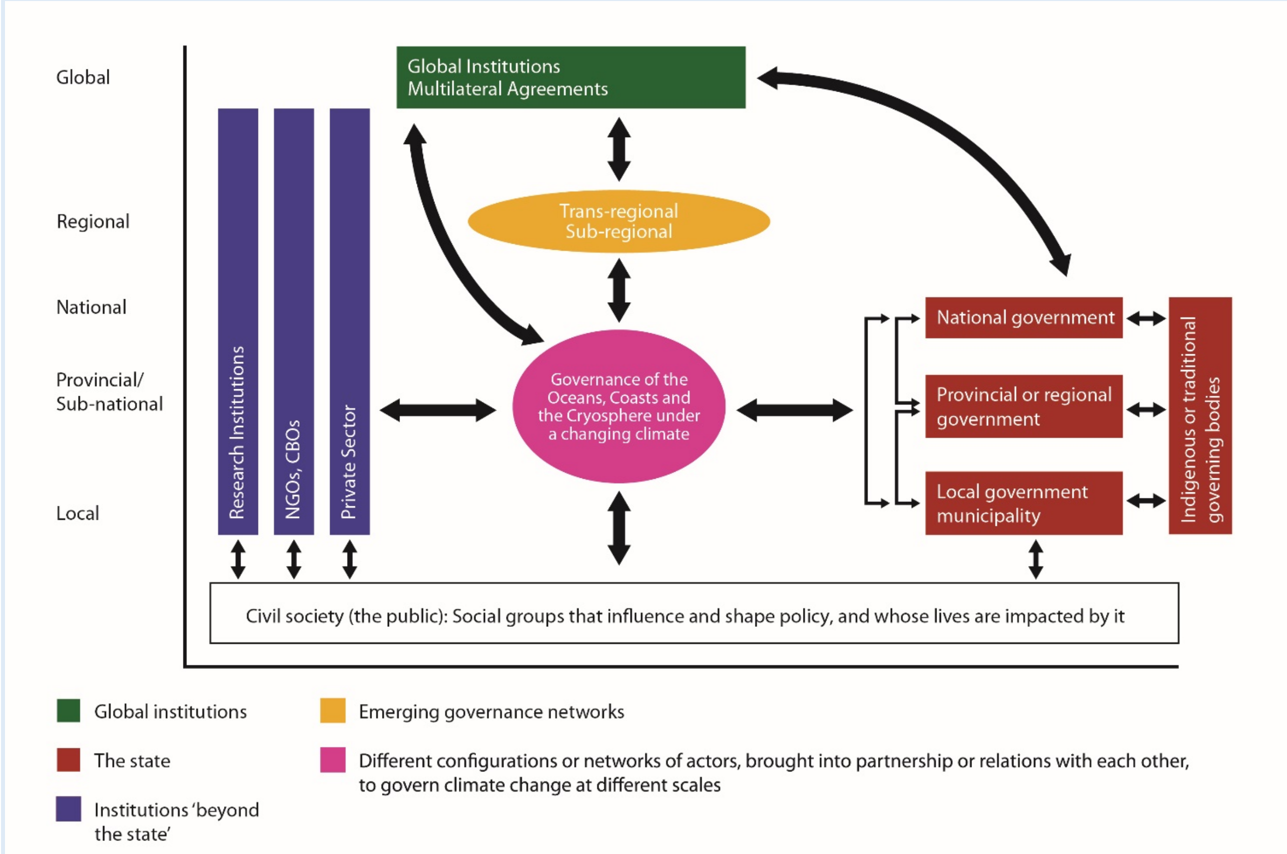
Climate governance refers to efforts to collectively prevent, mitigate and adapt to the challenges and risks posed by a changing climate. Efforts are underway in many countries to take climate change into account in planning processes (Knieling and Leal Filho, 2013). New interactions and synergies are emerging and institutional innovation is taking place, including in ocean, coastal and cryosphere settings. At the same time, resistance to such efforts is commonplace.

Climate change challenges existing governance arrangements in a variety of ways. First, there are complex interconnections between climate change and other processes that influence the ocean, coasts and cryosphere, making it difficult to untangle climate governance from other governance efforts. Second, the timeframes for societal decision-making and government terms are mismatched with the long-term commitment of climate change. Third, governance choices have to be made in the face of uncertainty about the rate and scale of change that will occur in the medium to long-term future (Cross-Chapter Box 4). Lastly, novel transboundary conflicts and challenges are emerging: new multi-level governance structures for regional co-operation, which strengthen arrangements for shared decision-making among States and other actors have been developed (Case 1); the prospects of 'disappearing states', glacier retreat, and increasing water scarcity, resulting in States redefining complex water-sharing agreements, are becoming more evident (Case 2); and coastal risk is escalating, requiring participatory governance responses and the co-production of knowledge at the local scale (Case 3).

Addressing these governance challenges, in part, depends on political will and substantial effort to coordinate cooperative efforts across sectors, spheres and scales of governance. Furthermore, climate change progressively alters existing (and introduces new) governance challenges, requiring continual innovation and adjustment of governance arrangements (Bisaro and Hinkel, 2016; Roggero et al., 2018). The complexities of governance arrangements in the ocean, coasts and cryosphere (Cross-Chapter Box 2, Figure 1), and the interactions and emergence of relationships between different governance actors across various spatial scales (Cross-Chapter Box 2, Figure 2) are illustrated below.



Cross-Chapter Box 2, Figure 1: Spatial distribution of governance frameworks for the ocean, coasts and cryosphere.



Cross-Chapter Box 2, Figure 2: Interactions and emergence of networks of governance actors for the ocean, coasts and cryosphere across different scales. Source: Adapted from Sommerkorn et al. (2015).

***Case Study 1 — Multi-level Interactions and Synergies in Governance-* UN Convention on the Law of the Sea and the Arctic:** Sea Level Rise may change the baseline of coastal states, and the areas where they exercise their coastal rights under UNCLOS, and, in extreme cases, may lead to complete loss of territory (Vidas et al., 2015). UNCLOS lacks precision in the formulation of the 'law of the sea' provisions, enforcement, compliance, monitoring and dispute settlement mechanisms (Vidas, 2000; De Lucia, 2017; Grip, 2017). Shifts from traditional state-based practices of international law to multi-level and informal governance structures that involve states and non-state actors (including Indigenous Peoples) may help to address these challenges (Cassotta, 2012; Shadian, 2014; Young, 2016; Andreone, 2017) - (*medium confidence*). For example, the Arctic Council (AC), is a regionally focused governance structure blending new forms of formal and informal multi-level regional cooperation (Young, 2016) that employs mainly soft law mechanisms and draws upon best available practices and standards from multiple knowledge systems (Cassotta and Mazza, 2015; Pincus and Ali, 2015). Reconfigurations and restructuring of the AC have been proposed in order to address emerging trans-regional and global problems (Baker and Yeager, 2015; Pincus and Ali, 2015; Young, 2016) - (*high confidence*). Within its scope, the AC has amplified the voice of Arctic people affected by the impacts of climate change, such as by producing and disseminating the Arctic Climate Impact Assessment (ACIA) and mobilizing action (Koivurova, 2016).

Case Study 2 — Mountain Governance: Water management in Gilgit-Baltistan, Pakistan. Gilgit-Baltistan is an arid territory in a mountainous region of northern Pakistan. Meltwater-fed streams supply irrigation water for rural livelihoods (Nüsser and Schmidt, 2017). The labour-intensive work of constructing and maintaining gravity-fed irrigation canals is done by *jirga,* traditional community associations. As glaciers retreat due to climate change, water sources at the edge of glaciers have dried up, reducing water available for irrigation. In response, villagers constructed new channels accessing more distant water for irrigation needs (Parveen et al., 2015). The Aga Khan Development Network (AKDN) supported this substantial task by providing funding and developing a new kind of cross-scale governance network, drawing on local residents for staff (Walter, 2014), and strengthening community resources, training and networks. Challenges remain, including the potential for increased rainfall causing landslides that could damage new canals, and possible expansion of Pakistan's hydropower infrastructure that would further diminish water resources and displace villages (Shaikh et al., 2015). On a geopolitical scale, decreased water supplies from the glaciers could trigger a breakdown of the 1960 Indus Water Treaty, established between India and Pakistan, resulting in numerous impacts on water management throughout the entire Indus watershed (Uprety and Salman, 2011).

Case Study 3 — Coastal Governance: Risk management for sea level changes in the City of Cape Town, South Africa. Sea level rise and coastal flooding are the focus of the City of Cape Town's coastal climate adaptation efforts. The Milnerton coastline High Water Mark, a non-static line marking the high tide, is creating a governance conflict by moving landwards (due to sea level rise) and intersecting with private property boundaries, threatening public beaches and the dune cordon, and placing private property and municipal infrastructure at risk in storm conditions (Sowman et al., 2016). Private property owners are using a mixture of formal and ad hoc, and in some cases illegal, coastal barrier measures to protect their assets from sea level and storm risks, but these are creating additional erosion impacts on the coastline. Legally, the City of Cape Town is not responsible for remediating private land impacted by coastal erosion (Smith et al., 2016). However, city officials feel compelled to take action for the common good using a progressive, multi-stakeholder participatory approach. This involves opening up opportunities for dialogue and co-producing knowledge, instead of a purely legalistic and state-centric compliance approach (Colenbrander et al., 2015). The city's actions are both mindful of international frameworks on climate change and responsive to national and provincial legislation and policy. A major challenge that remains is how to navigate the power struggles that will be triggered by this consultative process, as different actors define and negotiate their interests, roles and responsibilities.

Conclusions

These cases illustrate four important points. First, new governance issues are emerging due to climate change, including: disruptions to long-established cultures, livelihoods and even territorial sovereignty (Case 1); changes in the accessibility and availability of vital resources (Case 2); and the blurring of public and private boundaries of risk and responsibility through accelerated coastal erosion (Case 3) (Cross-Chapter

Box 2, Figure 1). Second, new governance arrangements are emerging to address these challenges, including participatory and networked structures, and those linking formal and informal networks, and involving state, private sector, indigenous and civil society actors in different configurations (Cross-Chapter Box 2, Figure 2). Third, climate governance is a complex, contested and unfolding process, with governance actors and networks having to learn from experience, to innovate and develop context-relevant arrangements that can be adjusted in the face of ongoing change. Lastly, there is no single climate governance panacea for the ocean, coasts and cryosphere. Empirical evidence and 'good governance' norms indicate the importance of inclusivity, fairness, deliberation, reflexivity, responsiveness, social learning, the co-production of knowledge, and respect for ethical and cultural diversity.

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[END CROSS-CHAPTER BOX 2 HERE]

1.8 Knowledge Systems for Understanding and Responding to Change

Assessments of how climate change interacts with the planet and people are largely based on scientific knowledge. Scientific knowledge includes observations, experiments, and modelling to understand physical and ecological systems (Section 1.8.1), societies (e.g., Cross-Chapter Box 1, Section 1.5.2) and institutions (e.g., Cross-Chapter Box 2). However, humans integrate information from multiple knowledge systems to observe and interact with their environment, respond to changes, and solve problems. Accordingly, SROCC also utilises Indigenous knowledge and local knowledge that reflects how human communities understand and react to changes in the ocean and cryosphere (Sections 1.8.2, 1.8.3; Cross-Chapter Box 3).

1.8.1 Scientific Knowledge

1.8.1.1 Ocean and Cryosphere Observations

Scientific knowledge of physical and ecological changes in the ocean and cryosphere has advanced greatly since the mid-20th century (Figure 1.3; Rhein et al., 2013; Vaughan et al., 2013), enabling improvements in the detection, attribution, and prediction of ocean and cryosphere changes (Sections 1.3 and 1.4). Some of the best monitored parameters for the ocean and cryosphere include ocean temperature, sea level, and glacier length, whereas biogeochemical, ecological and polar datasets are typically shorter and sparser than the examples shown in Figure 1.3. Many areas of the ocean and cryosphere remain poorly sampled or even unsampled.

In situ ocean physical observations are derived from moored (Cronin et al., 2012; Foltz et al., 2018) and drifting buoys (Lumpkin et al., 2017), expendable bathythermographs (Cheng et al., 2016), subsurface Argo array floats (Riser et al., 2016), shipboard measurements (e.g., Talley et al., 2016), tide gauges (PSMSL, 2016), and animal-borne sensors (Roquet et al., 2017). Argo floats have provided near-global coverage of temperature and salinity observations down to 2000 m since 2005 (Riser et al., 2016) (Figure 1.3; Appendix 1.A, Figure 1.1). Under-sampled ocean regions which are crucial for improved climate and ecological impact studies include marginal seas, boundary currents, and sea-ice covered areas of the polar oceans (e.g., Abraham et al., 2013; Cheng and Zhu, 2014; von Schuckmann et al., 2016; Johnson et al., 2018). Full-depth observations (e.g., from autonomous platforms (Johnson et al., 2017) and repeated ship-based sampling lines (e.g., Talley et al., 2016)) are crucial for tracking long-term oceanic signals (Purkey and Johnson, 2010; Desbruyères et al., 2016) and for validating Argo float profiles. Purposely designed, long-term observational programs are particularly important for monitoring ocean process such as the El Niño-Southern Oscillation (McPhaden et al., 2010), Atlantic Meridional Overturning Circulation (Lozier et al., 2017; McCarthy et al., 2017; Meinen et al., 2018) and boundary current regimes (e.g., Hu et al., 2015), which have potentially large societal impacts (Sections 6.5 and 6.7). Rescue of historical shipboard measurements from early exploration and trade vessels is extending the length of ocean physical observations (Domingues and Palmer, 2015). Some of the longest records for biological variables extend over 30 years, and in some cases to more than 100 years (Reid et al., 2003; Seafarers et al., 2017; Miloslavich et al., 2018). However, assessments of long-term ocean ecosystem changes are currently only feasible for a limited subset of variables (Miloslavich et al., 2018; Section 5.2).

Observations of the cryosphere in Arctic and high mountain regions can extend across multiple centuries, particularly for glacier length (WGMS, 2017). Generally, however, scientific data are scarce for remote areas (and particularly the Antarctic), limiting the ability to detect human-induced change (Jones et al., 2016). Indigenous knowledge and local knowledge can, in some cases, provide ways to overcome these limitations (Cross-Chapter Box 3). Permafrost change estimates rely on extrapolation from a small number of observations at individual sites (Section 3.4.2.2), and being subsurface, remote-sensing techniques have limited power.

Developments in satellite monitoring since the late 1970s have continued to revolutionise knowledge of the ocean and cryosphere (Dowell et al., 2013; Parkinson and DiGirolamo, 2016; Visbeck, 2018). Remote sensing observations include sea level, sea surface temperature and salinity, ocean colour (productivity), ocean and ice mass, and the area/extent of glaciers, ice sheets, sea ice, and snow cover (Shutler et al., 2016; Figure 1.3). Almost all monitoring of the Greenland and Antarctic ice sheets, and sea ice across the polar oceans, relies upon satellite observations. Aircraft missions (e.g., Babonis et al., 2016) are also yielding new observational data on ice sheet structure and velocity.

1.8.1.2 Palaeoclimate Evidence

Direct observations of the ocean and cryosphere are scarce prior to the mid-20th century, so establishing the nature of earlier ocean and cryosphere changes, including those prior to anthropogenic climate change (Abram et al., 2016), necessitates the use of indirect methods (Masson-Delmotte et al., 2013). Palaeoclimate records utilise the accumulation of physical, chemical or biological properties within a natural archive that can be related to properties of the climate at the time when the archive formed. Commonly used palaeoclimate evidence for ocean and cryosphere change come from marine sediments, ice layers and bubbles, tree growth rings, past shorelines and shallow reef deposits. Since AR5, extensive community efforts have compiled palaeoclimate records into databases (PAGES2k Consortium, 2017) that allow for regional-scale syntheses of ocean (McGregor et al., 2015; Tierney et al., 2015) and cryosphere (Stenni et al., 2017; Thomas et al., 2017) conditions prior to instrumental observations. The availability of palaeoclimate records diminishes towards present day (Figure 1.3), reflecting when the records were collected.

Palaeoclimate records provide a long-term context for assessing if recent observed changes are unprecedented and attributable to anthropogenic climate change (e.g., Sections 3.2, 3.3; Abram et al., 2016; Jones et al., 2016). They provide evidence for what ocean and cryosphere changes are possible within the Earth system, including abrupt climate change events not witnessed in observational history (e.g., Section 6.7), and the responses to past climates that were regionally or globally warmer than present day (e.g., Section 4.2.2.1; Hansen et al., 2016; Fischer et al., 2018). This provides context for the temperature limits of the Paris Agreement, established to not exceed thresholds expected to cause dangerous changes in the Earth system (Lüning and Vahrenholt, 2017; Fischer et al., 2018). Palaeoclimate data establish the transient sensitivity and longer-term equilibrium responses of Earth's climate to atmospheric greenhouse gases (PALAEOSENS Project Members, 2012; Snyder, 2016), and are critical 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).

1.8.1.3 Modelling Products

Climate model output provides a way of testing the mechanisms of ocean and cryosphere change, for attributing observed changes to specific forcings (Section 1.3), and represent the best available information for assessing future change (Figure 1.3). Models are approximated numerical representations of the climate system. They typically simulate the atmosphere, ocean, sea ice, and land surface, and sometimes also incorporate terrestrial and marine ecosystems. Ice sheets have also been included in some global climate models since 2010. Earth System Models (ESM) are climate models that explicitly include the carbon cycle. The systematic set of model experiments (Taylor et al., 2012) used in AR5 and in SROCC (Section 1.9.1) were produced by the Coupled Model Intercomparison Project Phase 5 (CMIP5), and have enabled greater international cooperation in the production and assessment of climate model outputs.

Models may differ in their spatial resolution, and in the extent to which processes are explicitly represented or estimated (parameterised). Model output has biases due to uncertainties in their physical equations or parameterisations, specification of initial conditions, knowledge of external forcing factors (Hawkins and Sutton, 2009; Deser et al., 2012; Gupta et al., 2013; Lin et al., 2016), and missing processes and feedbacks (Collins et al., 2013). Downscaling, including the use of regional climate models, makes it possible to better resolve past and future climate change in specific areas (Kotlarski et al., 2015) (Sections 2.2, 3.2, 3.3).

Successful testing of models against observational and palaeoclimate data is critical for model evaluation and development (Bracegirdle et al., 2016). The use of empirical relationships established through observational and palaeoclimate data alongside model products for well-modelled parameters (such as future global temperature change), can also allow for estimates of how interconnected but less-well modelled elements of the Earth system (such as sea level rise; Section 4.2.3) may respond to future climate change (Rahmstorf et al., 2012).

1.8.1.4 Reanalysis Products

Reanalysis products combine observational data (satellite and *in-situ*) with numerical models to produce physically consistent, and spatially complete climate products. Over the last decade, reanalyses products have improved due to increased model resolution, improved physics and observational constraints, and advances in data assimilation methods (Lellouche et al., 2018; Storto et al., 2018; Zuo et al., 2018), as well as through international cross-validation (Balmaseda et al., 2015). Reanalysis products that cover the whole 20th century (Giese et al., 2016; de Boisséson et al., 2018) suffer from biases as a result of inhomogenous early observational data available for assimilation (Figure 1.3; Yang et al., 2017).

Reanalysis products are used for climate diagnostics (Balmaseda et al., 2013; Hu and Sprintall, 2016; Carton et al., 2018), including near real-time climate monitoring (Lellouche et al., 2013; Xue et al., 2017), for seasonal and decadal climate predictions (Pohlmann et al., 2013; Zhu et al., 2013), and for operational climate and marine services (e.g., Blunden et al., 2017; von Schuckmann et al., 2018). Downscaled and regional reanalyses benefit from higher resolution and regional specificities, including coupling with sea ice or ocean biogeochemistry components (Pinardi et al., 2015; Sotillo et al., 2015; Hamon et al., 2016; Chevallier et al., 2017; Xie et al., 2017).

In SROCC, ocean reanalyses are widely used to understand changes in physical properties (Section 5.2), extremes (Section 6.3), and circulation (Section 6.7.1). Atmospheric reanalysis products are also used extensively, and in the context of SROCC are particularly important for assessing the climate change process that cause changes in the ocean and cryosphere (e.g., Sections 2.2, 3.3, 3.4, 4.2, 6.3, 6.6.). The weather forecasts and seasonal predictions associated with reanalysis products also have important applications in aiding human adaptation to extreme events (Sections 6.3.5, 6.5.3).

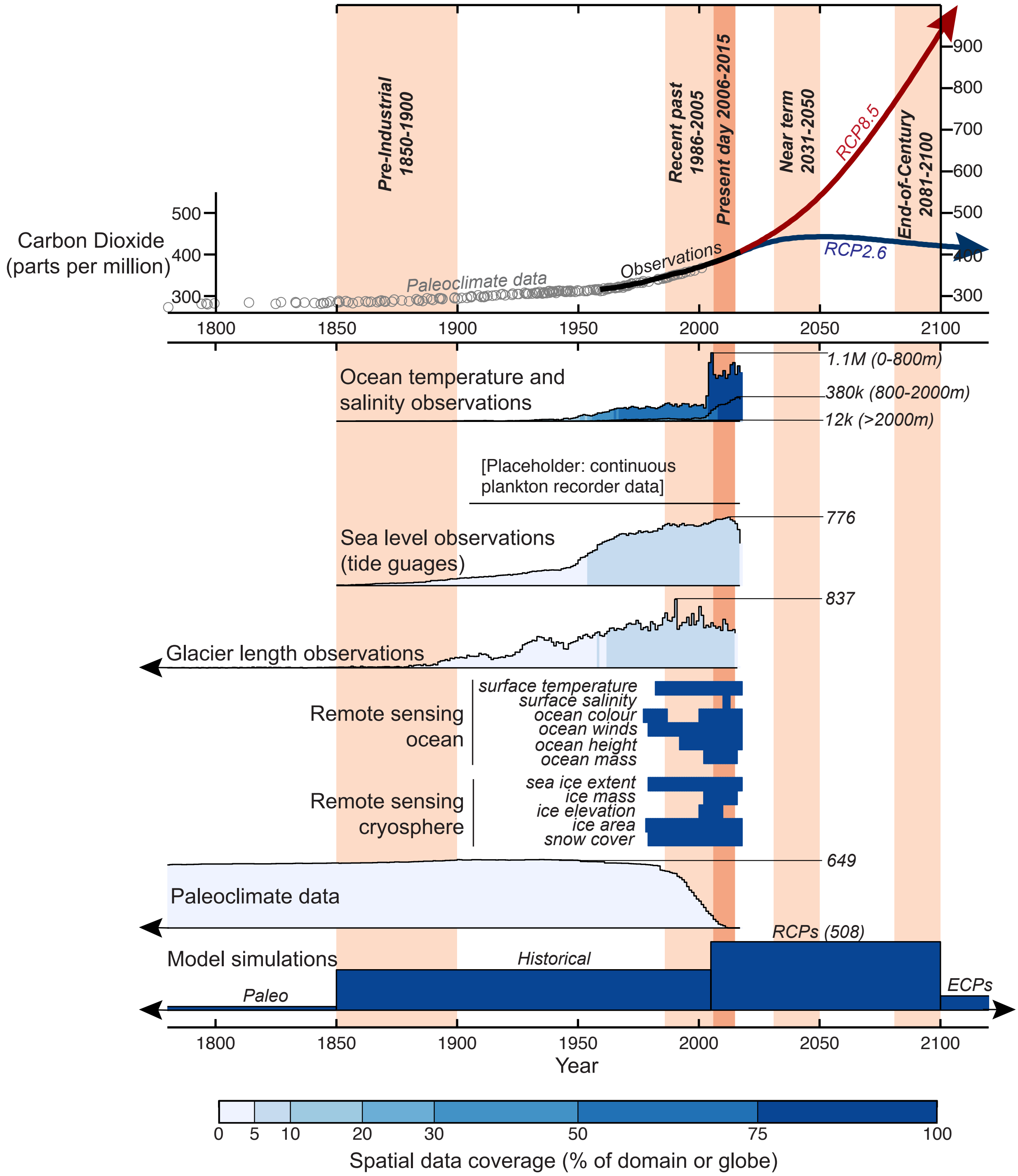

Figure 1.3: Major time periods covered in SROCC and examples of ocean and cryosphere data coverage over these times. Upper panel displays observed (Keeling et al., 1976) and reconstructed (Bereiter et al., 2015) atmospheric carbon dioxide (CO_2) concentrations, as well as the Representative Concentration Pathways (RCP) of CO_2 for low (RCP2.6) and high (RCP8.5) future emission scenarios (Van Vuuren et al., 2011; Section 1.9.1.3). Lower panel gives examples of available data for the ocean and cryosphere (Section 1.8.1; Boyer et al., 2013; Dowell et al., 2013; PSMSL, 2016; PAGES2k Consortium, 2017; WGMS, 2017). Heights depict the number of observations, parameters or simulations available through time expressed relative to the maximum annual data availability (maximum values given on plot; M = million, k = thousand). Colour scale depicts spatial coverage of data across the globe or the relevant domain, calculated for 3° x 3° spatial grids for ocean and palaeoclimate data, and relative to total number of glaciers in World Glacier Monitoring Service database for glacier length. See Appendix 1.A: Supplementary Material for further details. Shaded bars across both panels depict the key time periods referred to throughout SROCC (Section 1.9.1.2), including pre-industrial (1850–1900), recent past (1986–2005), present day (2006–2015), near-term (2031–2050) and end-of-century (2081–2100).

1.8.2 Indigenous Knowledge and Local Knowledge

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). Indigenous knowledge (IK) refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. It is not only passed on from generation to generation, but is also flexible and adaptive in present-day changing conditions. Local knowledge (LK) is the system that makes non-indigenous communities, both in rural and urban environments, successful in living on a daily and lifelong basis.

IK and LK are ways of knowing that stand on their own, and also enrich and complement scientific knowledge. For example, the Indigenous oral history of Australian Aboriginal groups provide empirical corroboration of the sea level rise 7,000 years ago that inundated coastal Australia (Nunn and Reid, 2016), while their seasonal weather calendars are still used to direct hunting, fishing, planting and conservation, and to detect unusual changes today (Green et al., 2010). Local knowledge influences the ways in which individuals and communities engage with climate change (Lee et al., 2015).

IK and LK guide how people interact, respond, and adapt (Sillitoe, 2007; Gearheard et al., 2013; Yeh, 2016). Both are used increasingly in climate change research and policy efforts to engage affected communities, and to facilitate site-specific understandings of, and responses to, the local effects of climate change (Crate, 2011; Hiwasaki et al., 2014; Hou et al., 2017; Mekonnen et al., 2017). IK and LK contribute richly to climate resilient development pathways, perhaps most critically by engaging multiple stakeholders and the diversity of socio-economic, cultural, and linguistic contexts of populations affected by changes in the ocean and cryosphere (Cross-Chapter Box 3). Each chapter of SROCC explores IK and LK related to ocean and cryosphere change.

IK and LK are increasingly recognised in global environmental assessments (Riedlinger and Berkes, 2001; Berkes et al., 2006; Thaman et al., 2013; Beck et al., 2014; Diaz et al., 2015). References to IK increased 60% from AR4 to AR5, and highlighted the exposures and vulnerabilities of Indigenous populations to climate change risks related to socio-economic status, resource-based dependence, and geographic location (Ford et al., 2016a). In 2018, all four assessments of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, 2018a; IPBES, 2018d; IPBES, 2018b; IPBES, 2018c) demonstrated the contributions that IK and LK make (Diaz et al., 2015; Roué and Molnar, 2017; Díaz et al., 2018). Peer-reviewed research on IK and LK is burgeoning (Savo et al., 2016), providing information that can guide responses and inform policy (Huntington, 2011; Nakashima et al., 2012; Lavrillier and Gabyshev, 2017; Lavrillier and Gabyshev, 2018). However, most global 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).

IK and LK provide case-specific information that may not be easily extrapolated to the scales and kinds of disturbance that society is exerting on natural systems (Wohling, 2009). Some forms of IK and LK are also not amenable to being captured in peer-reviewed articles or published reports, and efforts to translate IK and LK into qualitative or quantitative data may mute the multidimensional, dynamic, and nuanced features that give IK and LK meaning (DeWalt, 1994; Roncoli et al., 2009; Goldman and Lovell, 2017). Nonetheless, increasingly effective efforts to collect IK and LK from knowledge holders (Baptiste et al., 2017; Karki et al., 2017; Roué et al., 2017; Roué and Molnar, 2017) and to systematically assess published IK and LK literature in parallel with scientific knowledge enables use of the multiple ways of knowing to better characterise and address ocean and cryosphere change (Huntington et al., 2017).

[START CROSS-CHAPTER BOX 3 HERE]

Cross-Chapter Box 3: Indigenous Knowledge and Local Knowledge

Authors: Susan Crate (USA), William Cheung (Canada), Bruce Glavovic (New Zealand), Sherilee Harper (Canada), Hélène Jacot Des Combes (Fiji/France), Monica Ell Kanayuk (Canada), Ben Orlove (USA), Joanna Petrasek MacDonald (Canada), Anjal Prakash (Nepal/India), Pasang Yangjee Sherpa (Nepal), Martin Sommerkorn (Norway/Germany)

Introduction

This Cross Chapter Box demonstrates how Indigenous knowledge (IK) and local knowledge (LK) are different and unique sources of knowledge, which are critical to observing, understanding, and governing the ocean and cryosphere in a changing climate. International organisations have recognised the importance of IK and LK in global assessments, including UN Environment, UNDP, UNESCO, IPBES and the World Bank. IK and LK are utilised throughout SROCC, recognising that many climate change impacts affect, and will require responses from, local communities that maintain a close connection with the ocean and/or cryosphere (Sections 1.8.2, 1.8.3, and Chapters 2-6).

Attention to IK and LK in understanding global change is relatively recent, but demonstratively important. For instance, the Alaska Eskimo Whaling Commission was formed by Alaskan Inuit in response to science that underestimated the Bowhead whale population. The commission facilitated an accurate population count using a study design based on Indigenous knowledge, indicating a stable population (Huntington, 2000). Combined knowledge systems are also utilised, such as the Mi'kmaw Elders' concept of Two Eyed Seeing: which is 'learning to see from one eye with the strengths of Indigenous knowledges, and from the other eye with the strengths of Western [scientific] knowledges, and to use both together, for the benefit of all' (Bartlett et al., 2012), to preserve the distinctiveness of each, while allowing for fuller understandings and actions (ibid: 334).

Contributions to SROCC

Observations, responses and governance are three important contributions that IK and LK make in ocean and cryosphere change:

Observations: IK and LK observations document glacier and sea ice extent, permafrost dynamics, coastal processes, etc. (Sections 2.1, 3.2, 3.4, 4.3.2, 5.5.3.2.1.4, 6.8.3), and how they interact with social-cultural factors (West and Hovelsrud, 2010). Researchers have begun documenting IK and LK observations only recently (Gearheard et al., 2013; Sections 2.3.1.1, 2.4.1.1, 3.2, 3.4, 3.5, 4.3.2, 5.3.2, 6.8.3).

Responses: Either IK or LK alone (Yager, 2015), or used alongside scientific knowledge (Nüsser and Schmidt, 2017) inform responses (Sections 2.4.1.4.1, 4.4.3, 5.4.3.2.3, 6.8.4). Utilising multiple knowledge systems requires continued development, accumulation and transmission of LK, IK and scientific knowledge understandable to a people's specific ecological and cultural context (Crate and Fedorov, 2013; Jones and O'Neill, 2016), resulting in the incorporation of local and culturally appropriate priorities into adaptation initiatives (Sections 2.4.7, 3.5, 4.4.4, 5.4.2.4.2, 6.8.4).

Governance: Utilising IK and LK in climate decision- and policy-making engages customary Indigenous and local institutions (Karlsson and Hovelsrud, 2015). For example, Indigenous communities can be engaged in an integrated approach for disaster risk reduction in response to cryosphere hazards (Carey et al., 2015). Effectively engaging communities and stakeholders in decisions includes utilising multiple knowledge systems (Chilisa, 2011; Sections 2.4.1.3.1, 2.4.3.3, 3.5, 4.4.4, 5.4.2.4.6, 6.8.4).

Examples from regions covered in this report

IK and LK in the Pacific: Historically, Pacific communities, who depend on marine resources for essential protein (Pratchett et al., 2011), use local management systems to determine access to, and closure of, fishing grounds (the latter to respect community deaths, sacred sites and customary feasts). Today, a hybrid system of Locally Managed Marine Protected Areas (LMMAs) proliferate, integrating local governance with NGO or government agency interventions (Jupiter et al., 2014). Although not specifically including climate change adaptation (ibid), expected benefits support climate change adaptation (Roberts et al., 2017) and potentially mitigation through improved carbon storage (Vierros, 2017). Despite the accepted benefits of LMMAs, there are also challenges in upscaling LMMAs (Roberts et al., 2017; Vierros, 2017), and in assessing their efficiency as climate change adaptation solutions due to non-compliance with LMMA regulations (Rohe et al., 2017; Section 5.4).

IK and Pikialasorsuaq: Pikialasorsuaq (North Water Polynya), in Baffin Bay, is the Arctic's largest polynya and one of the most biologically productive regions in the Arctic (Barber et al., 2001). Adjacent Inuit communities depend on Pikialasorsuaq for their food security and subsistence economy (Hastrup et al., 2018). They use Inuit knowledge in daily and seasonal activities (ICC, 2017). The sea-ice bridge north of the Pikialasorsuaq has become increasingly less stable and as such has been cause for a geographically and seasonally less defined polynya (Ryan and Münchow, 2017). In response, the Inuit Circumpolar Council initiated the Pikialasorsuaq Commission which recommended an Inuit-led management authority to: (1) manage activities in the Pikialsorsuuaq, (2) oversee monitoring and research, and (3) establish a free travel zone for Inuit across the Pikialasorsuaq region (ICC, 2017; Box 3.2).

LK in the Alps: Villagers in Switzerland, who have knowledge of the particular areas within mountains with high avalanche risk, draw on LK for risk management. A study in eastern Switzerland lists specific techniques of forest and meadow management which reduce avalanche risk, including hay cutting techniques on slopes to protect meadow soils; tree felling patterns that maximise forest stand; and managing grazing to promote regeneration (Reichel and Frömming, 2014; Section 2.3.2).

LK to Manage Flooding: Climate change is increasing glacial meltwater and rain-induced disasters in the Himalayan region and affected communities in China, Nepal, and India use LK to adapt (Nadeem et al., 2012). For instance, rains upstream in Gandaki (Nepal) flood downstream areas of Bihar, India. Local communities' knowledge of forecasting floods has evolved over time through the complexities of caste, class, gender, and ecological flux, and is critical to flood forecasting and disaster risk reduction. Local communities manage risk by using a diverse set of knowledge, including phenomenological (e.g., river sound), ecological (e.g., red ant movement), and riverine (e.g., river colour) indicators, alongside meteorological and official information (Acharya and Poddar, 2016; Section 2.3.2).

Knowledge Holders' Recommendations for Utilising IK and LK

Perspectives from the Himalayas: IK and LK holders in the Himalayas have conducted long-term systematic observations in these remote areas for centuries. Contemporary IK details change in phenology, weather patterns, and flora and fauna species, which enriches scientific knowledge of glacial retreat and potential glacial lake outbursts (Sherpa, 2014). The scientific community can close many knowledge gaps by engaging IK and LK holders as counterparts. Suggestions towards this objective are: work with affected communities to elicit their knowledge of change, especially IK and LK holders with more specialised knowledge (farmers, herders, mountain guides etc.); use location- and culture-specific approaches to share scientific knowledge and utilise it with IK and LK.

Perspectives from the Inuit Circumpolar Council (ICC), Canada: Engaging Inuit as partners across all climate research disciplines ensures that our Inuit knowledge and priorities guide research, monitoring, and the reporting of results in our homeland. Doing so enhances the effectiveness, impact, and usefulness of global assessments, and ensures that our knowledge is appropriately reported in assessments. Inuit seek to achieve self-determination in all aspects of research carried out in our homeland (e.g., ITK 2018). Inuit actively produce and utilise climate research (e.g., ITK, 2005; ICC, 2015) and lead approaches to address climate challenges as we great incentive to develop innovative solutions. Engaging Inuit representative organisations and governments as partners in research recognises that the best available knowledge includes IK, enabling more robust climate research that in turn informs climate policy. When interpreted and applied properly, IK comes directly from research by Inuit and from our perspective (ICC, 2018). This can be achieved by working with Inuit on scoping and methodology for assessments and supporting inclusion of Inuit experts in research, analysis, and results presentation.

Cross-Chapter Box 3, Figure 1: Using the analogy of a braid, this figure illustrates how each of the three knowledge systems can stand alone and also can work in concert with each other, either paired or in a triage, to produce an increasingly fuller understanding. Because each is empirical and evidence-based, but also each captures information uniquely, the various combinations have both complementary and overlapping qualities, visualized here as being different shades of the same color. In the context of global climate change, utilizing combinations of all available knowledge types about ocean and cryosphere change provides the most robust information base for the multiple stakeholders involved.

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[END CROSS-CHAPTER BOX 3 HERE]

1.8.3 Utilising Scientific Knowledge, Indigenous Knowledge, and Local Knowledge

Utilising multiple ways of knowing can inform policy and governance (Riedlinger and Berkes, 2001; Huntington, 2011; Mistry and Berardi, 2016), but the question remains: where do scientific knowledge, Indigenous knowledge, and local knowledge meet? They can complement each other methodologically via the use of quantitative and qualitative information, and by engaging both climate data and people's observations, responses, and values (Huntington, 2000; Crate and Fedorov, 2013). However, the process is complex and IK and LK possess uncertainties of a different nature from those of scientific knowledge (Kahneman and Egan, 2011).

Conceptual frameworks guiding utilisation of different knowledge systems acknowledge each as valid, useful (Özesmi and Özesmi, 2004; Giles et al., 2007; Berkes and Berkes, 2009; Tengö et al., 2014; Grunblatt and Alessa, 2017), and harmonious rather than conflictual (Rathwell et al., 2015). The use of relevant knowledge ('triangulation' of knowledge systems) can involve scenario building across stakeholder groups to capture the multiple ways people perceive their environment and act within it (Klenk and Meehan, 2015), or working with communities to identify shared values and perceptions that enable context-specific adaptation strategies (Grunblatt and Alessa, 2017).

Working across disciplines (interdisciplinarity) (Klenk and Meehan, 2015), or engaging multiple stakeholders, including affected communities, local and regional representatives, policy makers, managers, and organisations (transdisciplinarity) (Burnham et al., 2016), are approaches used to bridge across knowledge systems (Strang, 2009). Such broad engagement has the potential to effectively utilise all relevant knowledge, assuring that assessments include broad local stakeholder input (Obermeister, 2017), and producing results that reduce the disproportionate influence that educated and economically advantaged groups often exert in scientific assessments (Castree et al., 2014).

Diverse ways of knowing are also relevant to climate literacy (e.g., Sections 3.5, 4.3, 4.4). To avoid dangerous climate change, substantial changes in the day-to-day activities of individuals, families, communities, firms, and governance will be required (Ostrom, 2010). Globally, public understanding of climate change and humanity's role have increased in the last decade (Milfont et al., 2017), but levels of climate literacy and action still vary greatly across the world (Lee et al., 2015). Education has the strongest effect on raising climate change awareness, and people understand climate change as a serious threat when they experience it in their lives and have knowledge of its human causes (Lee et al., 2015). How people and communities engage with climate change information depends on a community's perception of how the world works and access to information that is understandable within that worldview (Crate and Fedorov, 2013). The values people hold also affect their acceptability of the behavioural changes, technological solutions and climate policies that climate change action requires (Moser, 2016). Thus, scientific data and climate literacy alone are not sufficient to promote climate action; sensitivity to communities and their use of multiple knowledge systems is necessary to motivate effective responses to the existential threats posed by climate change.

1.9 Approaches Taken in this Special Report

1.9.1 Scenarios, Baselines, and Time Frames Considered

1.9.1.1 Temporal and Spatial Scales

The time scales of ocean and cryosphere change vary from days to decades, to centuries, to many millennia. SROCC assesses past ocean and cryosphere changes mainly on decades to centuries, and also documents daily to interannual changes in the context of climate extremes and natural hazards. The spatial scales relevant to ocean and cryosphere change may range from local (less than 100,000 km^2), to regional (100,000 to 10 million km^2), to continental (10 to 100 million km^2), and to global. For climate model outputs, 'regional' generally refers to a high-resolution model that is embedded within or forced with a lower-resolution global climate model, in order to investigate specific processes and changes relevant for local to continental-scale climate change.

1.9.1.2 Baselines and Time Periods

A baseline provides a reference period from which changes can be evaluated. In the context of anthropogenic climate change, the baseline should ideally approximate the 'pre-industrial' conditions before Industrial era greenhouse gas emissions led to significant human influences on the climate. AR5 and SR1.5 (Allen et al., in press-b) use 1850–1900 as the 'pre-industrial' baseline for assessing historical and future climate change. This period is not ideal as it includes several major volcanic eruptions, and atmospheric greenhouse gas concentrations had already begun to rise from early industrialisation (Abram et al., 2016; Hawkins et al., 2017; Schurer et al., 2017). However, the scarcity of reliable ocean and cryosphere observations represents a major challenge for quantifying earlier pre-industrial states (Figure 1.3) (Hawkins et al., 2017). To maintain consistency with other IPCC reports, SROCC uses (wherever possible) the 1850–1900 pre-industrial baseline, which is a compromise between data coverage and representativeness of typical pre-industrial forcing conditions.

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 SROCC, the 1986–2005 reference interval used in AR5 is referred to as the 'recent-past', while a 2006–2015 period is used for 'present-day', consistent with SR1.5 (Allen et al., in press-b). The 2006–2015 reference interval incorporates near-global ocean and cryosphere data coverage (Section 1.8.1), and aligns this report with a more current reference than the 1986–2005 reference adopted by AR5. The caveat is that this 10-year 'present-day' period is short relative to natural variability. However, natural variability at this decadal scale will generally be small compared to long-term changes of the 'present day' interval compared to conditions during the 'pre-industrial' (1850-1900) baseline, and to future climate assessment intervals (see below). There is also no indication of average temperatures in either 1986–2005 or 2006–2015 being substantially biased by short-term variability (Allen et al., in press-b), consistent with the AR5 finding that each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (IPCC, 2013).

SROCC 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 broadly compatible, for example, with the SDGs. An 'end-of-century' interval of 2081–2100 represents the average climate conditions reached at the conclusion of the standard CMIP5 future climate simulations (Section 1.9.2.3). In some cases, such as the assessment of future sea level rise where changes may be committed or irreversible over multi-century timescales, SROCC also considers model evidence for 'long-term' changes beyond the end of the current century (Figure 1.3).

In SROCC, timeframes are also relevant for the assessment of the significance and rates of ocean and cryosphere change. Inhomogeneous 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' (ToE), defined as the time at which a signal of climate change emerges from the noise of natural variability (Section 1.3, Box 5.1). ToE calculations require 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 (Hawkins and Sutton, 2012; Mora et al., 2013). In SROCC, assessments of trends and the ToE provide details of these methodological choices as they are relevant to a particular case of ocean and/or cryosphere change.

1.9.1.3 Scenarios and Pathways

Climate model simulations of future change use radiative forcing pathways based on assumptions about future demographic and socioeconomic development and technological change. Representative Concentration Pathways (RCP) are a set of time series of plausible future greenhouse gas concentrations, aerosols and chemically active gases, and associated land use changes (Moss et al., 2008) (Appendix 1.A, Figure 2). There are four pathways, identified by their approximate total radiative forcing of greenhouse gases by the year 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 reference, the current radiative forcing by long-lived greenhouse gases is approximately 2.5 - 3 W m^{-2} (SR1.5), yielding a net radiative imbalance in the climate system of about 0.5 - 1 W m^{-2} (Trenberth et al., 2014). RCP2.6 is the pathway considered most compatible with the Paris

Agreement goal of limiting global warming to well below 2°C (Schellnhuber et al., 2016; Rogelj et al., 2018), but would require implementation of not-yet-possible negative emissions technologies to remove greenhouse gases from the air (e.g., bioenergy with carbon capture and storage, direct CO_2 capture, enhanced mineral weathering) alongside existing nature-based strategies (e.g., growing forests) (Gasser et al., 2015; Sanderson et al., 2016; Royal Society, 2018). The RCPs were used for the CMIP5 future climate experiments (Taylor et al., 2012), and are generally the basis for future change assessments within SROCC. In some cases, however, assessments use the earlier Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000), which includes four qualitative storylines that yield four sets of emission scenarios called 'families' (Appendix 1.A, Figure 2).

The RCPs are complemented by the Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2017) (Appendix 1.A, Figure 2). SSPs allow future scenarios to be structured according to varying socio-economic challenges to adaptation and mitigation (e.g., population, economic growth, education, urbanisation and the rate of technological development). Together, the RCPs set plausible pathways for greenhouse gas concentrations and the amount of climate warming that could occur, and the SSPs set the stage on which reductions in emissions will – or will not – be achieved within the context of the underlying socioeconomic characteristics and shared policy assumptions of that world. The SSPs describe five alternative socio-economic futures that could shape future society, 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).

1.9.2 Methodologies Relevant to this Report

SROCC 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, social science and humanities works. In some cases, grey-literature sources (for example, published reports from governments, industry, research institutes, and non-government organisations) are used where there are important gaps in available peer-reviewed literature. It is recognised that published knowledge from many parts of the world most vulnerable to ocean and cryosphere change is still limited (Czerniewicz et al., 2017).

Where possible, SROCC draws upon established methodologies and/or frameworks. Cross-Chapter Boxes address methodologies used for assessing and reducing risk (Cross-Chapter Box 1), for governance options relevant to a problem or region (Cross-Chapter Box 2), and for utilising Indigenous knowledge and local knowledge (Cross-Chapter Box 3, Section 1.8.3). It is recognised in the assessment process that multiple and non-static factors determine human vulnerabilities to climate change impacts (Section 1.5.2), and that ecosystems provide essential services that have both commercial and non-commercial value (Section 1.5.1). Economic methods are also important in SROCC, for estimating the economic value of natural systems and for aiding decision-making around mitigation and adaptation strategies (Section 1.6).

1.9.3 Communication of Certainty in Assessment Findings

SROCC uses calibrated language for the communication of certainty in the assessment process (Mastrandrea et al., 2010; Mach et al., 2017). Calibrated language is designed to consistently evaluate and communicate uncertainties that arise from incomplete knowledge due to a lack of information, or from disagreement about what is known or even knowable. The IPCC calibrated language uses qualitative expressions of confidence based on the robustness of evidence for a finding, and (where possible) uses quantitative expressions to describe the likelihood of a finding (Figure 1.4).

Qualitative expressions (*confidence scale*) 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 (Figure 1.4, step 2). *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 evidence and/or low agreement among different lines of evidence, and are only presented in SROCC if they address a major topic of concern.

Quantitative expressions (likelihood scale) are used where findings can be assigned a probabilistic estimate (Figure 1.4, step 3). In the scientific literature, a finding is often said to be significant if it has a likelihood exceeding 95% confidence. Using calibrated IPCC language, this level of statistical confidence would be termed *extremely likely*. Lower levels of likelihood (e.g., *very likely*, *likely*) can also be assigned by expert judgement to take into account structural or measurement uncertainties within the products or data used to determine the probabilistic estimates. Likelihood statements may be used to describe how climate changes relate to the ends of distribution functions, such as in detection and attribution studies that assess the likelihood that an observed climate change or event is different to a reference climate state (Section 1.3). In other situations likelihood statements refer to the central region across a distribution of possibilities. Examples are the estimates of future changes based on large ensembles of climate model simulations, where the central 66% of estimates across the ensemble (i.e., the 17–83% range) would be termed a *likely* outcome (Figure 1.4, step 3).

It is increasingly recognised that effective risk management requires assessments not just of 'what is most likely' but also of 'how bad things could get' if low likelihood-high impact scenarios occur (Mach et al., 2017; Weaver et al., 2017; Xu and Ramanathan, 2017; Sutton, 2018). Low likelihood-high impact events may be difficult to assign quantitative likelihood statements such as *very unlikely*, or may be characterised by *limited* or *emerging* evidence, and the phenomena may instead be discussed according to plausible scenarios of impact (e.g., Chapter 6). In some cases, *deep uncertainty* may exist in current scientific assessments of the rate, timing and magnitude of future ocean and cryosphere changes. Nevertheless, comprehensive risk assessment that informs adaptation planning would also address such highly uncertain changes that could have catastrophic consequences (Cross-Chapter Box 4).

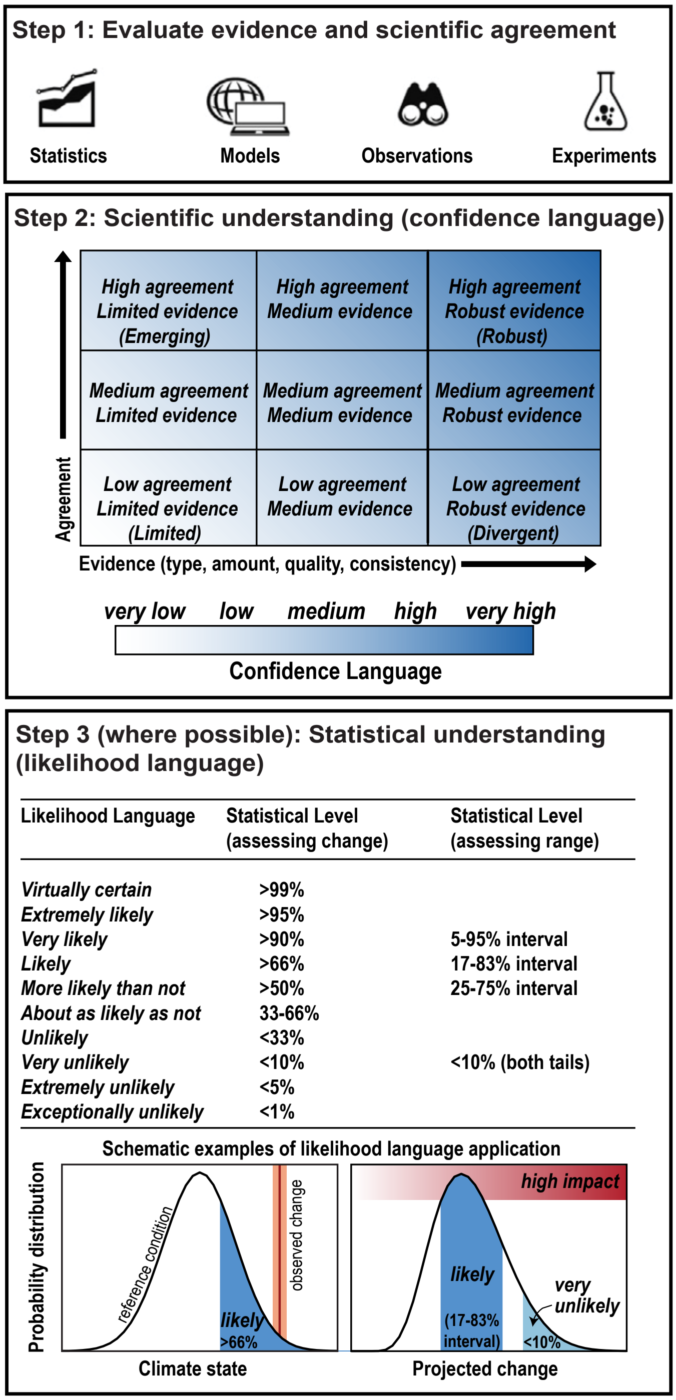

Figure 1.4: Schematic of the IPCC treatment of certainty in the assessment process, including definitions of the calibrated language used in this report for confidence (step 2) and likelihood (step 3) statements. Figure developed after Mastrandrea et al. (2010), Mach et al. (2017) and Sutton (2018).

[START CROSS-CHAPTER BOX 4 HERE]

Cross Chapter Box 4: Confidence and Deep Uncertainty

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

Definition and Context

Characterising, assessing and managing risks to climate change involves dealing with inherent uncertainties. Uncertainties can lead to complex decision-making situations for managers and policy-makers tasked with risk management, particularly where decisions relate to possibilities assessed as having low or unknown confidence/likelihood, but that would have high impacts if realised. While uncertainty can be quantitatively or qualitatively assessed (Section 1.9.3), a situation of *deep uncertainty* exists when experts or stakeholders do not know or cannot agree on: appropriate conceptual models that describe relationships among key driving forces in a system (type 1); the probability distributions used to represent uncertainty about key variables and parameters (type 2), and/or; how to value the desirability of alternative outcomes (type 3) (adapted from Lempert et al., 2003).

The concept of deep uncertainty has been debated in the literature for some time, with various terms used such as 'great uncertainty' (e.g., Hansson and Hirsch Hadorn, 2017), 'contested uncertain knowledge' (Douglas and Wildavsky, 1983), 'ambiguity' (Ellsberg, 1961), and 'Knightian' uncertainty (Knight, 1921), among others, all referring to multiple components of uncertainty that need to be considered in decision making.

The purpose of this Cross-Chapter Box is to constructively engage with the concept of deep uncertainty, by first providing some context for how the IPCC has dealt with it, followed by experiences relevant to the ocean and cryosphere through examples of cases discussed in more detail within the chapters of SROCC, where deep uncertainty has been addressed to advance assessment of risks and their management.

How has the IPCC and other literature dealt with deep uncertainty?

The IPCC, and earlier assessments, encountered deep uncertainty when assessing numerous aspects of the climate change problem. Examining these cases sheds light on approaches to quantifying and reducing deep uncertainty. An assessment by the US National Academy of Sciences (Charney, 1979, commonly referred to as the Charney Report) provides a classic example. Evaluating climate sensitivity to a doubling of carbon dioxide concentration, and developing a probability distribution for it, was challenging because only two 3-D climate models and a handful of model variants and realisations were available. The panel invoked three strategies to eliminate some of the uncertainty in these simulations: (1) using multiple lines of evidence to complement the limited model results; (2) estimating 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. This triage yielded "probable bounds" of 2°C–3.5°C on 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". The panel did not report its confidence in these judgments.

The literature has expanded greatly since, allowing successive IPCC assessments to 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) were assessed to determine that "Equilibrium climate sensitivity is *likely* in the range 1.5°C to 4.5°C (*high confidence*), *extremely unlikely* less than 1°C (*high confidence*), and *very unlikely* greater than 6°C (*medium confidence*)" (Church et al., 2013). The Charney report began the process of convergence of opinion around a single probability range (essentially, type 2 in the definition of deep uncertainty), at least for sensitivity arising from fast feedbacks captured by global climate models (Hansen et al., 2007), while the subsequent assessments increased confidence, eliminating deep uncertainty about this part of the sensitivity problem.

Dynamical ice loss from Antarctica provides an example of lack of knowledge about processes, and disagreement about appropriate models and probability distributions for representing uncertainty (types 1 and 2 in the definition of deep uncertainty). The IPCC Third Assessment Report (TAR) 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, p.642). New observations disagreeing with decade-scale predictions of these models (Lemke et al., 2007) led to deep uncertainty which manifest itself as the inability of the IPCC Fourth Assessment Report (AR4) to estimate the dynamical contribution of either the Greenland or Antarctic ice sheet. AR5 (Church et al., 2013) used the results of a statistical model with limited process description to derive a *likely* range of –0.06 to 0.14 m across RCPs for the Antarctic ice sheet contribution to sea level rise for 2081–2100 compared to 1986–2005. AR5 also used expert judgment to re-characterise the *very likely* range of the model estimates as the *likely* range, and invoked multiple lines of evidence to characterise the potential for an additional Antarctic contribution larger than these values, due to marine ice sheet instability (Section 4.2.3): "literature suggests (with *medium confidence*) that its potential magnitude is several tenths of a metre" (Church et al., 2013, p.1174). Like the climate sensitivity case, AR5 narrowed uncertainty using both quantitative and qualitative strategies drawing on multiple lines of evidence and expert judgment.

Cases of Deep Uncertainty from SROCC

Case A — Permafrost carbon and greenhouse gas emissions: AR5 reported the estimated size of the organic carbon pool stored frozen in permafrost zone soils, but uncertainty estimates were not available (Tarnocai et al., 2009; Ciais et al., 2014). AR5 further reported that future greenhouse gas emissions (CO_2 only) from permafrost were the most uncertain biogeochemical feedback on climate of the ten factors quantified (Figure 6.20 of AR5). *Low confidence* assigned by AR5 for permafrost was not in this case due to a small number of studies, but rather the state of deep uncertainty about both the conceptual framework relating changes in permafrost carbon and future greenhouse-gas emissions, as well as the probability distribution of key variables. Most large-scale carbon-climate models still lack key landscape-level mechanisms that are known to abruptly thaw permafrost and expose organic carbon to decomposition (e.g., abrupt thaw), and many do not include mechanisms needed to differentiate the release of methane versus carbon dioxide with their very different global warming potentials. Studies since AR5 on potential methane release from laboratory soil incubations (Schädel et al., 2016; Knoblauch et al., 2018), actual methane release from the Siberian shallow Arctic ocean shelves (Shakhova et al., 2013; Thornton et al., 2016), changes in permafrost carbon stocks from the Last Glacial Maximum until present (Ciais et al., 2011; Lindgren et al., 2018), and potential carbon uptake by future plant growth (Qian et al., 2010; McGuire et al., 2018) have widened rather than narrowed the uncertainty range (Section 3.4.3.1.1).

Accounting for greenhouse gas release from polar, high mountain (Box 2.2) and temperate permafrost introduces an element of deep uncertainty into determining emissions pathways consistent with Article 2 of the Paris Agreement (Comyn-Platt et al., 2018). With stakeholder needs in mind, scientists have been actively engaged in narrowing and characterising this uncertainty by using multiple lines of evidence, expert judgment, and joint evaluation of observations and models. As a result, SROCC has reduced uncertainty and introduced confidence assessments across many components of this problem (Section 3.4.3.1.1.).

Case B — Antarctic ice sheet and sea level rise: Based on modelling of marine ice sheet instability not possible for AR5, SROCC has further reduced uncertainty in the Antarctic contribution to sea level rise. The *likely* range including the effect of this instability is quantified as 0.03–0.31 m for 2081–2100 (and 0.03–0.45 m for 2100) compared to 1986–2005 across RCPs (*medium confidence*). However, the magnitude of additional rise beyond 2100 and the probability of contributions of greater magnitude than the *likely* range before 2100 remain deeply uncertain (Section 4.2.3).

Policymakers at various levels of governance are considering adaptation investments (e.g., hard infrastructure, retreat, and nature-based defences) for multi-decadal time horizons that take into account projection uncertainty (Sections 4.4.2, 4.4.3). 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 or sooner at many low-lying coastal locations (Section 4.4.3). Sea level rise exceeding the *likely* range, or an alternate pathway to the assumed climate change scenario (e.g., which RCP is used in risk estimation), could alter these projections and both factors are characterised by deep uncertainty. Among the strategies used to reduce deep uncertainty in these cases are formal and informal elicitation of expert judgment to project ice sheet behaviour (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; Bamber et al., 2018), and development of plausible sea level rise scenarios, including extreme cases (Sections 4.2.3, 4.4.5.3). Frameworks for risk management under deep uncertainty in the context of time lags between emissions mitigation and committed changes in ice sheet response, and between coastal adaptation planning and implementation are currently emerging in the literature (Section 4.4.5.3.4).

Case C — Compound risks and cascading impacts: Compound risks and cascading impacts (Sections 6.1, 6.8, Figure 6.1) arise from multiple coincident or sequential hazards (Zscheischler et al., 2018). Compound risks are an example of deep uncertainty because their rarity means that there is often a lack of data or modelling to characterise the risks statistically under present conditions and future changes (Gallina et al., 2016), and the potential that climate elements could cross tipping points (e.g., Cai et al., 2016). However, effective risk reduction strategies can arise without knowing the statistical likelihoods by acknowledging the possibility that an event can occur (Dessai et al., 2009). Such strategies are typically well-hedged against a variety of different futures and adjustable through time in response to emerging information (Lempert et al., 2010). Raising awareness of the possibility of compound events can be achieved through case studies, which provide valuable learnings for decision makers in the form of analogues (McLeman and Hunter, 2010), and can be used to devise scenarios to stress test systems in other regions for the purposes of understanding and reducing risk.

For example, the compound events experienced across the Australian state of Tasmania in 2015/2016 (Box 6.1) resulted in compound risks that could not have been estimated due to deep uncertainty. This compound climate event 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 linking Tasmania's electricity grid to the mainland that led to energy shortages. The dry prevailing conditions and a lightning storm caused severe bushfires in world heritage forests. Later in the summer a major flooding event in the state's northeast, caused by an extra-tropical cyclone, challenged the capacity of the state's emergency services, who were simultaneously responding to both fires and floods. Meanwhile an unprecedented marine heatwave off the east coast had a significant impact on the state's aquaculture industry. The total cost of the co-occurring fires, floods and marine heat wave to the state government was assessed at about $300 million USD, and impacts on the food, energy and manufacturing sectors reduced Tasmania's anticipated economic growth by approximately half (Eslake, 2016). In the aftermath of this event, the government increased funding to relevant agencies responsible for flood and bushfire management and independent reviews have recommended major policy reforms that are now under consideration (Blake, 2017; Tasmanian Climate Change Office, 2017).

What can we learn from SROCC cases in addressing deep uncertainty?
Using the adapted version of the Lempert et al. (2003) definition, we find that each of the three cases described in this Box involve at least one of the three ways that deep uncertainty can manifest. In Case A (Permafrost carbon and greenhouse gas emissions), incomplete knowledge on relationships and key drivers and feedbacks (type 1), coupled with broadened probability distributions as a result of post-AR5 literature (type 2), are key sources of deep uncertainty. In Case B (Antarctic ice sheet and sea level rise), the inability to characterise the probability of marine ice sheet instability due to lack of adequate models resulting in divergent views on the probability of ice loss lead to deep uncertainty of types 1 and 2. In Case C, the Australian example provides insights on the inadequacy of models or previous experience for estimating risk of multiple simultaneous extreme events, contributing to the exhaustion of resources which were then insufficient to meet the need for emergency response. This case also points to the complex task of addressing multiple simultaneous extreme events, and the multiple ways of valuing preferred outcomes in seeking to reduce future losses (type 3).

The three cases demonstrate the continued iterative process required to meaningfully engage with deep uncertainty in situations of risk, through means such as elicitation, deliberation, and application of expert judgment, scenario-building, and invoking multiple lines of evidence. These approaches can feasibly reduce or eliminate deep uncertainty in complex situations, keeping in mind the importance of depicting sources for disagreement that can lead to situations of deep uncertainty (Adler and Hirsch Hadorn, 2014). However, obstacles should not be underestimated and reducing deep uncertainty can take decades.

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[END CROSS-CHAPTER BOX 4 HERE]

1.10 Integrated Storyline of this Special Report

Each chapter of SROCC 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.

This report does not attempt to assess all aspects of the ocean and cryosphere in a changing climate. Examples of research themes that will be covered in elsewhere in the IPCC Sixth Assessment Cycle and not SROCC include: assessments of ocean and cryosphere changes in the Sixth Coupled Model Intercomparison Project (CMIP6) experiments (AR6); cryosphere changes outside of polar and high mountain regions (e.g., temperate and low altitude snow cover and permafrost; AR6); and a thorough assessment of mitigation options for reducing climate change impacts (SR1.5, AR6 WGIII).

The chapters that follow in this special report are framed around geographic or climatic aspects where the ocean and/or cryosphere are particularly important for natural and human systems. Chapter 2 assesses *High Mountain* areas outside of the polar regions, where glaciers, snow and/or permafrost are persistent features that provide life-giving freshwater resources and present 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 examines *Sea Level Rise on Low-Lying Regions, Coasts and Communities*, caused by thermal expansion of the ocean and ice melt, and including the spatial and temporal modulation of sea level impacts by factors such as subsiding/uplifting coasts, tides, storm surges, and waves. The multitude of ways in which *Low-Lying Islands and Coasts* are exposed and vulnerable to the impacts of ocean and cryosphere change, along with resilience and adaptation strategies, opportunities and governance options specific to these settings, is highlighted in integrative Cross-Chapter Box 7. Chapter 5 focuses on the *Changing Ocean*, with a particular focus on how climate change impacts on the ocean (excluding polar ocean changes already assessed in chapter 3) are altering *Marine Ecosystems* and affecting *Dependent Communities,* and response options including ocean-based mitigation (blue carbon) and adaptation. 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 ocean and cryosphere and the challenges this brings to *Managing Risk*.

[START FAQ1.1 HERE]

FAQ 1.1: How do changes in the ocean and cryosphere affect our life on planet Earth?

The ocean and cryosphere—a collective name for the frozen parts of the Earth—are essential to the climate and life-giving processes on our planet (FAQ 1.1, Figure 1). Human-induced climate change can affect crucial elements of these processes, with consequences for the well-being of people around the world.

Changes in the ocean and cryosphere have occurred naturally throughout Earth's history, but the speed, magnitude, and pervasiveness of the changes happening right now are very unusual. Scientific evidence shows that the majority of ocean and cryosphere changes observed in the past few decades are the result of human influences on Earth's climate. Continued emissions of greenhouse gases, and the climate changes they cause, are putting the ocean and cryosphere on a path toward conditions that they had not experienced in millions of years.

About 27% of the global population (1.9 billion people) live in areas less than 100 km from the coastline and less than 100 m above sea level, and livelihoods of millions more are tied closely to the ocean through trade, food, transportation, and recreation. Marine fish and shellfish contribute about 20% of the non-grain protein in human diets, while approximately 80% of international imports and exports are by marine transport. Near high mountains and in the Arctic, people live in close contact with the cryosphere, depending on the environment it provides for their livelihoods, food and water security and cultures.

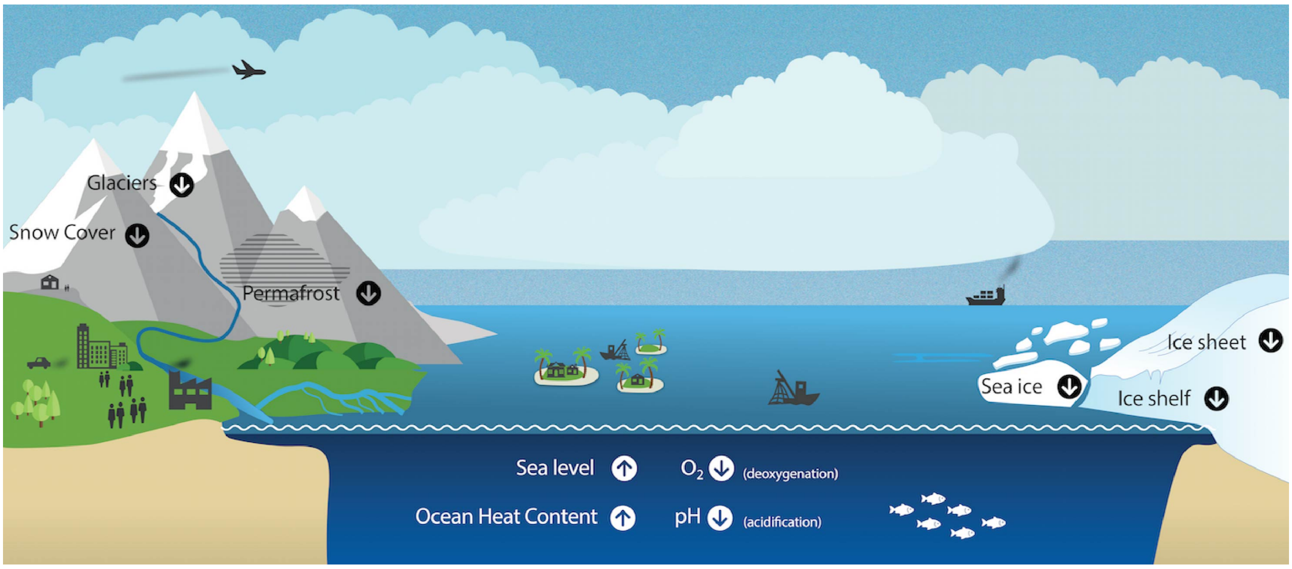
Even people living far from the ocean and cryosphere depend on those systems for human and planetary well-being. The ocean is taking up more than 90% of the extra heat accumulating in the Earth system, limiting the atmospheric warming that people and ecosystems are exposed to. The ocean is the primary conduit to transport heat around the planet, and the movement of heat from low to high latitudes, and from the sea surface to the deep ocean, influence both our weather and climate. With rising water temperatures, the ocean expands and requires more space, which represents one of the primary mechanisms driving sea level rise. Warming at the surface also causes the upper layer of the ocean to become more buoyant. This reduces the transport of oxygen from the surface to depth, where it would be needed for breathing and the breakdown of organic matter for other parts of the food web. The ocean has also taken up around 30% of the carbon dioxide (CO_2) that has been released by human activities, reducing the magnitude of greenhouse warming. However, dissolving CO_2 into the ocean triggers a chemical reaction, increasing the acidity of seawater. This makes the water more corrosive for marine organisms, such as corals and mussels, that build their shells and structures out of mineral carbonates. Thus, the ocean is threatened by three major climate change-induced stressors: warming, deoxygenation, and acidification. These stressors are global in nature, extend to deeper than 1000 m, and affect all marine ecosystems.

Marine ecosystems respond to ocean changes, in different ways. Coral reefs, for example, are increasingly subject to mass-mortality from bleaching due to the increase in water temperatures and marine heat waves. Ocean acidification makes it more difficult for marine organisms, including corals, to build carbonate shells and reef structures. These climate-change stressors occur with other human-driven stressors such as eutrophication (excess nutrients), over-harvesting, and pollution. For example, fish populations are changing both in response to climate change and fishery pressures. Climate change is also driving changes in the geographic ranges of marine organisms, resulting in loss of organisms from regions or the introduction of new species. The consequences of these shifts include changes in the availability and type of biological resources to local human communities.

Changes in the cryosphere are pervasive too. Ice is being lost from mountain glaciers, the Arctic ocean, and from the vast ice sheets of Greenland and Antarctica, due to warming of the atmosphere and ocean. Of particular concern is the melting of the base of large ice sheets where they are in direct contact with seawater. This leads to not only a much more rapid rate of melting, but could also greatly accelerate the ice flows further upstream, draining ice from some inland parts of Antarctica within a few hundred years. The resulting rapid increases in sea level rise and elevated storm surges threaten millions of lives, livelihoods, and billions of dollars in infrastructure. Thawing of permafrost (areas of ground which remain frozen over years) in a warming climate is also of special concern, since in addition to destabilising human infrastructure and natural systems, it has the potential for releasing vast quantities of methane into the atmosphere and further exacerbate climate change.

Many changes in the ocean and cryosphere feedback to influence climate change. Changes in evaporation from the ocean surface alters the water cycle that sustains life on Earth. In polar and high mountain areas, ice from glaciers and ice sheets formed over millennia, and from sea ice on the ocean surface, reflect solar energy rather than absorb it. The loss of ice thus allows more solar energy to be absorbed, further amplifying the climate changes that are causing ice losses.

By reducing greenhouse gas emissions, risks can be reduced or even avoided, and the effectiveness of adaptation efforts improved. However, some changes, such as sea level rise and ice-sheet loss will continue for several centuries, even if emissions are halted. As some ocean and cryosphere changes are not reversible (on timescales of decades to centuries), urgent actions to reduce emissions and mitigate climate changes, and adapt to their imminent occurrence, are essential.



FAQ 1.1, Figure 1: Schematic summarising key components of Earth's ocean and cryosphere, and the ways that they are changing with climate warming. [PLACEHOLDER FOR FINAL DRAFT: development of infographic proposed]

[END FAQ1.1 HERE]

[START FAQ1.2 HERE]

FAQ 1.2: How will changes in the ocean and cryosphere affect meeting the Sustainable Development Goals?

The Sustainable Development Goals (SDGs) were adopted by the United Nations in 2015 to support action for people, planet and prosperity (FAQ 1.2, Figure 1). The 17 goals, and their 169 targets, strive to end poverty and hunger, protect the planet, and reduce gender, social and economic inequities by 2030.

'Climate Action' is SDG 13, which explicitly recognises that changing climatic conditions are a global concern. Climate change is already impacting food, water and health securities, with consequences for achieving SDG 2 (Zero Hunger), SDG 3 (Good Health and Wellbeing), SDG 6 (Clean Water and Sanitation), and even SDG 1 (No Poverty). Climate change is altering the Earth's ocean and cryosphere in many ways (See FAQ 1.1) that affect the environmental goals for ocean (SDG 14) and land (SDG 15) and will make it more difficult to meet many of the other SDGs.

Water security (SDG 6) will be affected by ocean and cryosphere changes. Melting of mountain glaciers brings an initial increase in water, but as glaciers continue to shrink so too will the essential water they provide to millions of mountain dwellers, downstream communities and cities. These populations also depend on water flow from the high mountains for drinking, sanitation and irrigation, and for Affordable and Clean Energy (SDG 7). Changes in the magnitude and seasonality of rainfall, driven by rising ocean temperatures, threatens water security by increasing the risk of severe storms and flooding in some areas, and by increasing the risk of more severe or more frequent droughts in others. Among other effects, on-going sea level rise is allowing salt water to intrude further inland, contaminating drinking water and irrigation sources for coastal populations. Actions to address these threats will likely require new infrastructure to manage rain, melt-water and river flow, in order to make water supplies more reliable. These actions would also benefit SDG 3 (Good Health and Well-Being for People) by reducing risk of flooding and disease posed by extreme rainfall and outbursts of glacial melt.

Climate change impacts on the ocean and cryosphere also have many implications for progress on food security (SDG 2 – Zero Hunger). Changes in rainfall patterns caused by ocean warming will increase aridity in some areas, and bring more (or more intense) rainfall to others. This brings varying challenges for maintaining reliable crops and livestock production. Some adaptation opportunities might be found in developing strains of crops and livestock, better adapted to the future climate conditions, but this response option is also challenged by the rapid rate of climate change. In the Arctic, very rapidly warming temperatures and melting sea ice and permafrost are restricting the habitats and migration patterns of reindeer and several marine mammals (SDG 15 – Life on Land), bringing reduced hunting opportunities for staple foods that communities here depend upon.

Food security from the ocean also presents both positive and negative implications for SGD 2. Rising temperatures, and changes in ocean nutrients, acidity, and salinity are altering Life Below Water (SDG 14). Some fish species supporting long-established fisheries may decline, whereas the range of fish populations may move to become available in some new coastal and open ocean areas. Coral reef ecosystems are particularly threatened by current and projected increases in ocean temperature. Ocean changes are of particular concern for Small Island Developing States (SIDS) and coastal cities and communities. Beyond possible reductions in marine food supply, these populations face a multitude of other challenges from sea level rise and warming oceans. Inundation of coastal homes and infrastructure, more powerful tropical storms, declines in established economies (e.g., tourism), and losses of cultural heritage and identity, all threaten lives, livelihoods and well-being in ways that are linked to several SDGs, including 3 (Good Health and well-being), 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure) and 11 (Sustainable Cities and Communities). The measures needed to adapt to these threats require improved community and coastal infrastructure, relocation of critical services, and more effective and faster disaster responses from health care and other emergency services, although for some populations migration may become the only viable response.

There are limits to the adaptation measures that can be made to meet the SGDs in the face of on-going ocean and cryosphere change. Urgent action to reduce climate warming (mitigation) will provide the best possibility to limit the extent of ocean and cryosphere change and give more options for effective adaptation and sustainable development. Progress on SDG 4 (Quality Education), SDG 5 (Gender Equality) and SDG 10 (Reduced Inequalities) will reduce the vulnerabilities that shape people's risk to ocean and cryosphere change, while SDG 12 (Responsible Consumption and Production), SDG 16 (Peace, Justice and Institutions) and SDG 17 (Partnerships for the Goals) will help to facilitate the scales of adaptation and mitigation responses required to achieve sustainable development. Investment in social and physical infrastructure that supports adaptation to inevitable ocean and cryosphere changes will enable the poor to participate in initiatives to achieve the SDGs. Current and past IPCC efforts have focused on identifying 'climate-resilient development pathways', and such adaptation and mitigation strategies, supported by adequate investments, could also constitute pathways for progress on the Sustainable Development Goals.

FAQ 1.2, Figure 1: Interaction of the Sustainable Development Goals with ocean and cryosphere change

[END FAQ1.2 HERE]

[START FAQ1.3 HERE]

FAQ 1.3: How do indigenous knowledge and local knowledge help us understand and respond to the ocean and cryosphere in a changing climate?

To understand how climate change interacts with and affects the ocean and the frozen parts of planet Earth, none as the cryosphere, and to respond to those changes, people around the world use different knowledge systems. Overall, Indigenous, local and scientific knowledge form these knowledge systems and provide precious stores of information for responding to climate change.

Most of the globally published knowledge about the ocean and cryosphere in a changing climate is founded upon scientific measurements and observations. Scientific knowledge tells us important aspects of global change. However, scientific knowledge does not tell the whole story. Populations living in close contact with and dependence on the ocean and/or cryosphere have specific observations and knowledge of those systems, knowledge that can increase the overall understanding of our changing world. This knowledge is referred to as either Indigenous knowledge or local knowledge.

Indigenous knowledge is one part of a people's cultural legacy, including information pertinent to success in their environment. It is not only passed on from generation to the next, but is also flexible and adaptive to changing conditions. Local knowledge is what non-indigenous communities use in both rural and urban environments to be successful in living on a daily and lifelong basis. Both Indigenous knowledge and local knowledge are evidence-based and empirical, founded upon observation, experience and documentation, and are increasingly included in peer-reviewed literature.

Utilising the diversity of knowledge systems relevant to the local impacts of global changes allows for the fullest understanding of and the most appropriate ways of adapting to that change. Moreover, knowing how an affected community understands their world facilitates the translation of scientific information into their understanding and bolsters appropriate local responses.

Indigenous knowledge and local knowledge not only put global change into local contexts, they add depth and breadth to scientific study by providing on-the-ground observations and understandings of how global climate change is playing out in a people's immediate ecosystem and impacting daily life, perceptions, understandings, and responses.

[END FAQ1.3 HERE]

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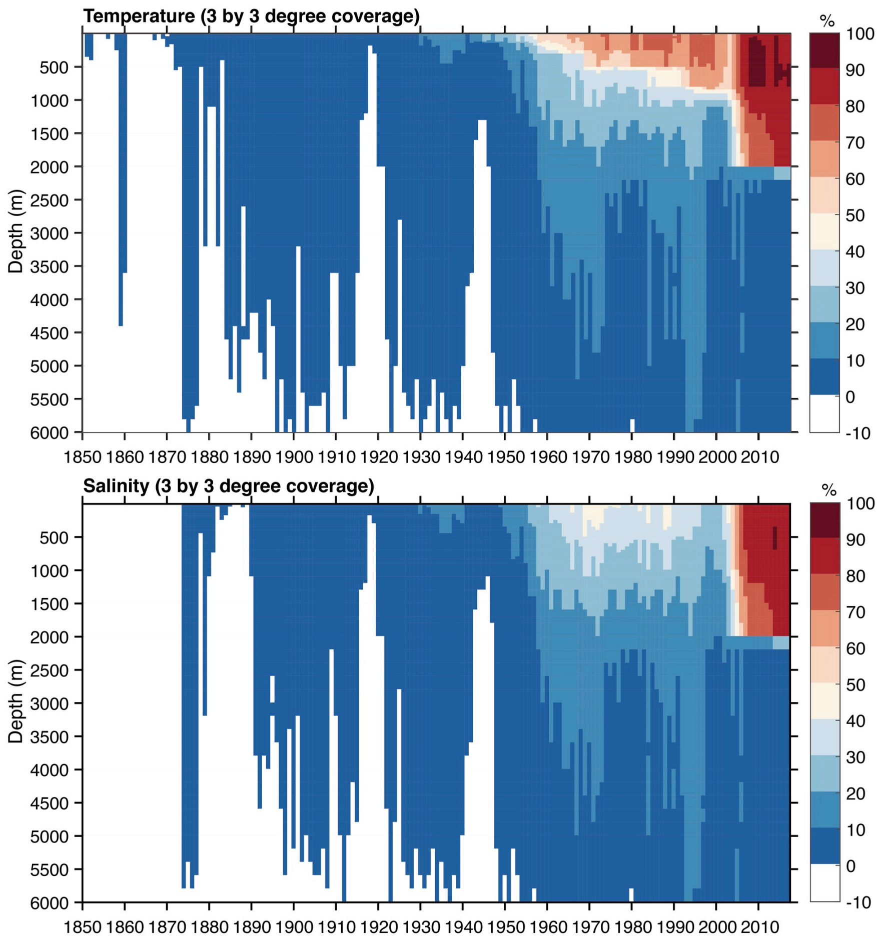
Appendix 1.A: Supplementary Material

Supplementary Material for Figure 1.3

The lower panel of Figure 1.3 gives examples of available data/output for the ocean and cryosphere (Section 1.8.1). 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:

- *Ocean temperature and salinity observations* are from the World Ocean Database (Boyer et al., 2013). The data in Figure 1.3 shows the number of observations in the database through time for three depth layers, relative to maximum annual values of 1,102,401 for the 0–800 m layer, 382,619 for the 800–2000 m layer, and 12,875 for observations deeper than 2000 m. Spatial coverage is calculated as the percentage of 3° x 3° ocean grid cells that have observations. Additional detail of the spatial coverage of ocean temperature and salinity observations by depth is given below in Appendix 1.A, Figure 1. Database: https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html



Appendix 1.A, Figure 1: Further detail on the spatial coverage of ocean *in situ* temperature (upper) and salinity (lower) observations from the sea surface to 6000 m depth in the World Ocean Database (Boyer et al., 2013). Coverage is calculated as the percentage of 3° x 3° ocean grid cells that have observations and is adjusted for the changing lateral extent of the ocean at different depth levels.

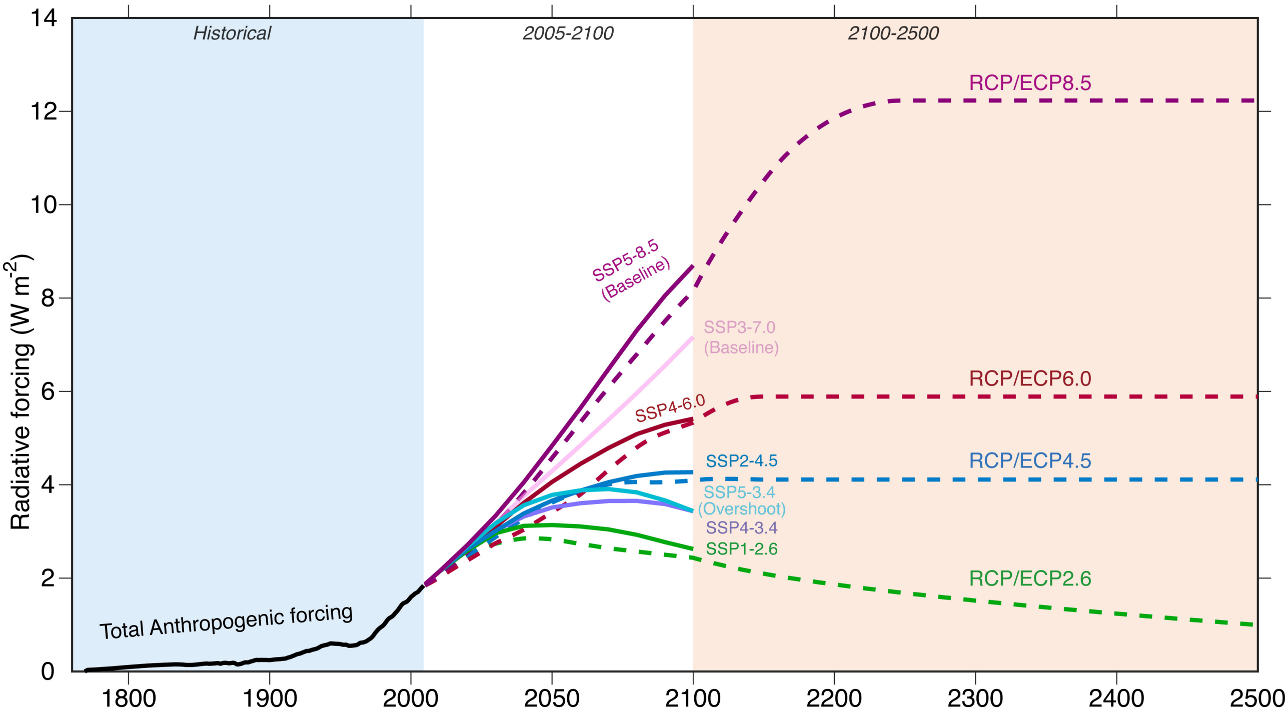
- *Sea level observations* are from tide gauge data archived in the Permanent Service for Mean Sea Level (PSMSL) (PSMSL, 2016). There are a total of 1508 tide gauge sites in the PSMSL database and these are located around the world's coastal and island regions. The maximum number of tide gauges giving measurements in a single year in the PSMSL database is 776. Data coverage is calculated as the percentage of 3° x 3° ocean grid cells that have observations, and the low level (<10%) of ocean coverage reflects the siting of tide gauges on coasts, rather than across the open ocean. Database: https://www.psmsl.org/data/obtaining/

- *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

- *Remote sensing (ocean)* shows the availability through time of six surface ocean parameters derived from satellite monitoring; sea surface temperature, sea surface salinity, ocean colour, ocean wind, ocean height and ocean mass. *Remote sensing (cryosphere)* shows the availability through time of five cryosphere parameters; sea ice extent/area, ice mass, ice elevation, ice area and snow cover (Dowell et al., 2013).

- *Palaeoclimate 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 1.3 shows the number of palaeoclimate 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 palaeoclimate data. Database doi: 10.6084/m9.figshare.c.3285353

- *Model simulation* outputs in Figure 1.3 are 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).



Appendix 1.A, Figure 2: Radiative forcing (W m^{-2}) time series for historical data (1765–2004), and for future scenarios from the Special Report on Emission Scenarios (SRES; 2005–2100), the Representative Concentration Pathways (RCP; 2005–2100) and their continuation as the Extended Concentration Pathways (ECP; 2100–2500), and the Shared Socio-economic Pathways (SSP; 2005–2100). The RCP/ECP scenarios are shown as dashed curves, and SSPs are shown as solid curves ('Marker' scenarios are used). Note the change in x-axis scale for the 2005–2100 interval to give an improved illustration of radiative forcing scenarios during the 21st century. [PLACEHOLDER FOR FINAL DRAFT: SRES data to be added].

The RCP/ECP scenarios were used for future climate experiments as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5), and their number refers to the total radiative forcing level at 2100 (Section 1.9.1.3).

Five SSP narratives describe alternative pathways for future society. Each SSP looks at how the different RCPs could be achieved within the context of the underlying socioeconomic characteristics and shared policy assumptions of that world. The SSPs five alternative socio-economic futures compromise: 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). Across these five SSP narratives there are a total of 23 'Marker' SSP scenarios. Appendix 1.A, Figure 2 shows some specific SSP Markers compared with the RCPs, according to O'Neill and Graham (2016). SSP5-8.5 represents the high end of the range of future pathways, corresponding to RCP8.5. SSP3-7.0 lies between RCP6.0 and RCP8.5, and represents the medium to high end of the range of future forcing pathways. SSP4-6.0 corresponds to RCP6.0, fills in the range of medium forcing pathways. SSP2-4.5 represents the medium part of the range of future forcing pathways and updates RCP4.5. SSP5-3.4 (Overshoot) fills a gap in existing climate simulations by investigating the implications of a substantial 21st century overshoot in radiative forcing relative to a longer-term target. SSP4-3.4 fills in the range of low forcing pathways, and there is substantial mitigation policy interest in this scenario that reaches 3.4 W m^{-2} by 2100. SSP1-2.6 is similar to RCP2.6. It is anticipated that it will produce a multi-model mean of less than 2°C warming by 2100.

SRES includes four qualitative storylines, yielding four sets of scenarios called 'families': A1, A2, B1, and B2. The A1 family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A1 family develops into three groups distinguished by their technological emphasis: fossil-fuel intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). The A2 family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. The B1 family describes a convergent world with a global population that peaks in mid-century and declines thereafter (as in the A1 storyline), but with rapid changes in economic structures toward a service and information economy, reductions in material intensity, and the introduction of clean and resource-efficient technologies. The B2 family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. With respect to radiative forcing, RCP4.5 is close to SRES B1 , RCP6.0 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 (Cubasch et al., 2013; Stocker et al., 2013).