# Summary for Policymakers

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## Introduction

The Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) was prepared following a decision of governments in preparation for the Sixth Assessment Cycle[1]. By assessing new scientific literature[2], this report responds to proposals for Special Reports from governments and observer organizations provided at the start of the IPCC Sixth Assessment cycle. The SROCC has been produced alongside other IPCC reports, including the Special Report on Global Warming of 1.5°C.

This Summary for Policymakers (SPM) compiles key findings of the report. The level of confidence associated with each key finding in the three sections of this SPM (observed changes, projected changes, responses) is reported using IPCC calibrated language[3].

**Startup Box: The importance of the ocean and cryosphere for people**

The global ocean covers 71% of the Earth surface stretching from the poles to equatorial regions and contains about 97% of the Earth's water. The cryosphere refers to frozen components of the Earth system: snow, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground. Around 10% of Earth's land area is covered by glaciers or ice sheets, which together with permanent snow hold about 69% of Earth's freshwater. The ocean and cryosphere support unique habitats, and are interconnected with other components of the climate system through global exchange of water, energy and carbon. {Box 1.1, 1.2}

All people on Earth depend directly or indirectly on the ocean and cryosphere. Services provided to people by the ocean and/or cryosphere include the uptake and redistribution of anthropogenic carbon dioxide and heat by the ocean, food production and ecosystem support, supply of freshwater and renewable energy, and benefits associated with health and wellbeing, cultural values, tourism, trade, and transport. {1.1, 1.2, 1.5}

Human communities in close connection with polar, mountain, and coastal environments are particularly exposed to ocean and cryosphere change. Today, around 4 million people live permanently in the Arctic region, of whom 10% are Indigenous. The low-lying coastal zone[4] is currently home to around 680 million people (around 11% of the 2010 global population), projected to reach more than one billion by 2050. Around 670 million people (nearly 10% of the 2010 global population) live in high mountain regions[5], where population is projected to reach between 740 to 840 million by 2050. {Figure SPM.1, 1.1, 2.1, 3.1, Cross-Chapter Box 9}

The responses of the ocean and cryosphere to past and current human-induced greenhouse gas emissions and ongoing global warming include changes over decades to centuries that cannot be avoided, thresholds of

[1] The decision to prepare a Special Report on Climate Change and Oceans and the Cryosphere was made at the Forty-Third Session of the IPCC in Nairobi, Kenya, 11 - 13 April 2016.

[2] Cut-off dates: 15 October 2018 for manuscript submission, 15 May 2019 for acceptance of publication

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

[4] Population in the low elevation coastal zone is calculated for land areas connected to the coast that are less than 10 metres above sea level {Cross-Chapter Box 9}.

[5] Population in high mountain regions is calculated for areas less than 100 kilometres from glaciers or permafrost in mountain areas assessed in this report {2.1}. Projections for 2050 give the range of population in these regions across all five of the Shared Socioeconomic Pathways {Cross-Chapter Box 1 in Chapter 1}.

abrupt change, and irreversibility. This implies that, in order to manage risks and avoid escalating risks, adaptation of ecosystems and societies to ocean and cryosphere change is needed, in addition to greenhouse mitigation {1.1, 1.3}. The state of the ocean and cryosphere interacts with each aspect of sustainability reflected in the United Nations Sustainable Development Goals (SDGs), including poverty reduction, thus making the future of the ocean and cryosphere a worldwide social concern. {1.1}

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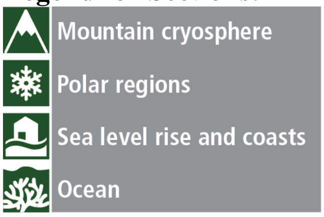



## SPM.A OBSERVED CHANGES AND IMPACTS

### *Observed Physical Changes*

**A1.** Earth's terrestrial cryosphere is shrinking, through mass-loss from glaciers and ice sheets (*very high confidence*), reduced seasonal snow (*high confidence*), and degradation of permafrost (*high confidence*). {2.2, 2.3, 3.3, 3.4, Figures SPM.1, SPM.2}

**A1.1** Ice sheets and glaciers worldwide are losing mass (*very high confidence*). In 2006–2015, the Greenland Ice Sheet lost ice mass at a rate of 278 ± 11 Gigatonnes $yr^{-1}$ (Gt $yr^{-1}$), and the Antarctic Ice Sheet lost mass at a rate of 155 ± 19 Gt $yr^{-1}$. This corresponds to global sea level rise contribution of 0.77 ± 0.03 and 0.43 ± 0.05 mm $yr^{-1}$. Ice loss from Antarctica is dominated by the rapid thinning and retreat of major glaciers draining the West Antarctic Ice Sheet (*very high confidence*). In Greenland, mass loss has been dominated by surface melting (*high confidence*). Glaciers (that are not part of the ice sheets) lost mass at a rate of 278 ± 113 Gt $yr^{-1}$ in 2006–2015, corresponding to a sea level contribution of 0.77±0.31 mm $yr^{-1}$. {3.3.1, 4.2.3, Appendix 2.A, Figures SPM.1, SPM.2}

**A1.2** Arctic June snow cover extent declined by 13.4 ± 5.4% per decade from 1967 to 2018 (*high confidence*). Reductions in snow cover duration are directly attributed to extratropical temperature increases, with approximately 800,000 $km^2$ of snow cover lost per °C warming in both autumn and spring (*high confidence*). The depth, extent and duration of snow cover has declined in nearly all mountain regions with a *likely* range of 0-10 days per decade, especially at lower elevation (*high confidence*). {2.2.2, 3.4.1, Figures SPM.1, SPM.2}

**A1.3** Changes in high mountain glaciers and snow melt and Arctic hydrology have caused changes in river runoff (*high confidence*). From 1976 to 2018, annual discharge into the Arctic ocean increased for large Eurasian and North American rivers by 3.1 ± 2.0% and 2.6 ± 1.7%, respectively (*medium confidence*). Retreat of glaciers and thaw of permafrost have decreased the stability of high-mountain slopes (*high confidence*). The number and area of glacier lakes has increased in most regions in recent decades (*high confidence*). {2.3.1, 2.3.2, 3.4.1, Figure SPM.2}

**A1.4** Permafrost temperatures have increased to high levels unprecedented in the observational record (1980s-present) (*very high confidence*), for example increasing across polar and mountain regions globally by 0.29 ± 0.12°C from 2007 to 2016. Permafrost region soils contain 1440-1600 Gt organic carbon (*medium confidence*), although evidence is divergent whether permafrost warming is currently causing the release of additional greenhouse gases to the atmosphere. {2.2.4; 3.4.1; 3.4.3, Figures SPM.1, SPM.2}

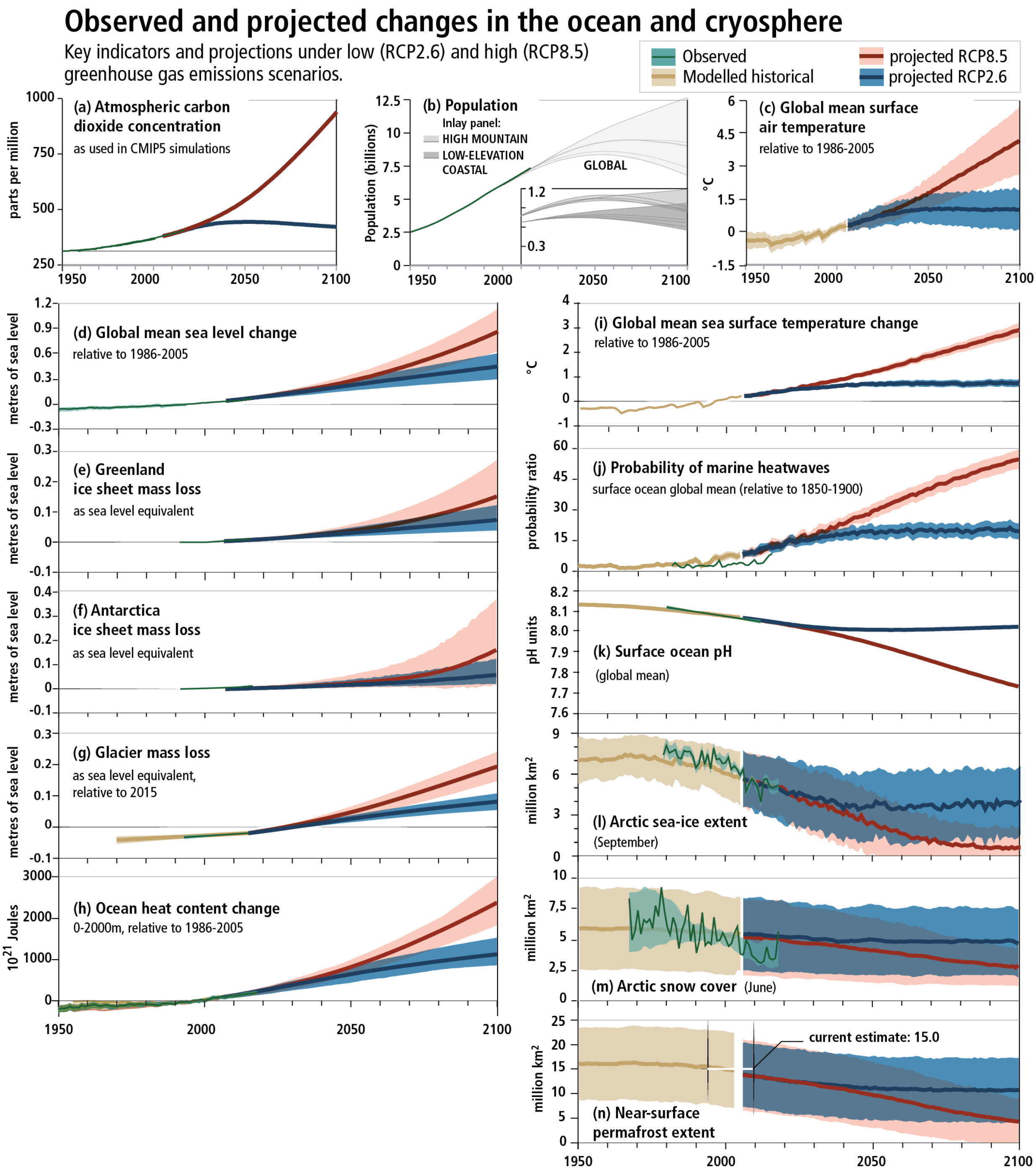



**Figure SPM.1:** Changes in the ocean and cryosphere that have already occurred, and projected future changes this century under low (RCP2.6) and high (RCP8.5) greenhouse gas emission scenarios. Context is shown by changes in: (a) atmospheric carbon dioxide concentration {Cross-Chapter Box 1 in Chapter 1, Figure 1.3}; and (b) global population including the range of future population scenarios for global, high mountain and low-elevation coastal populations across the Shared Socioeconomic Pathways. Additionally, around 4 million people live in the Arctic (2010), with an increase of 4% projected for 2030 {1.1, 2.1, 4.3, Cross-Chapter Box 1 in Chapter 1}. Pervasive and intensifying ocean and cryosphere changes are shown in lower panels for observed (green) and/or modelled historical (brown) changes, and contrasting differences in future changes under high (red; RCP8.5) and low (blue; RCP2.6) greenhouse gas emission scenarios. Changes are shown for: (c) global mean surface air temperature change relative to 1986-2005 with *likely* range. AR5 assessed that observed surface temperature increase from preindustrial (1850-1900) to 1986-2005 was 0.61 (± 0.6) °C {Cross-Chapter Box 1 in Chapter 1}; (d) Global mean sea level change (metres) relative to 1986-2005 with *likely* range {4.2.3}; (e, f) Greenland and Antarctic ice sheet mass loss, as contribution to global sea level (metres), relative to 1992 with ± 1 standard deviation range {3.3.1}; (g) Glacier mass loss, as contribution to global sea level (metres), relative to 2015 with *likely* range {Cross-Chapter Box 6 in Chapter 2, Table 4.1}; (h) Global ocean heat content change (0-2000 m depth; in $10^{21}$ joules) relative to 1986-2005 with 5-95% range {Figure 5.1}; (i) Global mean sea surface temperature change (°C) relative to 1986-2005 with 5-95% range. {Box 5.1, 5.2.2}; (j) Probability ratio of surface ocean marine heatwaves, global mean relative to 1850-1900 with 5-95% range. A probability ratio of 10 equals a 10-times increase in the probability of experiencing a marine heatwave relative to 1850-1900 {6.4.1}; (k) Global mean surface pH (on the total scale) with 5-95% range. Assessed observational trends between 1980-2012 are centred on 1996 and compiled from open ocean time series site longer than 15 years {Box 5.1, Figure 5.6, 5.2.2}; (l) Arctic sea ice extent in September (millions of $km^2$) with *likely* range. Observed shading denotes 5-95% range across three satellite-derived products {3.2.1, 3.2.2 Figure 3.3} (*Note*: Antarctic sea ice is not shown here due to *low confidence* in future projections {3.2.1}); (m) Arctic snow cover in June (land areas north of 60°N in millions of $km^2$) plotted as 5-year moving averages with *likely* range. Observed shading denotes 5-95% range across 5 snow products {3.4.1, 3.4.2, Figure 3.11}; (n) Near-surface permafrost extent (millions of $km^2$) with *likely* range {3.4.1, 3.4.2, Figure 3.10}. Differing baseline intervals and temporal coverage of observations reflect data limitations for quantifying the full extent of ocean and cryosphere change since the preindustrial {1.8.1, Figure 1.3}.

**A2.** The ocean is *likely* warming at all depths and undergoing loss of oxygen (*medium confidence*) and acidification (*virtually certain*). Arctic sea ice extent is declining (*high confidence*). Marine heatwaves are increasing in frequency and severity (*very high confidence*). {1.4, 3.2, 5.2, 6.4, 6.7, Figures SPM.1, SPM.2, SPM.3}

**A2.1** It is virtually certain that the ocean has warmed unabated since 2005, continuing well documented trends going back to at least 1970. That warming is attributable to anthropogenic global warming, with the ocean taking up more than 90% of the excess heat in the climate system since 1970 (*high confidence*). It is *virtually certain* the ocean has warmed over both the 0-700 m and 700-2000 m layers of the ocean between 1970 and 2017, with long-term warming trends of 4.35±0.8 ZJ $yr^{-1}$ (0-700m) and 2.25±0.64 ZJ $yr^{-1}$ (700-2000m)[6]. The Southern Ocean accounted for 35-43% of the total heat gain in the upper 2000 m global ocean between 1970 and 2017 (*high confidence*). Averaged between 2005 and 2017, the very likely warming rates have increased to 5.31±0.48 ZJ $yr^{-1}$ (0-700m) and 4.02±0.97 ZJ $yr^{-1}$ (700-2000m), while the proportion taken up by the Southern Ocean increased to 46-62% (*high confidence*). The deep ocean below 2000 m has *likely* exhibited warming since 1992, especially in the Southern Ocean. {1.4, 3.2.1, 5.2.2, Figures SPM.1, SPM.2}

**A2.2** Satellite observations show that marine heatwaves (periods of extremely high ocean surface temperatures) have *very likely* doubled in frequency from 1982 to 2016 and that they have also become longer-lasting, more intense and more extensive. It is *very likely* that between 84% and 90% of marine heatwaves that occurred between 2006 and 2015 can be attributed to anthropogenic warming. (*high confidence*) {6.4, Figures SPM.1}

**A2.3** Arctic sea ice extent is declining in all months of the year (*high confidence*). September sea ice reductions in the Arctic during the satellite era (1979-2018; *very likely* 12.8 ± 2.3% per decade) have resulted in unprecedented low sea ice extent for at least 1000 years (*high confidence*). It is *virtually certain* that Arctic sea ice has thinned, concurrent with a shift to younger ice: since 1979, the areal proportion of thick ice at least 5 years old has declined by approximately 90%. Approximately half of the observed sea ice loss is attributed to anthropogenic global warming (*medium confidence*). Antarctic sea ice extent has no statistically significant trend (1979 to 2018) and has been unusually low since 2016 (*high confidence*). {3.2.1, Figures SPM.1, SPM.2}

**A2.4** Arctic surface air temperature has *likely* increased by more than double the global average over the last two decades, with feedbacks from loss of sea ice and snow cover contributing to the amplified warming (*high confidence*). During the winters (January-March) of 2016 and 2018, surface temperatures in the central Arctic were 6°C above the 1981-2010 average, contributing to very unusual regional sea ice absence (*high confidence*). Reductions in Arctic sea ice extent have the potential to affect

[6] ZJ is Zettajoule and is equal to $10^{21}$ Joules. Warming the entire ocean by 1 °C requires about 5500 ZJ; 144 ZJ would warm the top 100 m by about 1 °C.

weather outside the Arctic on timescales of weeks to months by influencing the position and strength of the tropospheric jet stream and the stratospheric polar vortex (*medium confidence*). {3.2.1.1, Box 3.1, Box 3.2, Figure SPM.2}

**A2.5** There has been an increase in stratification in the upper ocean since 1970 (*very likely*), impacting ocean oxygen, nutrient supply, and net primary production. Observed surface ocean warming and high latitude freshening are making the surface ocean less dense relative to deeper in the ocean (*high confidence*) and inhibiting mixing between surface and deeper waters (*high confidence*). The spatial- and multi-year-mean stratification of the upper 200 m *very likely* increased by 2.30±0.12 % between the 1971-1990 average and the 1998-2017 average. {5.2.2}

**A2.6** It is *very likely* that the ocean has taken up between 20-30% of total anthropogenic carbon since the 1980s, causing further ocean acidification (*virtually certain)*. Open ocean surface pH has declined by a *very likely* range of 0.017 to 0.027 pH units per decade since the late 1980s. This decline means that it is *very likely* that the near surface ocean acidification signal has already emerged from the background natural variability for more than 95% of the ocean area. {3.2.1, 5.2.2, Box 5.1, Figure SPM.1}

**A2.7** The open ocean is losing oxygen overall with a *very likely* loss of 0.5 to 3.3% between 1970 and 2010 from the surface to 1000m (*medium confidence*). The oxygen loss is due primarily through changing ocean stratification, ventilation and biogeochemistry, which reinforce the smaller contribution due to reduced solubility from warming (*high confidence*). The oxygen minimum zones are *likely* expanding by 3-8%, most notably in the tropical oceans, but there is substantial decadal variability that affects the attribution of the overall oxygen declines to human activity in tropical regions (*high confidence*). {5.2.2}

**A2.8** Modern observations, climate simulations and paleoclimate reconstructions suggest that the Atlantic Meridional Overturning Circulation (AMOC) has weakened since the preindustrial (*medium confidence*). Nevertheless, there is insufficient evidence yet to quantify a *likely* range of the magnitude of the change {6.7}.

**A3.** Global sea level is rising (*virtually certain*) with regional variations and a rate that is accelerating in recent decades due to increasing rates of ice loss from the Greenland and Antarctic ice sheets, and from thermal expansion due to ocean warming. (*high confidence*) {3.3, 4.2, 6.2, 6.3, 6.7, 6.8, Figures SPM.1, SPM.2}

**A3.1** The combined rate of ice loss from the Greenland and Antarctic ice sheets has increased (*extremely likely, very high confidence*). Mass loss from the ice sheets in 2012-2016 was likely higher than in 2002-2011, and several times higher than in 1992-2001 (*extremely likely, high confidence*). {3.3.1, Figures SPM.1, SPM.2}

**A3.2** Acceleration of glacier flow, leading to rapid mass loss, is observed in the Amundsen Sea Embayment of West Antarctica and in Wilkes Land, East Antarctica (*very high confidence*). Due to insufficient observational data and models not representing ice flow processes adequately, there is low confidence in assessing whether these changes are the beginning of irreversible retreat linked with the onset of the Marine Ice Sheet Instability process. {3.3.1, Cross-Chapter Box 8 in Chapter 3, 4.2.3, Figure SPM.2}

**A3.3** The rate of ocean warming has more than doubled since 1993 (*likely*). The ocean warmed by 3.22 ± 1.61 ZJ yr-1 (0-700m) and 0.97 ± 0.64 ZJ yr-1 (700m-2000m) from 1969 to 1993, and 6.28 ± 0.48 ZJ yr-1 (0-700m) and 3.86 ± 2.09 ZJ yr-1 (700-2000m) from 1993 to 2017. {5.2.2, Figure SPM.1}

**A3.4** Observations show that global mean sea level (GMSL) is rising (*virtually certain*) and accelerating (*high confidence*). The sum of glacier and ice sheet contributions is now the dominant source of GMSL rise, exceeding the effect of thermal expansion of ocean water (*very high confidence*). The rate of

GMSL rise for 2005-2015 of 3.6 mm yr-1 (3.1 to 4.1 mm yr-1, 5th-95th percentile), is about 2.5 times the rate for 1901-1990 of 1.4 mm yr-1 (0.8 to 2.0 mm yr-1, 5th-95th percentile). Climate change has increased the height of extreme sea level events associated with a number of observed tropical- and extra-tropical cyclones (*high confidence*). {4.2.1., 4.2.2, 6.2.2, 6.3.1, 6.8.2, Figure SPM.1.}

**A3.5** Sea level has not risen uniformly across the globe. Thermal expansion, ocean dynamics and land ice loss contributions will generate regional departures of about ±30% around the global mean sea level rise. In addition, local anthropogenic subsidence and change in wave heights and tides are important contributors to changes in relative sea level at the coast (*high confidence*). {4.2.2, 5.2.2, 6.2.2, 6.3.1, 6.8.2, Figure SPM.2}

**A3.6** Anthropogenic climate change has increased observed precipitation, winds and extreme sea level events associated with some tropical- and extra-tropical cyclones, playing a role in multiple coincident or sequential extreme events that have led to cascading impacts (*high confidence*). Extreme wave heights across the globe have increased by around 5% over the past three decades (*medium confidence*). {4.2.2, 6.3, 6.7}

***Observed Impacts on Ecosystems***

**A4.** Cryosphere changes have impacted terrestrial and freshwater ecosystems in high-mountain and polar regions, affecting abundance and distribution of ecologically, culturally, and economically important plant and animal species, the appearance of landscapes, disturbance regimes, and ecosystem functioning (*high confidence*). {2.3.2, 2.3.3, 3.4.1, 3.4.3, Box 3.4}

**A4.1** Some species, including invasive species, have increased abundance, shifted their range, and established in new areas as glaciers receded and the snow-free season lengthened, and humans transported them (*high confidence*). Together with warming these changes have increased local species richness in high mountains, as lower elevation species migrate upslope (*very high confidence*). In polar and mountain regions, many species have extended seasonal activities or have otherwise changed their behaviour, especially in late winter and spring (*high confidence*). Some cold-adapted or snow-dependent species are declining in abundance, increasing their risk of extinction, notably on mountain summits (*high confidence*). {2.3.3, Box 3.4}

**A4.2** Climate-related changes to Arctic and mountain hydrology, wildfire and abrupt thaw are occurring (*high confidence*), with impacts on vegetation and wildlife including changes in the abundance and distribution of key species such as reindeer and salmon (*high confidence*). Area burned and frequency of fires (including extreme fires) are unprecedented over the last 10,000 years (*high confidence*). {2.3.3, 3.4.1, 3.4.3}

**A4.3** Across tundra and forests in high-mountain and polar regions, plant productivity has often increased, leading to an overall greening of the tundra biome, although there are some browning areas in tundra and boreal forest where productivity has begun to decrease (*high confidence*). Changes in ecosystem functioning due to cryospheric changes have affected ecosystem services, both positively and negatively (*medium confidence*). {2.3.1, 2.3.3, 3.4.1, 3.4.3}

**A5**. Geographical shifts in marine species' from plankton, fish to mammals and seabirds occur due to ocean warming and range hundreds of kilometers and more since the 1950s (*high confidence*) with consequences for species interactions that affect their abundance and cause cascading impacts on ecosystem structure (*medium confidence*). Alteration of species distribution, composition and maximum catch potential from the poles to equator have led to impacts on fisheries (*medium confidence*) {3.2.4, Box 3.4, 5.2.3, 5.3, 5.4.1}

**A5.1** Direct and indirect effects of ocean warming and cryosphere change have regionally variable impact on marine primary producers worldwide (*high confidence)*. Phytoplankton blooms in the Arctic are occurring earlier in the year, while their duration and intensity have increased in the last few decades (*high confidence*). In the Antarctic, such changes are regional and have been associated with locally-rapid environmental change, including retreating glaciers and sea ice change (*medium confidence*). {5.2.3, 3.2.3.1, 3.2.3.2}

**A5.2** Observed changes in the phenology, production and distribution of some Arctic zooplankton and a southward shift in the distribution of Antarctic krill population in the South Atlantic have accompanied changes in the size composition of their populations (*medium confidence*). The cascading effects of multiple climate-induced stressors on polar marine ecosystems impact fisheries (*high confidence*) {3.2.3., 3.2.4}

**A5.3** Rates of range shifts across different plant and animal groups since the 1950s are estimated to be 52 ± 33 km decade$^{-1}$ and 29 ± 16 km decade$^{-1}$ for organisms in the epipelagic and seafloor ecosystems, respectively (*very likely*). Warming-induced species range expansions have led to altered ecosystem structure and functioning such as in the North Atlantic, Northeast Pacific and Arctic oceans (*medium confidence*). {5.2.3, 5.3.2, 5.3.6, Box 3.4}

**A5.4** Increasing ocean acidification and oxygen loss are impacting two Pacific (California Current and Humboldt Current) of the four major Eastern Boundary upwelling systems in the ocean (*high confidence*). Ocean acidification and decrease in oxygen level in the California Current upwelling system altered primary productivity, ecosystem structure, with direct impacts on fisheries through their catches and species composition (*medium confidence*) {Box 5.3}.

**A5.5** In many regions, declines in the abundance of fish and shellfish stocks due to direct and indirect effects of global warming have already reduced fisheries catches. Abundance of some species has increased as a result of the expansion of suitable habitat (*high confidence*). Historical surveys and modelling indicate that ocean warming in the 20th century has contributed to an overall decrease in maximum catch potential (*medium confidence*). This is accompanied by changes in species composition of fisheries catches since the 1970s in many shelf seas ecosystems (*medium confidence*) {3.2.3, 5.4.1}

**A6.** Coastal ecosystems are under stress from ocean warming, intensified marine heat waves, ocean acidification, loss of oxygen, and sea level rise, in combination with adverse effects from human activities on ocean and land (*high confidence*). Impacts are already observed on species, biodiversity, ecosystem functioning as well as services (*high confidence*). {4.3.3, 5.3, 5.4.1, 6.4, Figure SPM.2}

**A6.1** Vegetated coastal ecosystems protect the coastline from erosion and help buffer the impacts of sea level rise. Nearly 50% of coastal wetlands have been lost over the 20th century since pre-industrial time, as a result of the combined effects of localised human pressures, sea level rise, warming and extreme climate events (*high confidence*). Ranges of seagrass meadows and kelp forests are contracting at low-latitudes attributed to warming since the late 1970s (*high confidence*), and in some areas with a loss of 36-43% following heatwaves (*medium confidence*). Mangrove encroachment into subtropical saltmarshes related to warming have been observed in the past 50 years, causing the loss of open areas with herbaceous plants that provide food and habitat for dependent fauna (*high confidence*). The carbon emission associated with the current rate of loss of vegetated coastal ecosystems is estimated to be 0.15–5.35 $GtCO_2$ yr$^{-1}$ (*high confidence*) {4.3.3.5; 5.3.2, 5.3.6, 5.4.1, 5.5.1, Figure SPM.2}.

**A6.2** Increased sea water intrusion in estuaries due to sea level rise has driven upstream redistribution of marine biotic species (*medium confidence*) and caused a reduction of suitable habitats for estuarine communities (*medium confidence*). Increased nutrient and organic matter loads in estuaries since the 1970s from intensive human development and riverine loads have exacerbated the effects of warming on bacterial respiration and eutrophication, leading to expansion of low oxygen areas (*high confidence*). {5.3.1, 5.3.2, 5.3.6, 6.4.2.1, Figure SPM.2}.

**A6.3** Marine heatwaves have negatively impacted marine organisms and ecosystems in all ocean basins over the last two decades, including critical foundation species (*very high confidence*). The frequency of large-scale coral bleaching events has increased since 1997-1998 due to warming, causing worldwide reef degradation and their shift towards algal-dominated reefs (*high confidence*). Similarly, sessile calcified organisms (e.g. barnacles, mussels) in intertidal rocky shores are highly sensitive to extreme temperature events and acidification (*high confidence),* a reduction in their biodiversity and abundance have been observed in naturally-acidified rocky reef ecosystems (*medium confidence*). {5.3.4, 5.3.5, Figure SPM.2}

**A6.4** The impacts of sea level rise on coastal ecosystems include habitat contraction, loss of functionality and biodiversity but also expansion, and migration. Impacts are exacerbated in cases of significant human disturbances (e.g. land reclamation), and where anthropogenic barriers prevent inland migration of marshes and mangroves and generate locations of reduced sediment supply (*high confidence*). Marshes and mangroves have generally kept up with fast rates of sea level rise (e.g., > 10 mm year-1), but the extent varies significantly depending on coastal factors (especially wave exposure, tidal range, sediment trapping and coastal squeeze) and, in the case of river deltas, on changes at catchment scale (especially changes in water and sediment availability) (*high confidence*) {4.3.3, 5.3.2, 5.3.3, 5.4.1}.

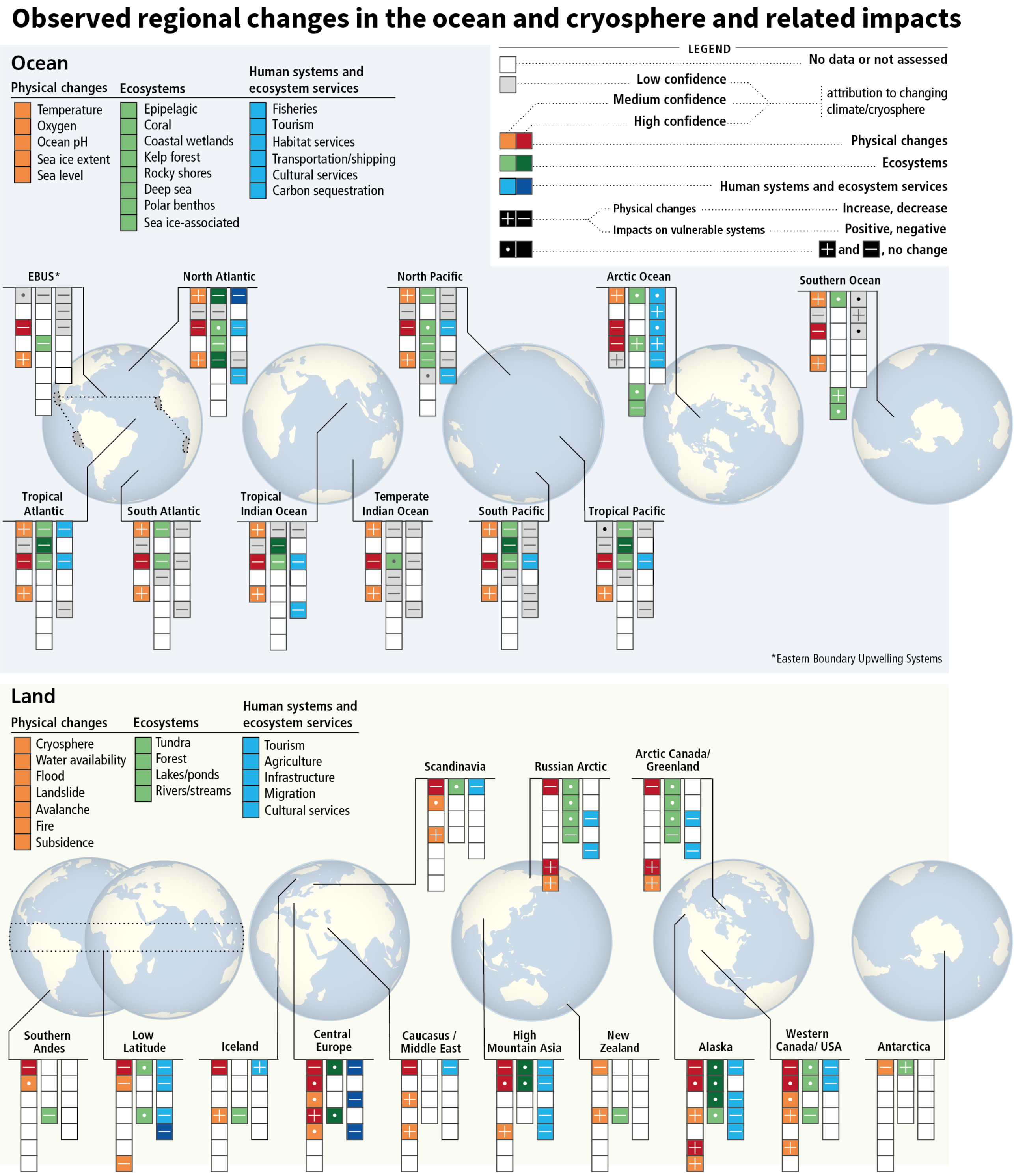



**Figure SPM.2:** Synthesis of regional consequences and impacts in ocean-, polar- and high mountain regions assessed in SROCC. For each region, physical changes (red boxes), impacts on key ecosystems (green boxes), and impacts on human systems and ecosystem services (blue boxes) are shown. Physical changes are attributable to rising greenhouse gas concentrations and associated warming at either global or regional scales with the indicated confidence. Physical changes in the oceans refer to averages horizontally and vertically for each of the named regions. For mountain regions, only impacts that are at least partly attributed to a change in the cryosphere are shown, and only if assessed at *medium* or *high confidence* for the respective region. For physical changes, + or – refers to an increase or decrease in amount or frequency in the measured parameter. For impacts on ecosystems, human systems and ecosystems services, + or – depicts a positive (beneficial) or negative (adverse) impact, respectively. A dot represents both positive and negative impacts being observed. The physical changes in the ocean are defined as: Temperature is change in 0-700m layer of the ocean, Oxygen in the 0-1200 m layer or oxygen minimum layer, Ocean pH as surface pH. Ecosystems in the ocean: Coral refers to coral reefs and cold water corals. For polar ecosystems, the pelagic realm which includes open waters deeper than 200m is included in the category epipelagic. Habitat services refer to supporting structures and services (e.g. habitat, biodiversity, primary production). Ecosystems on Land: Tundra refers to tundra and alpine meadows and terrestrial Antarctic ecosystems. The underlying information is given for land regions in SM2.11 (Appendix 2.A) and SM3.4, and for ocean regions in SM 5.11 and SM3.4. {2.3.7, 4.2.2, 5.2.2, 5.2.3, 5.3.3, 5.4, 5.6}

***Observed Impacts on People***

**A7.** Changes in the terrestrial cryosphere in the Arctic and high mountain regions have affected human societies through mostly negative impacts on freshwater supply, hydropower, infrastructure, transportation, food security, tourism and recreation, health and wellbeing, and culture and social values since the mid-20th century (*high confidence*) with impacts and benefits unequally distributed across populations. {1.1, 1.5, 1.6.2, 2.3, 2.4, 3.4, 3.5}

**A7.1** Changes in snow, lake and river ice, and permafrost have negatively affected food security and water quantity and quality in many Arctic regions (*high confidence*). Local to landscape level changes in the environment have disrupted access to, and food availability within, hunting, fishing, and gathering areas (*high confidence*). In some areas, where glacier and snow meltwater has decreased, especially where other climatic drivers or socio-economic stressors are also present, agricultural productivity has declined, e.g., in the Western USA, High Mountain Asia and the tropical Andes (*medium confidence*). {2.3.1, 3.4.1, 3.4.2, 3.4.3, 3.5.2}

**A7.2** Cryosphere changes have impacted livelihoods, health, and spiritual, aesthetic and other cultural aspects of high mountain and Arctic communities (*medium confidence*). In the Arctic, negative impacts to human health have included food- and waterborne illness, nutrition, and mental health challenges (*high confidence*). Adaptation that promotes health in the Arctic, ranges from local to international in scale, and includes community freezers to increase food security, community-based monitoring programs to reduce injury, and mentorship programs to increase mental wellness (*high confidence*). Indigenous knowledge in Arctic and mountain regions supports adaptation (*medium confidence*). {1.8, Cross-Chapter Box 4 in Chapter 1, 2.3.2, 2.3.6, Box 2.3, 3.4.3}

**A7.3** Arctic peoples have adjusted the timing of activities to respond to changes in seasonality and less safe ice travel conditions (*high confidence*); municipalities and industry are beginning to address infrastructure failures associated with flooding and thawing permafrost (*medium confidence*); and some coastal communities and cooperating agencies are planning for relocation (*medium confidence*). {3.5.2, 3.5.4, Cross-Chapter Box 9}

**A7.4** Hydropower facilities have experienced changes in seasonality and both increases and decreases in water input from high mountain areas, for example, in Central Europe, Iceland, Western US/Canada, and Low Latitude Andes, but there is only *limited evidence* of resulting impacts on operation and energy production. {2.3.1}

**A7.5** High mountain tourism and recreation activities, including ski and glacier tourism, and hiking and mountaineering, have been negatively impacted by cryosphere decline (*medium confidence*). Artificial snowmaking has been effective in many places as an adaptation measure for sustaining ski tourism (*medium confidence*). {2.3.5, Figure 2.8, Figure 2.9, Figure SPM.2}

**A8.** Climate-related changes in the ocean have modified or degraded marine ecosystem services (*high confidence*) and led to observed impacts on fisheries (*high confidence*). Other human dimensions impacted include food (*high confidence*), health and wellbeing (*medium confidence*), Indigenous culture (*medium confidence*), tourism (*medium confidence*) and trade and transport (*high confidence*). {1.1, 1.5, 3.2.1, 5.4.1, 5.4.2, 6.3, 6.4, 6.8}

**A8.1** Warming-induced changes in the spatial distribution and abundance of fish stocks have already challenged the management of some important fisheries and their economic benefits (*high* *confidence*). As a consequence, the effectiveness of existing international and national ocean and fisheries governance to achieve their objectives in securing ecosystem health, generating economic benefits, and supporting livelihood, culture and other aspects of human well-being will be challenged (*high confidence*). {3.2.4, 3.5.3, 5.4.2, 5.5.2, Figure SPM.2}

**A8.2** Harmful algal blooms (HABs) show range expansion and increased frequency in coastal areas since the 1980s in response to both climatic and non-climatic drivers (*high confidence*). The observed trends in HABs are attributed partly to the effects of ocean warming, acidification and loss oxygen as well as eutrophication and pollution (*high confidence*). HABs have negative impacts on food provisioning, tourism, the economy and human health (*high confidence*). Human communities in poorly monitored areas are among the most vulnerable to these biological hazards (*medium confidence*). {Box 5.4, 5.4.2}.

**A8.3** Shipping activity during the Arctic summer increased over the past two decades concurrent with reductions in Arctic sea ice and the shift to predominantly seasonal ice cover (*high confidence*). Increased Arctic ship-based transportation and tourism have implications for global trade, northern nations, and economies linked to traditional shipping corridors; they will also exacerbate local risks to marine ecosystems and coastal communities if further action to develop and implement regulations does not keep pace (*high confidence*). {3.2.1, 3.2.4, 3.5.4, 5.4.2}

**A9.** Human systems in the coastal zone are exposed to multiple climate-related ocean and cryosphere changes, including extreme sea levels, marine heat waves, and sea ice loss and permafrost thaw (*high confidence*). Extreme water levels at the coast are rising due to mean sea level rise, with observable impact on tidal flooding in some regions. A diversity of responses have been implemented worldwide, although mostly as a reaction to extreme events, with some large infrastructure projects which anticipate future sea level rise (*high confidence*). {3.2.4, 3.2.5, 3.4.3, 4.4.2, 4.3.3, 4.3.4, 4.4.2, 5.4.2, 6.8, Box 6.1, Cross Chapter Box 9, Figure SPM. 5}

**A9.1** Although coastal hazards will be exacerbated through sea level rise (*high confidence*), attribution of current changes in coastal human systems to sea level rise is not possible in most locations (*medium confidence*) since non-climatic drivers, such as development at the coast, human-induced land subsidence, pollution, habitat degradation, and loss of Indigenous Knowledge and Local Knowledge, have played a very important role in increasing exposure and vulnerability to climate change-related changes (*high confidence*). {4.3.3}

**A9.2** Coastal protection through hard measures is widespread, providing predictable levels of safety in many coastal cities and deltas (*very high confidence*). Ecosystem-based and hybrid approaches combining natural and built infrastructure are becoming more popular worldwide, but little is known about their cost and effectiveness (*high confidence*). Advance, which refers to the creation of new land by building seawards (e.g, land reclamation), has a long history in most areas where there are dense coastal populations and a shortage of land (*very high confidence*). Retreat is also observed, but is generally restricted to small human communities or is carried out for creating coastal wetland habitat (*high confidence*). Community-based approaches are increasingly used to adapt to sea level rise, especially in developing countries and to adapt to changing marine environments in the Arctic (*high confidence*). {3.5.3, 4.3.3, 4.4.2, 4.4.3, 4.4.4, 6.9.1, Cross-Chapter Box 9}

## SPM.B PROJECTED CHANGES AND RISKS

### *Projected Physical Changes*

**B1.** Widespread retreat of glaciers, decrease in snow cover duration, and thaw and degradation of permafrost, affecting river runoff, are projected to continue in the near-term (*high confidence*). The rates and magnitudes of terrestrial cryosphere losses are projected to increase further in the second half of the 21st century in a high greenhouse gas emissions scenario (*high confidence*). Deep reductions in greenhouse gas emissions in the coming decades are projected to likely reduce further changes in terrestrial cryosphere (excluding ice sheets and glaciers) beyond the near term (*high confidence*). {2.2, 2.3, Cross-Chapter Box 6 in Chapter 2, 3.3, 3.4, Figures SPM.1, SPM.2}

**B1.1** Projected glacier mass reductions between 2015 and 2100 range from 18 ± 7% for a low emissions scenario (RCP2.6[7]) to 36 ± 11% for a high emissions scenario (RCP8.5), corresponding to a sea-level contribution of 94 ± 25 mm sea-level equivalent for RCP2.6, and 200 ± 44 mm for RCP8.5 (*medium confidence*). In regions with relatively little ice cover (e.g., Central Europe, Caucasus, Low latitudes, North Asia, Scandinavia), glaciers are projected to lose more than 80% of their current mass by 2100 (*medium confidence*). The largest regional contributors are the polar regions including the Antarctic and Greenland periphery, Arctic Canada, Alaska, Russian Arctic, Iceland and Scandinavia, which combined make up more than 80% of the global glacier sea-level contribution by 2100 (RCP8.5) (*high confidence*). {Cross-Chapter Box 6 in Chapter 2, Figures SPM.1, SPM.2}

**B1.2** Arctic autumn and spring snow cover duration are projected to decrease by further 5-10% from current conditions in the near-term (2031-2050), followed by no further losses under RCP2.6, whereas a further 15-25% reduction in snow cover duration is projected by end of century under RCP8.5 (*high confidence*). Projected decreases in low elevation mean winter snow depth in mountain areas, compared to 1986–2005, are *likely* between 10 and 40% by 2031–2050, regardless of greenhouse gas emission pathway (*high confidence*). By 2081-2100 the projected decrease is *likely* between 50 and 90% for RCP8.5 and between 10 and 40 % for RCP2.6. {2.2.2; 3.3.2; 3.4.2} {2.2.2; 3.3.2; 3.4.2, Figures SPM.1, SPM.2}

**B1.3** Widespread thaw and degradation of permafrost are projected to occur this century (*very high confidence*). By 2100, near-surface permafrost area will decrease by 2-66% for RCP2.6 and 30–99% for RCP8.5. This is expected to release 10s to 100s of billions of tons (Gt C) of permafrost carbon as carbon dioxide and methane to the atmosphere with the potential to accelerate climate change; this release is expected to be smaller for lower emission scenarios (*medium confidence*). The level and timing of increased plant growth and replenishment of soil may compensate, in part, for permafrost carbon losses (*high confidence*). {3.4.2, 3.4.3, Figure SPM.1}

**B1.4** In high mountain areas, the retreat of glaciers and thaw of permafrost are projected to continue to decrease the stability of high-mountain slopes, and increase the number and area of glacier lakes (*medium confidence*). Landslides and floods, and cascading events resulting from them, will also manifest in new locations, where there is no documented record of previous events (*medium confidence*). Projected changes in snow avalanches include a decline of their number and runout distance, and more frequent snow avalanches involving wet snow, even in winter (*medium confidence*). Rain-on-snow floods will occur earlier in spring and later in autumn, and be more frequent at higher elevations and less frequent at lower elevations (*high confidence*). {2.3.2}

**B1.5** River runoff in snow-dominated and glacier-fed river basins are projected to change further in amount and seasonality in response to projected snow cover and glacier decline (*very high confidence*). The average winter runoff is projected to increase (*high confidence*), and spring peaks to occur earlier (*very high confidence*). Average annual runoff from glaciers in most mountain regions will have reached a peak that will be followed by declining runoff at the latest by the end of the 21st century (*high confidence*). {2.3.1}

[7] Projections and assessments of future climate, ocean and cryosphere changes in SROCC are commonly based on coordinated climate model experiments from the Coupled Model Intercomparison Project Phase 5 (CMIP5) forced with Representative Concentration Pathways (RCPs) of future radiative forcing. Current greenhouse gas emissions continue to grow at a rate consistent with a high emission future without effective climate change mitigation policies (referred to as RCP8.5). The SROCC assessment contrasts this high greenhouse gas emission future with a low greenhouse gas emission, high mitigation future (referred to as RCP2.6) that gives a two in three chance of limiting warming by the end of the century to less than 2°C above pre-industrial. {Cross-Chapter Box 1 in Chapter 1} (Figure SPM1)

**B2.** The ocean is projected to continue to warm throughout the 21st century, with further changes such as loss of Arctic sea ice, loss of oxygen, increased acidification, increasingly frequent marine heatwaves and weakening of the Atlantic meridional overturning circulation (*high confidence*). Increased stratification of the upper ocean will alter ocean oxygen, nutrient availability and net primary production. Under a high greenhouse gas emissions scenario, the rates and magnitudes of these ocean changes are projected to increase in the second half of the 21st century far more than for a low emissions scenario. {3.2, 5.2, 6.4, 6.5, 6.7, Figures SPM.1, SPM.3}

**B2.1** The direct relationship between summer Arctic sea ice extent, global temperatures and cumulative $CO_2$ emissions provides a basis for estimating the probability of a sea ice free Arctic ocean in September to be around 1% each year for stabilised global warming of 1.5°C, and 10-35% for global warming of 2°C (*high confidence*). There is *low confidence* in projections for Antarctic sea ice due to inadequate representation of key processes involving the atmosphere, ocean, and interactions with the adjacent ice sheet. {3.2.1, Figures SPM.1, SPM.2}

**B2.2** The ocean will continue to warm throughout the 21st century and upper ocean stratification will increase (*high confidence*). By 2100, the top 2000 m of the ocean is projected to take up 2 to 4 times as much heat under RCP2.6 (or 5 to 7 times as much under RCP8.5) as the observed accumulated ocean heat uptake since 1970 (*very likely*). The annual-mean stratification of the top 200 m, averaged between 60°S and 60°N, is projected to *very likely* increase by 1 to 9% for RCP2.6, and 12 to 30% for RCP8.5, for 2081 to 2100 relative to 1986 to 2005. {5.2.2, Figure SPM.1}

**B2.3** Globally, the frequency of marine heatwaves, is *very likely* to increase by a factor of approximately 50 by 2081-2100 under RCP8.5 and by a factor of approximately 20 under RCP2.6, relative to the frequency of occurrence in 1850-1900 (*medium confidence*). The largest frequency increases are projected for the Arctic Ocean and the tropical ocean (*medium confidence*). {6.4, Figures SPM.1, SPM.2}

**B2.4** Increased stratification of the upper ocean under RCP8.5 will alter nutrient availability, oxygen content and net primary production. By 2081-2100 under RCP8.5, globally averaged ocean oxygen is *very likely to* decline by 3-4 % *(medium confidence*) and upper ocean nutrients are projected to decline by 9-14%, especially in the tropics (*medium confidence*). In response to a combination of environmental drivers, global net primary production is projected to decline by a *very likely* range of 4-11% by 2081-2100 (*low confidence*). Under RCP2.6, global projected changes by 2081-2100 are reduced for oxygen loss (*very likely*), nutrient availability (*likely as not*) and net primary production compared to RCP8.5 (*high confidence*). {5.2.2, Box 5.1, Figure SPM.3}

**B2.5** Continued carbon uptake by the ocean to 2100 is *virtually certain* to exacerbate ocean acidification. The projected decrease in surface open ocean pH is *virtually certain* to be 0.3 pH units under RCP8.5 by 2081-2100. This is *very likely* to lead to year-round corrosive conditions for aragonite shell producing organisms in the open oceans regions of the Arctic, Southern, and some parts of the North Pacific and North Atlantic oceans (*high confidence)*. It is *very likely* that the projected shift to undersaturated conditions would be avoided in 2081-2100 under RCP2.6, but some eastern boundary upwelling systems may remain vulnerable. (*high confidence*). {3.2.3; 5.2.2, Box 5.1, Box 5.3, Figures SPM.1, SPM.3}

**B2.6** During this century, the ocean will experience the emergence a of new ocean climate that is unprecedented relative to preindustrial (1850-1900) climate variability with different environmental parameters emerging at different rates (*high confidence*). Oxygen loss will *very likely* emerge over 59-80% of the ocean surface by 2031-2050, rising to 79-91% by 2081-2100 under RCP8.5. These changes are *very likely* to remain detectable for over 30% of the ocean surface under RCP2.6 and over 60% of the ocean under RCP8.5 by 2081-2100. {Box 5.1, Box 5.1 Figure 1}

**B2.7** Extreme El Niño and La Niña events are *likely* to occur more frequently under RCP8.5 and are *likely* to be associated with more extreme responses in several regions across the globe that currently experience wetter or drying conditions during such events. Models show smaller increases in frequency for RCP2.6. {6.5}

**B2.8** The Atlantic Meridional Overturning Circulation (AMOC) is projected to *very likely* weaken over the 21st century (*high confidence*). A collapse is *very unlikely* but is nevertheless a plausible scenario (*medium confidence*). Should a substantial weakening of the AMOC occur, the additional impacts are projected to include a decrease in marine productivity in the North Atlantic, more winter storms in Europe, a reduction in Sahelian and South Asian summer rainfall, a decrease in the number of tropical cyclones in the Atlantic, and an increase in regional sea level along the northeast coast of North America (*medium confidence*). {6.7, Figure 6.8}

**B3.** Sea level is projected to continue to rise (*high confidence*) and extreme sea level events that are currently rare will occur frequently by 2050 (*high confidence*). Without major additional adaptation efforts relative to today, projected changes in mean sea level and extreme sea level events will markedly increase future flood risk to low-lying coastal communities (*high confidence*). Under a high emissions scenario, projections of global sea level rise by 2100 have been revised upwards since AR5 due to a projected larger contribution from the Antarctic ice sheet (*medium confidence*). Sea level rise will continue beyond 2100 and could exceed rates of several centimetres per year resulting in multi-metre rises in the long term (*medium confidence*) {Cross-Chapter Box 5 in Chapter 1, Cross-Chapter Box 8 in Chapter 3, 4.1, 4.2, 6.3, Figures SPM.1, SPM.4, SPM.5}

**B3.1** Global mean sea level rise under RCP2.6 is projected to be 0.40 m (0.28–0.54 m, *likely* range) for the period 2081–2100, and 0.43 m (0.29–0.59 m, *likely* range) in 2100 with respect to 1986-2005. For RCP8.5 the global mean sea level rise is 0.71 m (0.51-0.92, *likely* range) for 2081-2100 and 0.84 m (0.61-1.10 m*, likely* range) in 2100. These projections have been revised upwards since AR5 due to a projected larger contribution from the Antarctic sheet (*high confidence*). The Greenland and Antarctic ice sheets could each contribute up to 0.28 m of sea level rise (RCP8.5, upper end *likely* range) by 2100 {4.2.3, Figures SPM.1, SPM.2, SPM.4, SPM.5}

**B3.2** Wave heights are projected to increase across the Southern Ocean, tropical eastern Pacific and Baltic Sea and decrease over the North Atlantic and Mediterranean Sea under RCP8.5 (*high confidence*). An increase in the average intensity of tropical cyclones, and the associated average precipitation rates, is projected by 2100, with greater increases under RCP8.5 in comparison with RCP2.6 (*medium confidence*). There is *low* confidence in changes in the future frequency of tropical cyclones at the global scale. {6.3}

**B3.3** Extreme sea level events, such as surges from tropical cyclones, that are currently historically rare (for example today's hundred-year event) will become common by 2100 under all emissions scenarios due to increasing global mean sea level rise (*high confidence*). Under all future emissions scenarios, many low-lying megacities and small islands at almost all latitudes will experience such events annually by 2050. In the absence of strong adaptation, this will lead to increased occurrence of severe flooding (*high confidence*). {4.2.3, 6.3, Figures SPM.4, SPM.5}

**B3.4** The rate of sea level rise is estimated to be 15 mm $yr^{-1}$ (10-20 mm $yr^{-1}$, *likely* range) under RCP8.5 in 2100, and could exceed several centimetres per year in the 22nd century if high emissions continue beyond 2100. The uncertain timing of future ice-shelf loss and the extent of ice sheet instabilities could increase Antarctica's contribution to sea level rise to values higher than the likely range on century and longer time-scales (*low confidence*). The few model studies available addressing timescales of centuries to millennia indicate multi-meter rise in sea level for RCP8.5 (*medium confidence*). There is low confidence in threshold temperatures for ice sheet instabilities and the rates of global mean sea level rise they can produce. {Cross-Chapter Box 5 in Chapter 1, Cross-Chapter Box 8 in Chapter 3, 4.1, 4.2.3}.

***Projected Risks for Ecosystems***

**B.4** Future cryosphere changes will alter terrestrial and freshwater ecosystems in high-mountain and polar regions with major shifts in species distributions resulting in changes in biotic community structure and ecosystem functioning, e.g. productivity, and eventual loss of globally unique biodiversity (*medium confidence*). {2.3.3, 3.2.3, Box 3.4, 3.4.3}

**B4.1** In high-mountain regions, further upslope migration by lower-elevation species, range contractions, and increased mortality will lead to population declines of many alpine species, especially glacier- or snow-dependent species (*high confidence*), with local and eventual global species loss (*medium confidence*). Alpine species persistence and sustaining ecosystem services will depend on appropriate conservation and adaptation measures (*high confidence*). {2.3.3}

**B4.2** On Arctic land, a loss of globally unique biodiversity is projected as some High-Arctic species have limited access to refugia and hence will be outcompeted by more temperate species (*medium confidence*). Woody shrubs and trees are projected to expand to cover 24-52% of Arctic tundra by 2050 under high emission scenarios (*medium confidence*).  While the boreal forest expands at the northern edge, projections suggest it diminishes at the southern edge and is replaced by lower biomass woodland/shrublands *(medium confidence*). {3.4.3, Box 3.4}

**B4.3** Projected permafrost thaw or decrease in snow will affect Arctic and mountain hydrology and wildfire, with impacts on vegetation and wildlife (*medium confidence)*.  About 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is expected to increase small lake area by over 50% by 2100 for RCP8.5 (*medium confidence*). Even as the overall regional water cycle intensifies, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in snow and permafrost may lead to soil drying with consequences for ecosystem productivity and disturbances (*medium confidence*). Fire is projected to increase for the rest of this century across most tundra and boreal regions, including some mountains, while interactions between climate and shifting vegetation will influence future fire intensity and frequency (*medium confidence*). {2.3.3, 3.4.1, 3.4.2, 3.4.3}

**B5.** Global rates of biomass production as well as standing stocks are projected to decrease in ocean ecosystems and from the surface to deep seafloor (*medium confidence*). There will be further poleward shifts in species distributions leading to changes in community structure (*very likely*), and decreases in global fisheries catch potential under ocean warming in the 21st century (*medium confidence*). The rate and magnitude of decline will be highest in the tropics (*high confidence*), whereas mixed responses will occur in polar regions. Species' abundances, productivity and food-web interactions in ecosystems will be further compromised by ocean acidification (*medium confidence*), and oxygen loss (*medium confidence*) and sea ice reduction (*medium confidence*), which are exacerbated by human activities and regional conditions (*medium confidence*). {3.2.3, 3.3.3, 5.2.2, 5.2.3, 5.2.4, 5.4.1}

**B5.1** Ocean warming and changes in net primary production are projected to alter biomass, production and community structure of marine ecosystems (*high confidence*), especially in tropical regions *(high confidence*). The global-scale biomass of marine animals across the foodweb and the maximum catch potential of fisheries are projected to decrease by 15.0±5.9% (*very likely* range) and 16.2% to 25.5% by 2100 under RCP8.5. These changes by the end of the 21st century will *very likely* be three to four times larger under RCP8.5 than RCP2.6. {3.2.3, 3.3.3, 5.2.2, 5.2.3, 5.4.1, Figure SPM.3}.

**B5.2** Reduced nutrient supply due to enhanced stratification will cause tropical ocean net primary production to decline in the *very likely* range of 7-16% for RCP8.5 by 2100 (*medium confidence*). In contrast, warming, stratification and sea ice loss will increase net primary production in the Arctic (*medium confidence*) and around Antarctica (*low confidence*). Alterations in the sinking flux of organic carbon from the upper ocean will be largely linked to changes in net primary production (*high confidence*), leading to a decrease in deep sea (3000-6000m depth) seafloor biomass that is larger under RCP8.5 compared to RCP4.5 and RCP2.6 (*medium confidence*) {3.2.3, 5.2.2. 5.2.4, Figure SPM.3}

**B5.3** Projected warming, ocean acidification, reduced seasonal sea ice extent and continued loss of multi-year sea ice will impact polar marine ecosystems through direct and indirect effects on habitats, populations and their fitness (*medium confidence*). The range of ecologically-important Arctic marine species, including marine mammals, birds and fish is projected to contract, while the range of some sub-Arctic fish communities is projected to expand, further increasing pressure on high-Arctic species (*medium confidence*). Continued loss of Arctic multi-year sea ice will favour the formation of intense under-ice booms (*medium confidence*) and growth of microalgae (*medium confidence*), while future stratification could decrease upwelling of nutrients to the surface, possibly reducing rates of primary production in the future (*medium confidence*). These changes in primary production will impact whole ice-associated, seafloor and open ocean ecosystems. In the Southern Ocean, the habitat of Antarctic krill, a key prey species for penguins, seals and whales, will contract southwards with future ocean warming (*medium confidence*). {3.2.2, 3.2.3, 5.2.3}

**B5.4** Ocean warming, oxygen loss, ocean acidification and decrease in flux of organic carbon from the surface to the deep ocean will decrease calcification and exacerbate bioerosion and dissolution of non-living components of cold-water coral communities which support high biodiversity (*medium confidence*). Habitat-forming, cold-water corals will be particularly vulnerable where and when temperature and oxygen conditions are both outside the species' tolerances (*medium confidence*). Reduced particulate food supply is projected to be experienced by 95% of cold-water coral ecosystems by 2100 under RCP8.5 relative to the present, leading to a loss in their biomass (*medium confidence*). {Box 5.2}

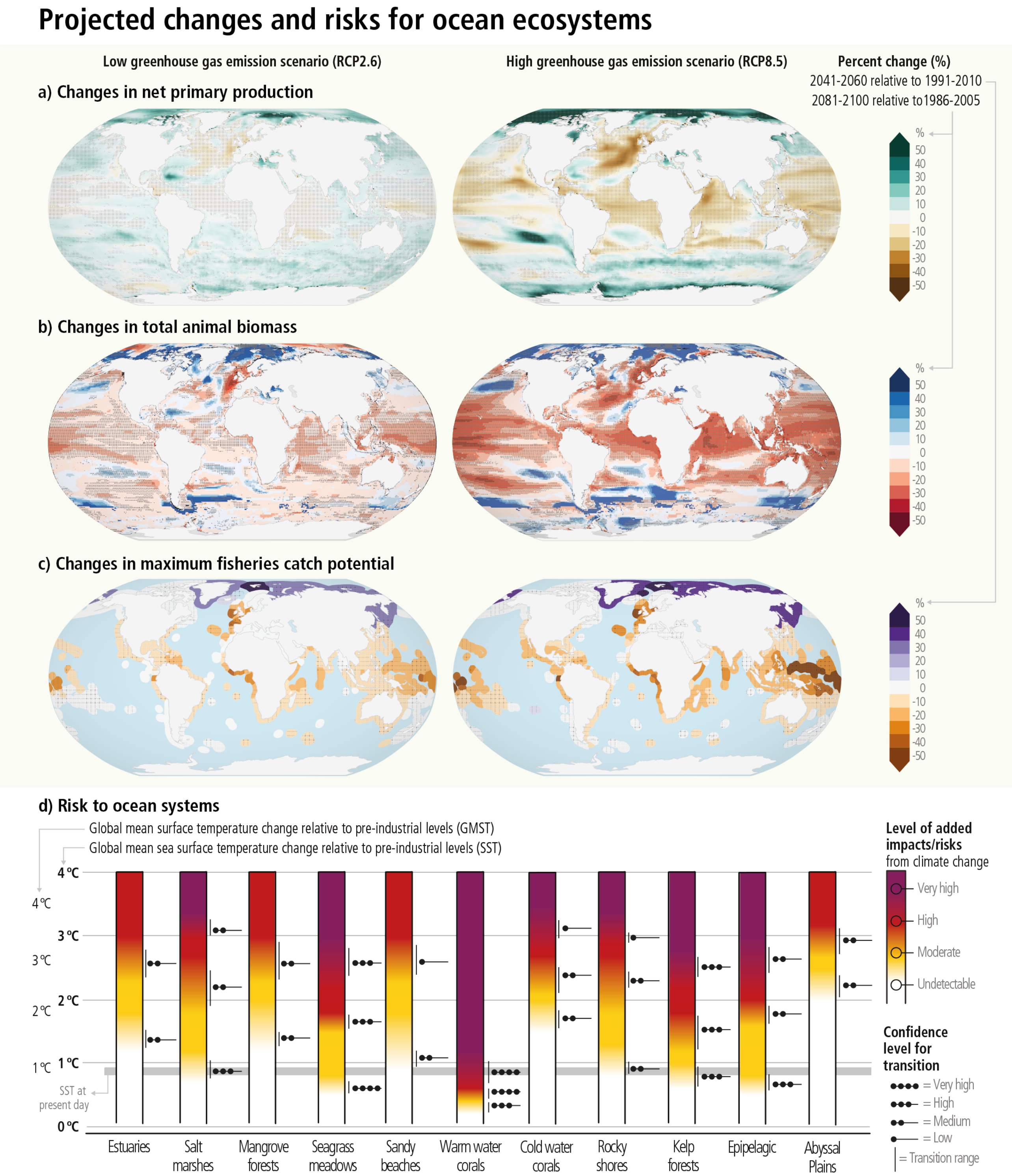



**Figure SPM.3:** Projected changes and risks for selected ocean regions under low (left, Representative Concentration Pathway RCP2.6) and high (right, RCP8.5) greenhouse gas emission scenarios. Projected average changes (%) in a) depth integrated net primary production based outputs from based on the Coupled Model Intercomparison Project 5 (CMIP 5) by 2081-2100, relative to 1986-2005. b) total animal biomass (including fishes and invertebrates) based on the average outputs from 10 sets of projections from the Fisheries and Marine Ecosystems Impact Model Intercomparison Project by 2081-2100, relative to 1986-2005. c) maximum fisheries catch potential in shelf seas based on the average outputs from two fisheries and marine ecosystem models by 2041-2060 relative to 1991-2010. Shaded areas indicate regions where models agree in the direction of change for: a) and b) at least three quarters of model projections, c) the two models. d) Risk assessments for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. 'Present day' is 2006-2015. Impacts and risks are shown in relation to changes in global mean surface temperature (left vertical axis) and global mean sea surface temperature (right axis) relative to pre-industrial levels. The relationship between global mean surface and sea surface temperature used here is based on RCP8.5 simulations {Figure SPM.1}. Impact and risk levels do not consider risk reduction strategies such as societal adaptation, or future changes in non-climatic hazards. In the polar regions, the projected change in (b) total animal biomass and (c) fisheries catch potential have *low confidence* due to uncertainties associated with multiple interacting drivers and ecosystem responses in the Arctic and Antarctic regions that are not fully-resolved in the global-scale models. {5.2, 5.3, 5.2.5, 5.3.7, SM5.5, SM5.7, Figure 5.16, Cross Chapter Box 1 in Chapter 1 Table CCB1}.

**B6.** By 2100, increasing risks of severe impacts on biodiversity, structure and function of coastal ecosystems are projected under high emissions scenarios. Expected ecosystem responses are loss of large areas of habitat and species richness, and degradation of ecosystem functions in the remaining areas. For sensitive ecosystems, risks will become high if global warming exceeds 1.5 °C above pre-industrial temperature, combined with other related climatic hazards (*high confidence*). Warm-water corals experience very high risk even below global warming of 1.5 °C (*very high confidence*). The capacity of ecosystems to respond and adapt can be facilitated by the reduction of human disturbances under low emission scenarios (*high confidence*). {5.3, Figure SPM.3}

**B6.1** All coastal ecosystems assessed will be at high to very high levels of risk under RCP8.5 by 2100, with risk levels for seagrass meadows (*high confidence*), kelp forests (*high confidence*) and coral reefs (*very high confidence*) becoming high to very high already at moderate global warming of 1.5 °C above pre-industrial temperatures. Intertidal rocky shores will be at very high risk under RCP8.5 (*medium confidence*) due to warming, acidification and exposure to extreme heat during emersion at low tide, causing reduction of calcareous species and loss of biodiversity (*high confidence*). The decline of kelp forests will continue at low latitudes due to warming, particularly under the projected intensification of marine heat waves, with high risk of local extinctions under RCP8.5 (*medium confidence*) {5.3, 5.3.5, 5.3.6, 5.3.7, 6.4.2., Figure SPM.3}

**B6.2** Globally, 20 to 90% of coastal wetlands are projected to be lost by 2100, depending on projected sea level rise and habitat degradation (*high confidence*). Some coastal wetlands are growing naturally where sediment supply is high and ecosystems can migrate landwards (*medium confidence*). Mangrove forests, seagrass meadows and saltmarshes can keep pace with sea-level rise under low emission scenarios for the whole 21st century, but only up to 2055 and 2070 under RCP8.5 (*medium confidence*). High risks of local losses of coastal vegetation are projected under RCP8.5 by 2100 (*medium confidence),* especially where landward migration is constrained by human modification of shorelines and urbanisation (*high confidence*) {4.3.3, 5.3.2, Figure SPM.3}

**B6.3** Projected warming, sea level rise and tidal changes in the 21st century will continue to expand salinization and hypoxia in estuaries (*high confidence*) with high risks for benthic and pelagic biota (migration, local extinction, and reduced survival) (*medium confidence*). These impacts will be more pronounced under RCP8.5 by 2100 in more vulnerable eutrophic, shallow and microtidal estuaries in temperate and high latitude regions (*medium confidence*). {5.2.2., 5.3.3, Figure SPM.3}

**B6.4** Almost all warm-water coral reefs will decline, even if global warming remains below 2°C (*high confidence*). The species composition and diversity of remaining reef communities will differ from present-day reefs (*very high confidence*). The decline in coral reefs will greatly compromise the services they provide to society, such as food provision (*high confidence*), coastal protection (*high confidence*) and tourism (*medium confidence*). {5.3.4, 5.4.1, Figure SPM.3}.

***Projected Risks for People***

**B7** Projected changes in the terrestrial cryosphere will affect water resources and their uses, such as hydropower, irrigated agriculture, and water quality in high mountain areas and downstream regions and food security and livelihoods in the Arctic (*medium confidence*). Changes in natural hazards, such as floods, avalanches, landslides, and ground destabilization, will contribute to negatively impact infrastructure, cultural, tourism and recreation assets (*medium confidence*). Risks are initially projected to increase independent of emission pathways (*medium confidence*) and become greater under higher emission pathways after 2050 (*high confidence*). {2.3, 3.4.3}

**B7.1** Given projected changes in the spatial distribution of natural hazards, and *high confidence* in increased exposure of people and infrastructure to natural hazards in high mountains and the Arctic, risks to human settlements and livelihood options in these areas will continue to increase (*medium confidence*). Current risk reduction and adaptation strategies are projected to become increasingly insufficient (*medium confidence*). {2.3.2, 3.4.3, 3.5.2}

**B7.2** Permafrost thaw and melting of ground ice may cause the land surface to subside and collapse, impacting overlying urban and rural infrastructure including distributed infrastructure for transportation and resource extraction in the Arctic and in high mountain areas (*medium confidence*). The majority of Arctic infrastructure will be located in regions where permafrost thaw is projected to intensify by mid century; adaptation measures taken in advance could reduce costs arising from thaw and other climate-change related impacts such as increased flooding, precipitation, and freeze-thaw events by half (*medium confidence*). {2.3.4, 3.4.1, 3.4.3}

**B7.3** Declining runoff is expected to reduce the productivity of irrigated agriculture in some regions (*medium confidence*). Reduced access to, and food availability within, herding, hunting, fishing, forage and gathering areas, infrastructure, and the emergence of new pathogens and diseases will diminish food and water security for Arctic communities (*high confidence*). {2.3.1., 3.4.1, 3.4.2, 3.4.3.}

**B7.4** Hydropower operations will increasingly be impacted by altered amount and seasonality of water supply from snow and glacier melt (*high confidence*). The release of heavy metals, particularly mercury, and other legacy contaminants currently stored in glaciers and permafrost, is projected to reduce water quality for freshwater biota, household use and irrigation (*medium confidence*). {2.3.1}

**B7.5** High mountain cultural assets and tourism and recreation activities are projected to be negatively affected by future cryospheric changes (*high confidence*). Current adaptation strategies, such as snowmaking technologies to support ski tourism, are projected to be less effective in most parts of Europe, North America, and Japan already at 1.5°C global warming, and will further decrease effectiveness beyond 2°C global warming (*high confidence*). Diversification through year-round activities supports adaptation of mountain tourism under future climate change (*medium confidence*). {2.3.5, 2.3.6}

**B8.** Projected decrease in abundance, shifts in distribution and potential fish catches due to climate change will affect income, livelihoods, and food security of resource-dependent communities (*medium confidence*). Moreover, long term climate change-induced loss and degradation of marine ecosystems amplified by increased frequency and intensity of marine heat waves, are projected to alter the ocean’s role in supporting culture, recreation, and intrinsic values that are important for human cultural identity and wellbeing (*medium confidence*). {3.2.4, 3.4.3, 5.4.1, 5.4.2, 6.4}

**B8.1** Projected geographical shifts and decreases of global marine animal biomass and fish catch potential elevate the risk of impacts on income, livelihood and food security of dependent human communities (*medium confidence*) and increase the possibility of conflicts among fishery area users and authorities or between communities (*medium confidence*). Challenges to fisheries governance are widespread under high emission scenarios with regional hotspots (*medium confidence*). {3.5.2, 5.4.1, 5.4.2, 5.5.2, 5.5.3, Figure SPM.3}

**B8.2** Climate change hazards are projected to increase the risk of impacts on seafood security and safety (*medium confidence*). Projected decreases in seafood availability from climate impacts on fisheries catch potential will elevate the risk of nutritional health impacts on some coastal communities (*medium confidence*), compounding risks from other shifts in diets and food system (*medium confidence*). Climate change can increase the exposure and bioaccumulation of contaminants, such as persistent organic pollutants and mercury, in marine plants and animals, (*medium confidence*), prevalence of waterborne *Vibrio* pathogens (*medium confidence*), and the likelihood of harmful algal blooms (*medium confidence*) and their risks of impacts on marine ecosystems and seafood safety (*medium confidence*). These risks are particularly large for human communities that have high consumption of seafood, including coastal Indigenous communities (*medium confidence*) {3.2.5, 5.4.2; Box 5.3}

**B8.3** Climate change impacts on marine ecosystems and their services threaten key cultural dimensions of lives and livelihoods (*medium confidence*). These threats include erosion of local and Indigenous cultures, knowledge, traditional diets, reducing food security and opportunities for aesthetic and spiritual appreciation and marine recreational activities (*medium confidence*). {3.2.4., 3.5.3., 5.4.2}

**B9.** Increases in mean and extreme sea level, together with ocean warming and acidification, will substantially exacerbate risks to low-lying coastal human communities in cities, small islands, deltas, river mouths, and the Arctic (*high confidence*). Urban atoll islands and low-lying Arctic communities will experience high risks even in low emissions futures (*medium confidence*). All types of responses to sea-level rise, including protection, accommodation, ecosystem-based adaptation, advance and retreat, have a role to play in an integrated and sequenced response to sea-level rise (*high confidence*). Some vulnerable communities, especially those in coral reef environments and polar regions, are expected to face adaptation limits well before the end of this century and even under a low greenhouse gas emission pathway (*high confidence*). {4.3.3.1, 4.3.3, 4.3.4, 5.4.2, 6.3.4, Cross-chapter Box 9, SM4.3, Figure SPM.5}

**B9.1** In the absence of major adaptation efforts, risks related to sea level rise and associated extreme events (including erosion, flooding, salinization and cascading impacts) are expected to significantly increase throughout this century under all greenhouse gas emission pathways (*very high confidence*). For example, annual flood damages are expected to increase by 2-3 orders of magnitude by 2100 (*high confidence*). {4.3.3, 4.3.4, Box 6.1, 6.8, SM4.3, Figure SPM.4; Figure SPM.5}

**B9.2** Urban atoll islands, delta regions and some Arctic communities will experience high to very high risks even under low emissions (RCP2.6) (*high confidence*). Without adaptation, sea level rise associated with a 2°C warmer world could submerge the homeland of 280 million people globally by 2100 (*low confidence*). Some island nations may become uninhabitable due to climate-related ocean and cryosphere change (*medium confidence*), but habitability thresholds remain extremely difficult to assess. {4.3.2, 4.3.4, 5.2.2, Cross-Chapter Box 9; Figure SPM5}

**B9.3** The benefits of adaptation are expected to vary between regions. A slower rate of climate-related ocean and cryosphere change provides greater opportunities for adapting (*high confidence*). Even with major adaptation efforts, loss and damage will occur due to residual risks (*medium confidence*), but limits to adaptation and residual risks remain difficult to assess. There is however *high confidence* that ambitious adaptation will help to buy time in many locations and therefore facilitate adaptation beyond 2100. {4.1.3., 4.3.4., 4.4.3, 6.4, 6.9.2, Cross-chapter Boxes 1-2 in Chapter 1, Cross-chapter Box 9, SM4.3, Figure SPM.5}

## Extreme sea level rise

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

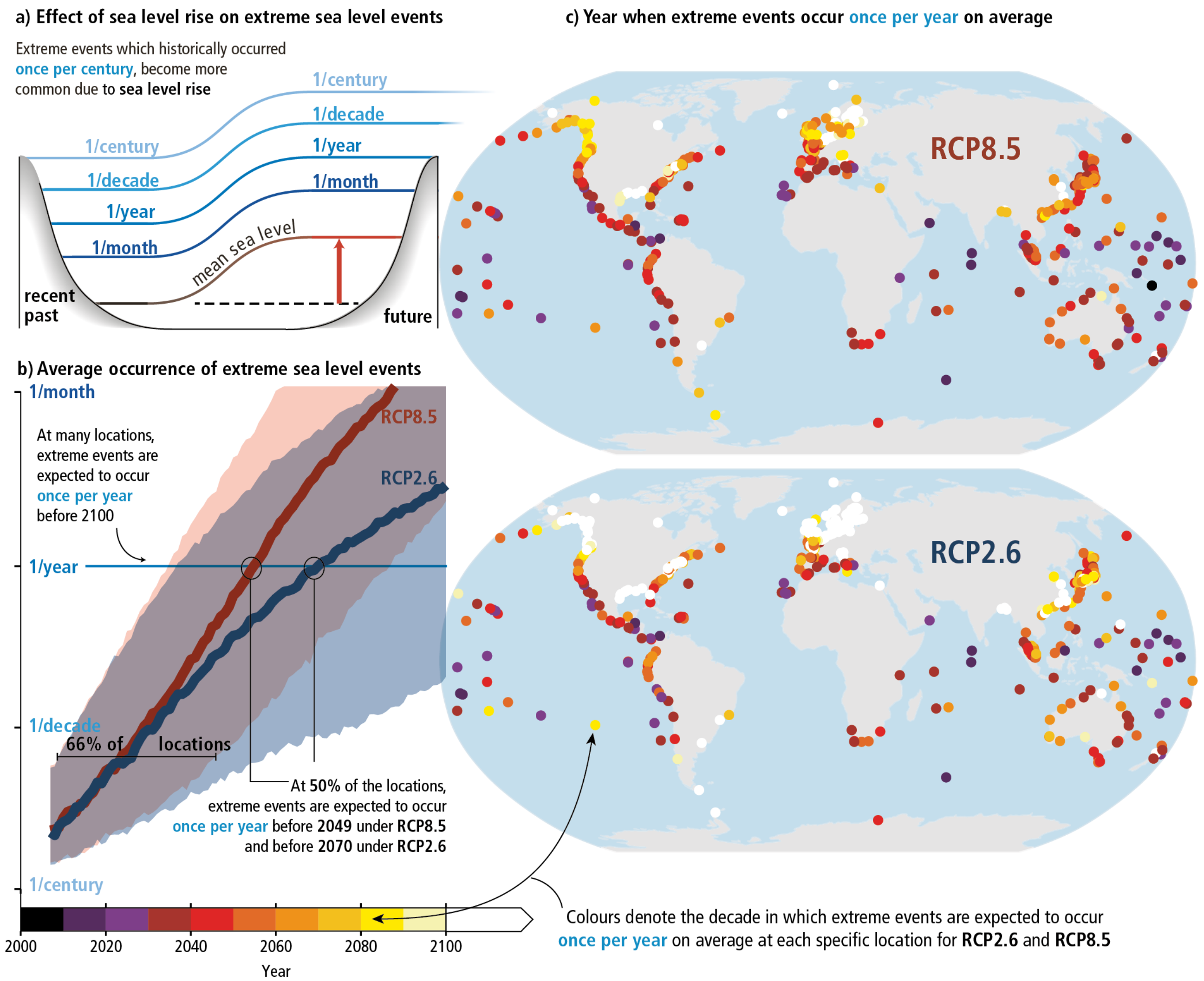



**Figure SPM.4:** The effect of mean (average) sea level rise on extreme sea level events at coastal locations. Extreme sea level events refer to coastal water levels which occurred on average once per century during recent past (1986-2005). a) Illustration of extreme sea level events and their average occurrence in the recent past and the future. As a consequence of mean sea level rise, the extreme sea levels will be reached more frequently in the future. b) The average occurrence of extreme sea level events at 439 coastal locations (shown in c)) projected from mean sea level rise under high (Representative Concentration Pathway RCP8.5) and low (RCP2.6) greenhouse gas emission pathways. The solid lines indicate the median of all locations; the shading denotes the 17-83 percentiles. The horizontal lines mark the years when the average occurrence of extreme sea level events is once per decade and once per year. c) The year in which extreme events are expected to occur once per year on average for individual coastal locations. The darker the circle, the earlier this is projected. White circles (33% of locations under RCP2.6 and 10% under RCP8.5) indicate that extreme sea level events are not expected to occur once per year by 2100. {4.2.3, Figure 4.12}

## SPM.C Responding to Changes: Challenges, Options and Enablers

***Challenges***

**C1**. Impacts from climate-induced changes in the ocean and cryosphere challenge the adaptive capacity of societies and ecosystems as well as their governance to address increasing and residual risks across local, regional, national, and international levels (*high confidence*) {1.5, 1.7, Cross-Chapter Boxes 2-3 of Chapter 1, 2.3.2, 2.3.3, 2.4, 3.2.4, 3.4.3, 3.5.2, 3.5.3, 6.9}.

**C1.1** Current governance structures are often not well-matched to the spatial and temporal scales of climate change impacts on ocean and cryosphere systems and their consequences for ecosystems and human societies. Such mismatches can create barriers which challenge the ability of societies to respond to these impacts. Examples include dealing with changes in risks associated with landslide, avalanche and flood hazards in high mountain environments, renewable resource management and biodiversity protection options in polar regions, and threats to some essential marine ecosystems (*medium confidence*). {2.3.2, 3.5.2, 3.5.3, 5.2, 5.3, 5.4, 5.5, 5.5.1, 5.5.2, 6.9}

**C1.2** Current governance systems are, in many contexts, too fragmented across administrative boundaries and sectors to address the increasing and cascading risks from changes in the ocean and cryosphere in an integrated way (*high confidence*). The capacity of governance systems in polar and ocean regions to respond to climate change has strengthened recently, but the development of these systems is not sufficiently rapid or robust to address risks posed by projected changes (*high confidence*). Actors within specific regions in high mountains and coasts face difficulties in coordinating responses to climate change, given climatic and non-climatic anthropogenic drivers (such as demographic and settlement trends, and anthropogenic subsidence) that interact across scales, sectors and policy domains (*high confidence*). {2.3.1, 3.5.3, 4.4.3, 5.4.2, Box 5.6, 6.9}

**C1.3** Barriers occur when addressing many of the expected negative climate change impacts in the ocean and cryosphere, impeding resilience building and implementation of risk reduction measures (*medium confidence*). Vulnerable human communities, especially those in coral reef environments, high mountains, and along Arctic coasts, may face adaptation limits well before the end of this century, even under low emission scenarios (*medium confidence*). The risk of reaching adaptation limits will increase and expand to more geographies beyond 2100, due to the long-term commitment of sea level rise (*medium confidence*). The extent of climate-related biophysical changes and capacity of societies to overcome barriers determine whether adaptation limits will be reached. However, determining limits and their timing precisely is currently difficult (*medium confidence*). {2.3.6, 2.3.7, 3.7, 4.3.4, 4.4.2, 5.5.2, Cross-Chapter Box 9}

***Options***

**C2** Options for assisting the future functional integrity of marine and cryospheric ecosystems, and the far-reaching services they provide, include protection, restoration, ecosystem-based management of renewable natural resources, and the reduction of pollution and other stressors (*high confidence*). However, ecological, financial, institutional and governance constraints for such actions exist, and the effectiveness of some ecosystem-based adaptation approaches will be compromised under high emission scenarios (*high confidence*). {2.3.1, 2.3.3, 2.4, 3.2.4, 3.5.2, 3.5.4, 5.2.2, Box 5.3, 5.4.2, 5.5.1, 5.5.2, Figure SPM.5}

**C2.1** Networks of protected areas, on land and at sea, help maintain existing ecosystem services and can also facilitate the poleward and altitudinal movements of populations, species and ecosystems that are already occurring in response to warming and sea-level rise (*high confidence*). Physical factors and land use changes limit the potential for future natural latitudinal and altitudinal migrations, in mountain regions, coastal habitats and the Arctic (*high confidence*). {2.3.3, 3.2.3, 3.3.2, 3.5.4, Box 3.4}

**C2.2** Terrestrial and marine habitat restoration, and ecosystem manipulations such as assisted species migration and coral gardening, can be locally effective (*high confidence*). Such actions will be most successful when they are community-supported and science-based, and when non-climatic stressors are reduced or removed (*high confidence*). The cost of coastal habitat restoration can be high (ranging from thousands to hundreds of thousands of US$ per ha), and its effectiveness is limited to low emission scenarios (*medium confidence*). {2.3.3, 4.4.2, 5.5.1, 5.5.2, Box 5.4}

**C2.3** Strengthening responsiveness and precautionary approaches of existing fisheries management strategies will reduce negative climate change impacts on fisheries, with benefits for regional renewable resource economies, cultures and the global supply of fish and shellfish, including krill (*medium confidence*). Adaptive management that combines annual and within-season measures informed by assessments of future ecosystem trends reduces risks for polar fisheries (*medium confidence*) but has limited ability to address ecosystem change. {3.2.4, 3.5.2, 5.5.3}

**C2.4** Rebuilding overexploited or depleted fisheries through sustainable fisheries management practices will improve catch, economic benefits, and fish stock biomass, thus reducing climate risks on fisheries, particularly at low emission scenarios (*medium confidence*). {5.4.2}

**C2.5** Well-managed coastal blue carbon ecosystems, such as mangroves, tidal marshes and seagrass meadows, provide coastal protection, reduce eutrophication, support fisheries, and contribute to climate mitigation for some nations through their uptake and storage of carbon (*high confidence*). Nevertheless, their mitigation potential is relatively modest at the global scale (offset of <2% of current emissions) (*medium confidence*). {Box 4.3, 5.4, 5.5.1, 5.5.2}

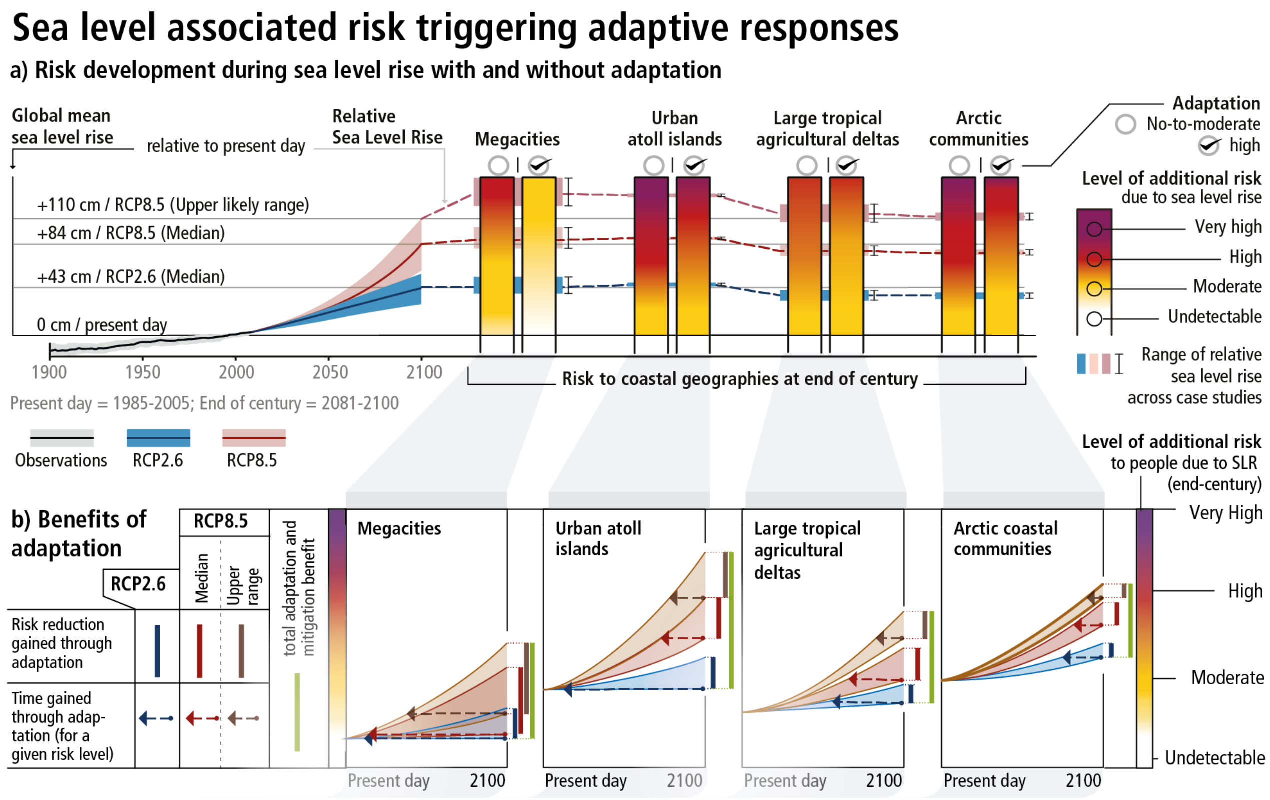
**C3.** In responding to sea level rise and associated extreme events, coastal societies face challenging but unavoidable choices in negotiating and crafting context-specific and integrated responses that carefully balance costs, benefits and trade-offs of available options and can be adjusted over time (*high confidence*). A range of decision analysis, land-use planning, public participation and conflict resolution approaches help to facilitate these choices (*high confidence*). {4.4.2, 4.4.3, 4.4.4, 6.9.1, Cross-Chapter Box 9; Figure SPM.5}

**C3.1.** Technical limits to hard coastal protection will generally not be reached under low emissions (RCP2.6), but are expected to be reached after 2100 under high emissions (RCP8.5) (*high confidence*). Where space is limited, and the value of exposed assets is high (e.g., in cities), hard protection is a cost-efficient response option (*high confidence*), but governments in resource-limited areas may be challenged to afford such investments. Where space is available, ecosystem-based adaptation can reduce coastal risk and provide multiple other benefits (*medium confidence*). Biophysical limits to ecosystem-based adaptation may manifest in the 21st Century but economic and social barriers may be faced well before (*medium confidence*). {4.3.2, 4.4.2, Box 4.1, Cross-Chapter Box 9}

**C3.2** Accommodation, such as flood-proofing buildings and early warning systems, is often both low cost and highly cost-efficient, particularly in low-density areas (*high confidence*). Limits are expected to arise well before those associated with hard protection. Where coastal risks are already high and total population and population density are low, or in the aftermath of a disaster, retreat is especially effective, albeit socially, culturally and politically challenging (*high confidence*). Limits to retreat are not well understood. {4.4.2, Box 4.1, Cross-Chapter Box 9}

**C3.3** Responses to sea-level rise presents society with profound governance challenges, resulting from the large uncertainty about future sea level rise, vexing trade-offs between societal goals (e.g., safety, conservation, economic development), limited resources, and conflicting interests and values among diverse stakeholders (*high confidence*). These challenges can be addressed using locally appropriate combinations of decision analysis, land-use planning, public participation and conflict resolution approaches that are adjusted over time as circumstances change (*medium confidence*). {Cross-Chapter Box 5 in Chapter 1, 4.4.3, 4.4.4, 6.9}

**C3.4** Despite the large uncertainties about future sea level rise, coastal decisions can be made now by favouring flexible responses (i.e., those that can be adapted over time), supported by establishing monitoring systems for early warning signals, periodically adjusting decisions (i.e., adaptive decision making), using robust decision-making approaches and invoking expert judgement, scenario-building, and multiple lines of evidence (*high confidence*). For stakeholders who have a low risk tolerance, it is beneficial to consider sea level rise above the likely range of RCP8.5 (i.e., above 1.10 m by 2100) (*high confidence*). This includes planning for physically plausible, high impact changes (such as high-end sea level rise scenarios) that would be severe without effective adaptation. {1.8.1, 1.9.2, 4.4.4, Figure 4.2, Cross-Chapter Box 5 in Chapter 1, Figure SPM.5}



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

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

| | | Responses {4.4.2} | Effectiveness* | Advantages | Co-benefits** | Drawbacks | Economic efficiency | Governance challenges |
|---|---|---|---|---|---|---|---|---|
| Protection | | Hard protection | Up to several meters of SLR ●●●— | Predictable levels of safety ●●●— | Multifunctional dikes | Flooding/erosion elsewhere, Destruction of habitat through coastal squeeze, lock-in, disaster in case of failure | High for urban coasts, low for rural coast | Long-term finance; Trade-offs between conservation, safety and tourism goals, Distributional conflicts |
| Protection | | Sediment -based | Depends on sediment availability | High flexibility | Beach preservation for tourism | Destruction of habitat | High if tourism revenues are high | Distributional conflicts |
| Ecosystem-based adaptation | Coral | Conservation | ●●●— Effective up to 0.5 cm/yr SLR ↑ Limited by climate change, and local human influences, e.g. pollution, infrastructure ↓ Effective up to > 1 cm/yr SLR at high sediment supply ●●— | Opportunity for community involvement | Carbon sequestration, tourism, fishery productivity, water quality, food, medicine, fuel/construction, cultural | Long-term effectiveness questionable | Limited evidence on benefit-cost ratios; Depends on population density and the availability of land | Permits difficult to obtain. Lack of finance, lack of enforcement of conservation policies |
| Ecosystem-based adaptation | Coral | Restoration | | | | High cost, only suitable for local application. | | |
| Ecosystem-based adaptation | Wetland | Conservation | | | | Global change impacts continue, safety levels less predictable. Development benefits not realised | | |
| Ecosystem-based adaptation | Wetland | Restoration | | | | Medium to High cost, safety levels less predictable, a lot of land required | | |
| | | Advance | Up to several meters of SLR ●●●— | Predictable levels of safety ●●●— | Generates land and land sale revenues | Goundwater salinisation, erosion, loss of coastal ecosystems/ human habitat | Very high for urban coasts | Social conflicts: New land access and distribution |
| | | Accommodation++ | Very effective for small SLR | Mature technology; deposited sediments can raise elevation | Maintains landscape connectivity | Does not prevent flooding/impacts | Very high for early warning systems and building-scale measures) | Effective institutional arrangements (Early warning) |
| | | Managed retreat# | Very high*** ●●●— | Risks can be eliminated completely*** | Optional improved services+, economy, jobs. | Loss of social cohesion, cultural identity, well-being. Possibly depressed services+, economy, jobs. | Limited evidence | Unpopular topic, high reputational risk for policy makers, unclear legal status of refugees |

+ health, education, housing; ++Flood-proof houses, early warning systems, etc.; +++but limited by ocean acidification/warming; # Migration, displacement, relocation; *technical/biophysical limits; ** beyond risk reduction; ***if sufficient safe land is available

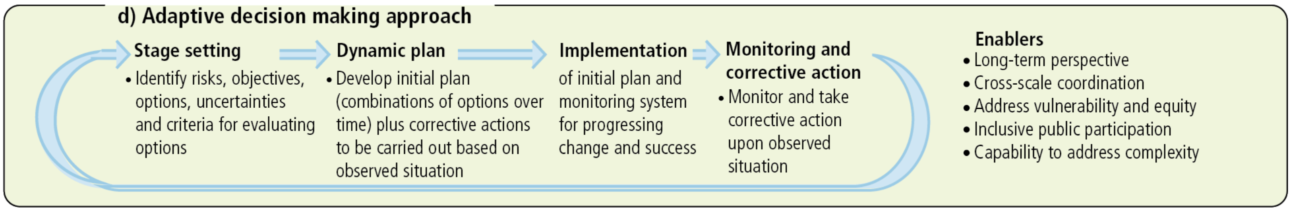



**Figure SPM.5:** Risk related to sea level rise for low-lying coastal areas, benefits of adaptation, response options and adaptive decision-making to address them. Panel a) global mean sea level rise (GMSL) scenarios and related risk to archetypal local geographies. This assessment focusses on the additional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

***Enablers***

**C4.** Key enablers for implementing effective responses to changes in the ocean and cryosphere include intensifying cooperation and coordination among actors across scales, boundaries, and planning horizons (*high confidence*). Education and climate literacy, monitoring and forecasting, funding, and institutional support are also essential and enable social learning and participation in context-specific adaptation and the negotiation of trade-offs and co-benefits between reducing immediate risks and building resilience (*high confidence*). {1.8.3, 2.3.1, 2.3.2, Figure 2.7, 2.4, 2.5, 3.5.2, 3.5.4, 5.2.2, Box 5.3, 5.4.2, 5.5.2, 6.4.3, 6.5.3, 6.9, Cross-Chapter Box 9}

**C4.1** Regional cooperation, treaties and conventions in the polar regions, and in some mountain areas and transboundary river basins can support adaptation action; however, the extent to which impacts and losses arising from changes in the ocean and cryosphere are translated into regional policy frameworks is currently limited *(high confidence*). In the Arctic and some mountain regions, institutional arrangements that provide strong multiscale linkages with local and indigenous communities benefit adaptation (*high confidence*). In the mountain context, consistency between national and transboundary regional policies on resource management increases the effectiveness of efforts to address risks to water security and losses to disasters (*medium confidence*). {2.3.1, 2.3.2, 2.3.5, 2.3.6, 2.4, Box 2.4, 2.5, 3.5.3, 3.5.4}

**C4.2** Investments in education at various levels and scales facilitates social learning and long-term capacity-building for context-specific formulation and implementation of strategies to reduce risk and enhance resilience in the Arctic and high mountain regions (*medium confidence*). Specific activities include the promotion of climate literacy, incorporation of multiple forms of knowledge into decision-making, and the engagement of knowledge-holders, practitioners, and stakeholders in adaptive governance systems and planning frameworks with close linkages to policy processes (*medium confidence).* Developing, and in many cases transforming existing institutions, enable such interactive and adaptive governance (*high confidence*). {1.8.3, 2.3.2, Figure 2.7, Box 2.4, 2.4, 3.5.2, 3.5.4}

**C4.3** Context-specific monitoring and forecasting of changes in the ocean and the cryosphere strongly supports adaptation planning and implementation, and facilitates robust decisions on trade-offs between short- and long-term gains (*medium confidence*). Sustained long-term monitoring and improved forecasts, including early warning systems to predict extreme El Niño/La Niña and marine heat waves, help to manage negative impacts from changes in the ocean such as losses in fisheries, impacts to human health, agriculture, coral reefs, aquaculture, wildfire, tourism, conservation, drought and flood (*high confidence*). {2.4, 2.5, 3.5.2, 4.4.4, 6.4.3, 6.5.3}

**C4.4** Experience to date in responding to sea level rise reveals the following enabling conditions: First, taking a long-term perspective when making short-term decisions, explicitly accounting for uncertainty of context-specific risks beyond 2050 (*high confidence*), and building governance capabilities to tackle the complexity of sea level rise risk (*medium confidence*). Second, improved coordination of sea level rise responses across scales, sectors and policy domains helps to address sea level rise impacts and risk (*high confidence*). Third, prioritising considerations for social vulnerability and equity underpins efforts to promote fair and just climate resilience and sustainable development (*high confidence*); and can be helped by creating safe community settings for meaningful public deliberation and conflict resolution (*medium confidence*). Finally, public awareness and understanding about sea level rise risks and responses can be improved by drawing on local, indigenous and scientific knowledge systems, together with social learning about locality-specific sea level rise risk and response potential (*high confidence*). {4.4.4, 4.4.5, Table 4.9, Figure SPM.5}

**C4.5** Enabling conditions for responding to sea level rise call for attention to time scales, coordination and integration, social vulnerability and learning. Key response enablers are: explicitly accounting for uncertainty of locality-specific risks beyond 2050 in short-term decision-making (*high* *confidence*), building governance capabilities to tackle complex risks (*medium confidence)* improved coordination of responses across scales, sectors and policy domains (*high confidence*), prioritising consideration of social vulnerability and equity to promote fair and just climate resilience and sustainable development (*high confidence*), creating safe community settings for meaningful public deliberation and conflict resolution (*medium confidence*), and improving public awareness, understanding, and social learning about sea level rise risk and response potential by drawing on local, indigenous and scientific knowledge (*high confidence*). {Cross-Chapter Box 5 in Chapter 1; 4.4.4, 4.4.5, Table 4.9, 6.9, Figure SPM.5}

**C5.** Enabling climate resilient and sustainable development depends critically on urgent, ambitious, coordinated and sustained implementation of a low emission pathway and adaptation actions to reduce climate change impacts on the Earth's life-sustaining oceans and cryosphere (*high confidence*). {IPCC SR1.58, 1.1, 1.5, 2.4, 3.5, 4.4, 5.4, 5.5, 6.9, Cross-Chapter Box 9}

**C5.1.** Nations will be challenged to adapt to observed and projected changes in the oceans and cryosphere, even with concerted efforts to reduce greenhouse gas emissions (*very high confidence*). Compared to high emission scenarios a low emissions pathway reduces the risks from ocean and cryosphere changes (*high confidence*), whilst also creating co-benefits. Under a high carbon emissions scenario, adaptation limits may be faced beyond 2100 by most ocean and cryosphere dependent communities, and even sooner for exposed and vulnerable populations. Profound economic and institutional transformations are therefore needed to achieve Climate Resilient Development Pathways in the ocean and cryosphere context (*high confidence*). {1.1, 1.4-1.7, Cross-Chapter Boxes 1-3 in Chapter 1, 2.3, 2.4, Box 3.2, Figure 3.4, Cross-Chapter Box 7 in Chapter 3, 3.4.3, 4.2.2, 4.2.3, 4.3.4, 4.4.2, 4.4.3, 4.4.6, 5.4.2, 5.5.3, 6.4.1, 6.8.5, 6.9.2, Cross-Chapter Box 9, IPCC SR1.5[8], IPBES 2019[9]}

**C5.2** This assessment reinforces findings in IPCC SR1.5 and IPBES (2019) about the benefits of resolute mitigation and adaptation for sustainable development and, conversely, the escalating costs and risks of delayed action to reduce climate-driven impacts and risks. The potential to chart Climate Resilient Development Pathways varies within and between different regions and nations. Realising this potential depends on prioritising timely, ambitious, coordinated and enduring action to reduce the impacts of climate change on ocean and cryosphere systems. (*medium confidence*). {1.1, 1.8, Cross-Chapter Box 1, 2.3, 2.4, 3.5, 4.2.1, 4.2.2, 4.3.4, 4.4, Table 4.9, 5.5, 6.9, Cross-Chapter Box 9, Figure SPM.5}

[8] IPCC SR1.5: IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland.

[9] IPBES 2019: Díaz, S. et al., 2019: Summary for policymakers of the global assessment report on biodiversity and ecosystem services - unedited advance version. IPBES, Bonn [Available at: https://www.ipbes.net/sites/default/files/downloads/spm_unedited_advance_for_posting_htn.pdf].