Technical Summary

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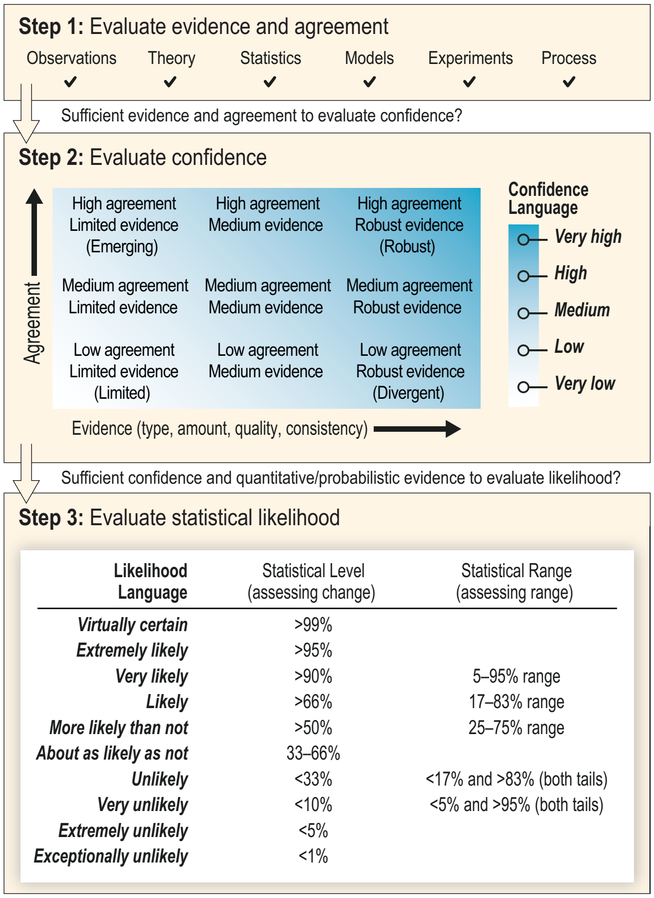
TS.0 Introduction

This Technical Summary of the *IPCC Special Report on Ocean and Cryosphere in a Changing Climate (SROCC)* consists of the Executive Summaries of all chapters (1–6) of the Special Report, the Executive Summary from the Integrative Cross-Chapter Box on Low-Lying Islands and Coasts, and supporting figures drawn from the chapters and the Summary for Policymakers. The Technical Summary follows the structure of the Report (Table TS.1).

Section TS.1 (Chapter 1) introduces important key concepts, summarizes the characteristics and interconnection of ocean and cryosphere and highlights their importance in the earth system and for human societies in the light of climate change. TS.2 (Chapter 2) assesses changes in high mountain cryosphere and their impacts on local mountain communities and far beyond. TS.3 (Chapter 3) evaluates the state of knowledge concerning changes and impacts in the Arctic and Antarctic ocean and cryosphere systems, including challenges and opportunities for societies. TS.4 (Chapter 4) focusses on regional and global changes in sea level, the associated risk to low-lying islands, coasts and human settlements, and response options. TS.5 (Chapter 5) assesses changes in the ocean and marine ecosystems, including risks to ecosystem services and vulnerability of the dependent communities. TS.6 (Chapter 6) examines extremes and abrupt or irreversible changes in the ocean and cryosphere in a changing climate, and identifies sustainable and resilient risk management strategies. All chapters and their Executive Summaries build on findings since the *IPCC Fifth Assessment Report (AR5)* and, whenever applicable, outcomes of the *IPCC Special Report on Global Warming of 1.5°C (SR15)*.

SROCC uses IPCC calibrated language[1] for the communication of confidence in the assessment process (see Chapter 1 and references therein). This calibrated language is designed to consistently evaluate and communicate uncertainties that arise from incomplete knowledge due to a lack of information, or from disagreement about what is known or even knowable. The IPCC calibrated language uses qualitative expressions of confidence based on the robustness of evidence for a finding, and (where possible) uses quantitative expressions to describe the likelihood of a finding (Figure TS.1).



High agreement Limited evidence (Emerging)	High agreement Medium evidence	High agreement Robust evidence (Robust)
Medium agreement Limited evidence	Medium agreement Medium evidence	Medium agreement Robust evidence
Low agreement Limited evidence (Limited)	Low agreement Medium evidence	Low agreement Robust evidence (Divergent)

Likelihood Language	Statistical Level (assessing change)	Statistical Range (assessing range)
Virtually certain	>99%	
Extremely likely	>95%	
Very likely	>90%	5–95% range
Likely	>66%	17–83% range
More likely than not	>50%	25–75% range
About as likely as not	33–66%	
Unlikely	<33%	<17% and >83% (both tails)
Very unlikely	<10%	<5% and >95% (both tails)
Extremely unlikely	<5%	
Exceptionally unlikely	<1%	

Figure TS.1 | Schematic of the IPCC usage of calibrated language (for more details see Section 1.9.2, Figure 1.4 and Cross-Chapter Box 5 in Chapter 1).

References to chapter sections, boxes, cross-chapter boxes as well as to figures and tables are provided in curly brackets {} at the end of each statement below.

Table TS.1 | Structure of the Technical Summary (TS) and Chapters included in the IPCC Special Report on Ocean and Cryosphere in a Changing Climate (SROCC).

TS.1	Chapter 1: Framing and Context of the Report
TS.2	Chapter 2: High Mountain Areas
TS.3	Chapter 3: Polar Regions
TS.4	Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities
TS.5	Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities
TS.6	Chapter 6: Extremes, Abrupt Changes and Managing Risks
TS.7	Integrative Cross-Chapter Box: Low-lying Islands and Coasts

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[1] 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*. This Report also uses the term 'likely range' or 'very likely range' to indicate that the assessed likelihood of an outcome lies within the 17–83% or 5–95% probability range. For more details see Chapter 1, Section 1.9.2 and Figure 1.4.

TS.1 Framing and Context of the Report

This special report assesses new knowledge since the IPCC 5th Assessment Report (AR5) and the Special Report on Global Warming of 1.5°C (SR15) on how the ocean and cryosphere have and are expected to change with ongoing global warming, the risks and opportunities these changes bring to ecosystems and people, and mitigation, adaptation and governance options for reducing future risks. Chapter 1 provides context on the importance of the ocean and cryosphere, and the framework for the assessments in subsequent chapters of the report.

All people on Earth depend directly or indirectly on the ocean and cryosphere. The fundamental roles of the ocean and cryosphere in the Earth system include the uptake and redistribution of anthropogenic carbon dioxide and heat by the ocean, as well as their crucial involvement of in the hydrological cycle. The cryosphere also amplifies climate changes through snow, ice and permafrost feedbacks. Services provided to people by the ocean and/or cryosphere include food and freshwater, renewable energy, health and wellbeing, cultural values, trade and transport. {1.1, 1.2, 1.5, Figure TS.2}

Sustainable development is at risk from emerging and intensifying ocean and cryosphere changes. Ocean and cryosphere changes interact with each of the United Nations Sustainable Development Goals (SDGs). Progress on climate action (SDG 13) would reduce risks to aspects of sustainable development that are fundamentally linked to the ocean and cryosphere and the services they provide (*high confidence*). Progress on achieving the SDGs can contribute to reducing the exposure or vulnerabilities of people and communities to the risks of ocean and cryosphere change (*medium confidence*). {1.1}

Communities living in close connection with polar, mountain, and coastal environments are particularly exposed to the current and future hazards of ocean and cryosphere change. Coasts are home to approximately 28% of the global population, including around 11% living on land less than 10 m above sea level. Almost 10% of the global population lives in the Arctic or high mountain regions. People in these regions face the greatest exposure to ocean and cryosphere change, and poor and marginalised people here are particularly vulnerable to climate-related hazards and risks (*very high confidence*). The adaptive capacity of people, communities and nations is shaped by social, political, cultural, economic, technological, institutional, geographical and demographic factors. {1.1, 1.5, 1.6, Cross-Chapter Box 2 in Chapter 1}

Ocean and cryosphere changes are pervasive and observed from high mountains, to the polar regions, to coasts, and into the deep ocean. AR5 assessed that the ocean is warming (0 to 700 m: *virtually certain;* 700 to 2000 m: *likely*), sea level is rising (*high confidence*), and ocean acidity is increasing (*high confidence*). Most glaciers are shrinking (*high confidence*), the Greenland and Antarctic ice sheets are losing mass (*high confidence*), sea ice extent in the Arctic is decreasing (*very high confidence*), Northern Hemisphere

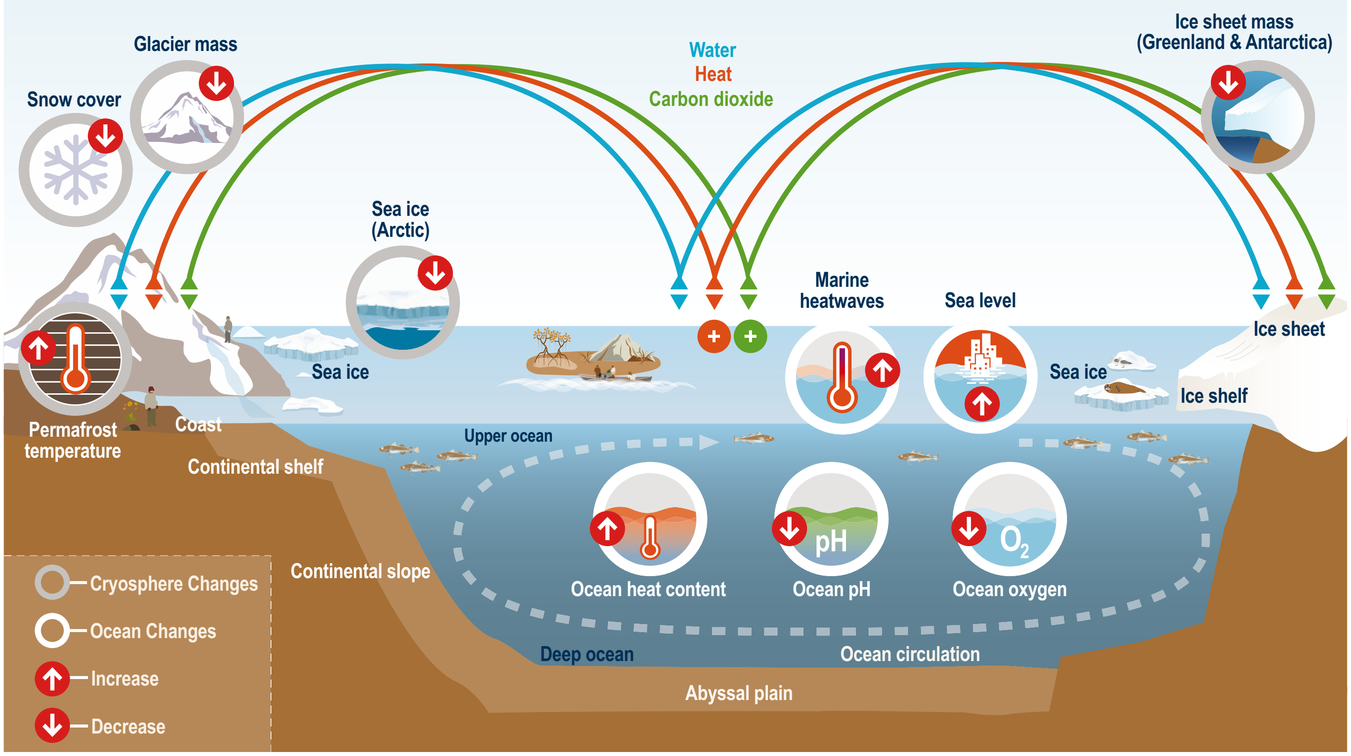

Figure TS.2 | Schematic illustration of key components and changes of the ocean and cryosphere, and their linkages in the Earth system through the global exchange of heat, water, and carbon (Section 1.2). Climate change-related effects (increase/decrease indicated by arrows in pictograms) in the ocean include sea level rise, increasing ocean heat content and marine heat waves, increasing ocean oxygen loss and ocean acidification (Section 1.4.1). Changes in the cryosphere include the decline of Arctic sea ice extent, Antarctic and Greenland ice sheet mass loss, glacier mass loss, permafrost thaw, and decreasing snow cover extent (Section 1.4.2). For illustration purposes, a few examples of where humans directly interact with ocean and cryosphere are shown (for more details see Box 1.1).

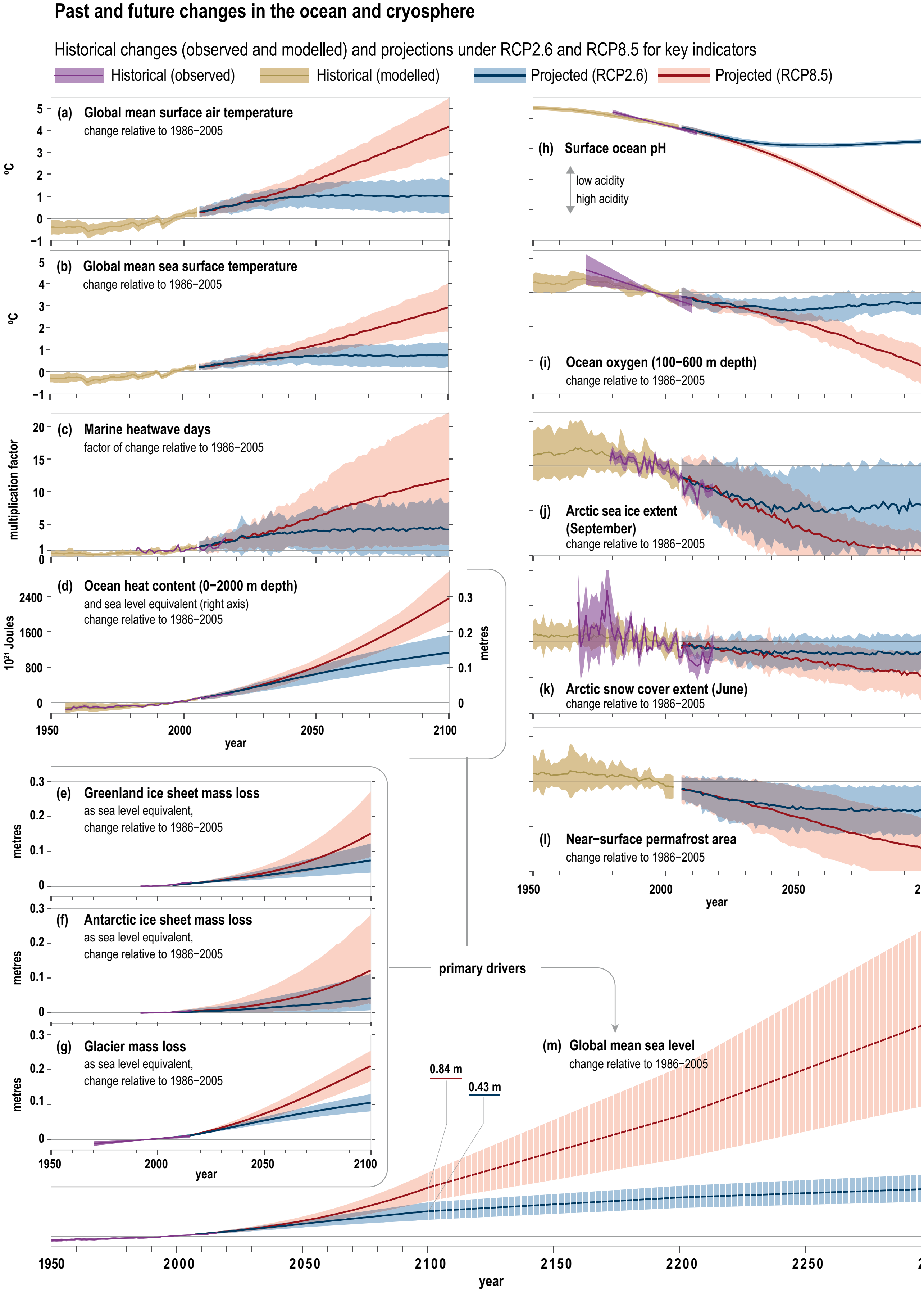
Past and future changes in the ocean and cryosphere
Historical changes (observed and modelled) and projections under RCP2.6 and RCP8.5 for key indicators
Historical (observed)
Historical (modelled)
Projected (RCP2.6)
Projected (RCP8.5)
(a) Global mean surface air temperature
change relative to 1986–2005
°C
5
4
3
2
1
0
−1
(b) Global mean sea surface temperature
change relative to 1986–2005
°C
5
4
3
2
1
0
−1
(c) Marine heatwave days
factor of change relative to 1986–2005
multiplication factor
20
15
10
5
1
0
(d) Ocean heat content (0–2000 m depth)
and sea level equivalent (right axis)
change relative to 1986–2005
10^{21} Joules
2400
1600
800
0
metres
0.3
0.2
0.1
0
1950
2000
2050
2100
year
(e) Greenland ice sheet mass loss
as sea level equivalent,
change relative to 1986–2005
metres
0.3
0.2
0.1
0
(f) Antarctic ice sheet mass loss
as sea level equivalent,
change relative to 1986–2005
metres
0.3
0.2
0.1
0
(g) Glacier mass loss
as sea level equivalent,
change relative to 1986–2005
metres
0.3
0.2
0.1
0
1950
2000
2050
2100
year
(h) Surface ocean pH
low acidity
high acidity
(i) Ocean oxygen (100–600 m depth)
change relative to 1986–2005
(j) Arctic sea ice extent (September)
change relative to 1986–2005
(k) Arctic snow cover extent (June)
change relative to 1986–2005
(l) Near-surface permafrost area
change relative to 1986–2005
1950
2000
2050
year
primary drivers
(m) Global mean sea level
change relative to 1986–2005
0.84 m
0.43 m
1950
2000
2050
2100
2150
2200
2250
year

Figure TS.3

Figure TS.3 | Observed and modelled historical changes in the ocean and cryosphere since 1950[2], and projected future changes under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios. Changes are shown for: **(a)** Global mean surface air temperature change with likely range. {Box SPM.1, Cross-Chapter Box 1 in Chapter 1} Ocean-related changes with very likely ranges for **(b)** Global mean sea surface temperature change {Box 5.1, 5.2.2}; **(c)** Change factor in surface ocean marine heatwave days {6.4.1}; **(d)** Global ocean heat content change (0–2000 m depth). An approximate steric sea level equivalent is shown with the right axis by multiplying the ocean heat content by the global-mean thermal expansion coefficient ($\varepsilon \approx 0.125$ m per 1024 Joules[3]) for observed warming since 1970 {Figure 5.1}; **(h)** Global mean surface pH (on the total scale). Assessed observational trends are compiled from open ocean time series sites longer than 15 years {Box 5.1, Figure 5.6, 5.2.2}; and **(i)** Global mean ocean oxygen change (100–600 m depth). Assessed observational trends span 1970–2010 centered on 1996 {Figure 5.8, 5.2.2}. Sea level changes with likely ranges for **(m)** Global mean sea level change. Hashed shading reflects low confidence in sea level projections beyond 2100 and bars at 2300 reflect expert elicitation on the range of possible sea level change {4.2.3, Figure 4.2}; and components from **(e,f)** Greenland and Antarctic ice sheet mass loss {3.3.1}; and **(g)** Glacier mass loss {Cross-Chapter Box 6 in Chapter 2, Table 4.1}. Further cryosphere-related changes with very likely ranges for **(j)** Arctic sea ice extent change for September[4] {3.2.1, 3.2.2 Figure 3.3}; **(k)** Arctic snow cover change for June (land areas north of 60°N) {3.4.1, 3.4.2, Figure 3.10}; and **(l)** Change in near-surface (within 3–4 m) permafrost area in the Northern Hemisphere {3.4.1, 3.4.2, Figure 3.10}. Assessments of projected changes under the intermediate RCP4.5 and RCP6.0 scenarios are not available for all variables considered here, but where available can be found in the underlying report. {For RCP4.5 see: 2.2.2, Cross-Chapter Box 6 in Chapter 2, 3.2.2, 3.4.2, 4.2.3, for RCP6.0 see Cross-Chapter Box 1 in Chapter 1}

snow cover is decreasing (*very high confidence*), and permafrost temperatures are increasing (*high confidence*). Improvements since AR5 in observation systems, techniques, reconstructions and model developments, have advanced scientific characterisation and understanding of ocean and cryosphere change, including in previously identified areas of concern such as ice sheets and Atlantic Meridional Overturning Circulation (AMOC). {1.1, 1.4, 1.8.1, Figure TS.3}

Evidence and understanding of the human causes of climate warming, and of associated ocean and cryosphere changes, has increased over the past 30 years of IPCC assessments (*very high confidence*). Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels (SR15). Areas of concern in earlier IPCC reports, such as the expected acceleration of sea level rise, are now observed (*high confidence*). Evidence for expected slow-down of AMOC is emerging in sustained observations and from long-term palaeoclimate reconstructions (*medium confidence*), and may be related with anthropogenic forcing according to model simulations, although this remains to be properly attributed. Significant sea level rise contributions from Antarctic ice sheet mass loss (*very high confidence*), which earlier reports did not expect to manifest this century, are already being observed. {1.1, 1.4}

Ocean and cryosphere changes and risks by the end-of-century (2081–2100) will be larger under high greenhouse gas emission scenarios, compared with low emission scenarios (*very high confidence*). Projections and assessments of future climate, ocean and cryosphere changes in the Special Report on the Ocean and Cryosphere in a Changing Climate (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 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, Table TS.2}

Characteristics of ocean and cryosphere change include thresholds of abrupt change, long-term changes that cannot be avoided, and irreversibility (*high confidence*). Ocean warming, acidification and deoxygenation, ice sheet and glacier mass loss, and permafrost degradation are expected to be irreversible on time scales relevant to human societies and ecosystems. Long response times of decades to millennia mean that the ocean and cryosphere are committed to long-term change even after atmospheric greenhouse gas concentrations and radiative forcing stabilise (*high confidence*). Ice-melt or the thawing of permafrost involve thresholds (state changes) that allow for abrupt, nonlinear responses to ongoing climate warming (*high confidence*). These characteristics of ocean and cryosphere change pose risks and challenges to adaptation. {1.1, Box 1.1, 1.3}

Societies will be exposed, and challenged to adapt, to changes in the ocean and cryosphere even if current and future efforts to reduce greenhouse gas emissions keep global warming well below 2°C (*very high confidence*). Ocean and cryosphere-related mitigation and adaptation measures include options that address the causes of climate change, support biological and ecological adaptation, or enhance societal adaptation. Most ocean-based local mitigation and adaptation measures have limited effectiveness to mitigate climate change and reduce its consequences at the global scale, but are useful to implement because they address local risks, often have co-benefits such as biodiversity conservation, and have few adverse side effects. Effective mitigation at a global scale will reduce the need and cost of adaptation, and reduce the risks of surpassing limits to adaptation. Ocean-based carbon dioxide removal at the global scale has potentially large negative ecosystem consequences. {1.6.1, 1.6.2, Cross-Chapter Box 2 in Chapter 1, Figure TS.4}

The scale and cross-boundary dimensions of changes in the ocean and cryosphere challenge the ability of communities, cultures and nations to respond effectively within existing governance frameworks (*high confidence*). Profound economic and institutional transformations are needed if climate-resilient development is to be achieved (*high confidence*). Changes in the ocean and cryosphere, the ecosystem services that they provide,

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[2] This does not imply that the changes started in 1950. Changes in some variables have occurred since the pre-industrial period.

[3] This scaling factor (global-mean ocean expansion as sea level rise in metres per unit heat) varies by about 10% between different models, and it will systematically increase by about 10% by 2100 under RCP8.5 forcing due to ocean warming increasing the average thermal expansion coefficient. {4.2.1, 4.2.2, 5.2.2}

[4] Antarctic sea ice is not shown here due to low confidence in future projections. {3.2.2}

Table TS.2 | Projected change in global mean surface air temperature and key ocean variables for the *near-term* (2031–2050) and *end-of-century* (2081–2100) relative to the *recent past* (1986–2005) reference period from CMIP5. Small differences in the projections given here compared with AR5 reflect differences in the number of models available now compared to at the time of the AR5 assessment (for more details see Cross-Chapter Box 1 in Chapter 1).

		Near-term: 2031–2050		End-of-century: 2081–2100	
	Scenario	Mean	5–95% range	Mean	5–95% range
Global Mean Surface Air Temperature (°C)[a]	RCP2.6	0.9	0.5–1.4	1.0	0.3–1.7
	RCP4.5	1.1	0.7–1.5	1.8	1.0–2.6
	RCP6.0	1.0	0.5–1.4	2.3	1.4–3.2
	RCP8.5	1.4	0.9–1.8	3.7	2.6–4.8
Global Mean Sea Surface Temperature (°C)[b] (Section 5.2.5)	RCP2.6	0.64	0.33–0.96	0.73	0.20–1.27
	RCP8.5	0.95	0.60–1.29	2.58	1.64–3.51
Surface pH (units)[b] (Section 5.2.2.3)	RCP2.6	–0.072	–0.072 to –0.072	–0.065	–0.065 to –0.066
	RCP8.5	–0.108	–0.106 to –0.110	–0.315	–0.313 to –0.317
Dissolved Oxygen (100–600 m) (% change) (Section 5.2.2.4)[b]	RCP2.6	–0.9	–0.3 to –1.5	–0.6	0.0 to –1.2
	RCP8.5	–1.4	–1.0 to –1.8	–3.9	–2.9 to –5.0

Notes:

[a] Calculated following the same procedure as the IPCC 5th Assessment Report (AR5). The 5–95% model range of global mean surface air temperature across CMIP5 projections was assessed in AR5 as the *likely* range, after accounting for additional uncertainties or different levels of confidence in models.

[b] The 5–95% model range for global mean sea surface temperature, surface pH and dissolved oxygen (100–600 m) as referred to in the SROCC assessment as the *very likely* range (see also Chapter 1, Section 1.9.2, Figure 1.4).

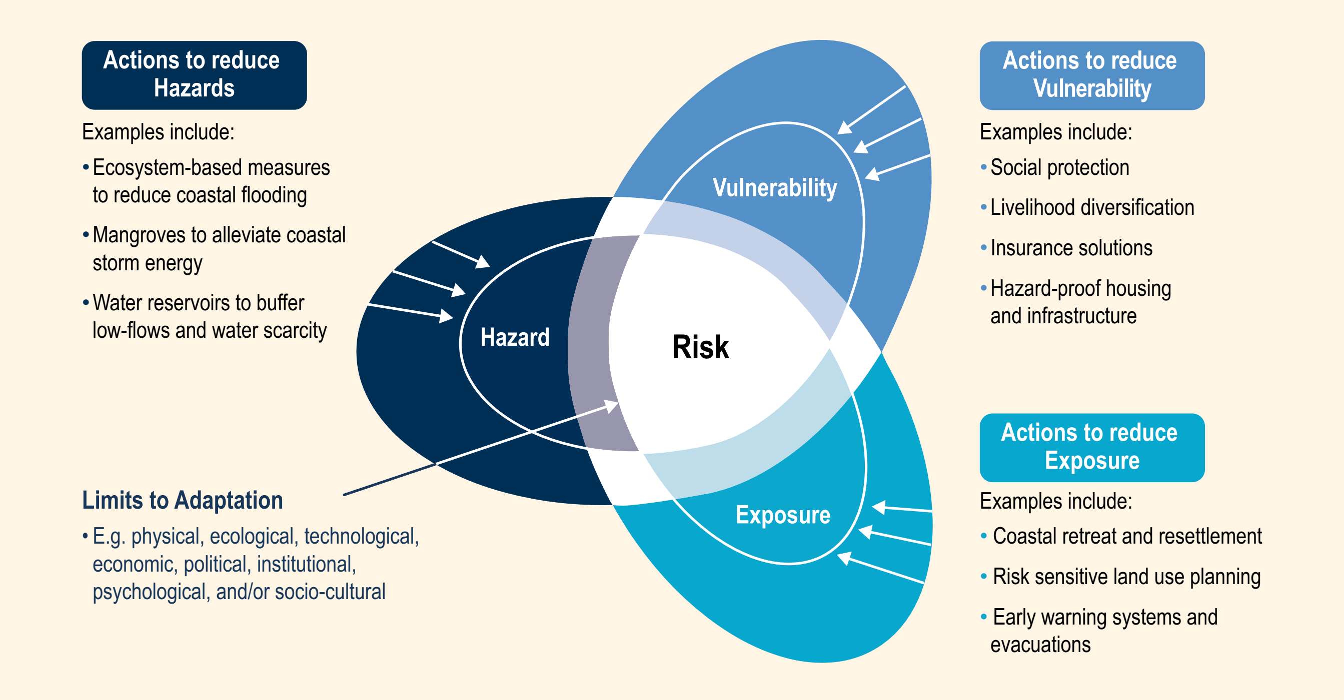

Figure TS.4 | There are options for risk reduction through adaptation. Adaptation can reduce risk by addressing one or more of the three risk factors: vulnerability, exposure, and/or hazard. The reduction of vulnerability, exposure, and/or hazard potential can be achieved through different policy and action choices over time until limits to adaptation might be reached. The figure builds on the conceptual framework of risk used in AR5 (for more details see Cross-Chapter Box 2 in Chapter 1).

the drivers of those changes, and the risks to marine, coastal, polar and mountain ecosystems, occur on spatial and temporal scales that may not align within existing governance structures and practices (*medium confidence*). This report highlights the requirements for transformative governance, international and transboundary cooperation, and greater empowerment of local communities in the governance of the ocean, coasts, and cryosphere in a changing climate. {1.5, 1.7, Cross-Chapter Box 2 in Chapter 1, Cross-Chapter Box 3 in Chapter 1}

Robust assessments of ocean and cryosphere change, and the development of context-specific governance and response options, depend on utilising and strengthening all available knowledge systems (*high confidence*). Scientific knowledge from observations, models and syntheses provides global to local scale understandings of climate change (*very high confidence*). Indigenous knowledge (IK) and local knowledge (LK) provide context-specific and socio-culturally relevant understandings for effective responses and policies (*medium confidence*). Education and climate literacy enable climate action and adaptation (*high confidence*). {1.8, Cross-Chapter Box 4 in Chapter 1}

Long-term sustained observations and continued modelling are critical for detecting, understanding and predicting ocean and cryosphere change, providing the knowledge to inform risk assessments and adaptation planning (*high confidence*). Knowledge gaps exist in scientific knowledge for important regions, parameters and processes of ocean and cryosphere change, including for physically plausible, high impact changes like high end sea level rise scenarios that would be costly if realised without effective adaptation planning and even then may exceed limits to adaptation. Means such as expert judgement, scenario building, and invoking multiple lines of evidence enable comprehensive risk assessments even in cases of uncertain future ocean and cryosphere changes. {1.8.1, 1.9.2, Cross-Chapter Box 5 in Chapter 1}

TS.2 High Mountain Areas

The cryosphere (including, snow, glaciers, permafrost, lake and river ice) is an integral element of high mountain regions, which are home to roughly 10% of the global population. Widespread cryosphere changes affect physical, biological and human systems in the mountains and surrounding lowlands, with impacts evident even in the ocean. Building on the IPCC's 5th Assessment Report (AR5), this chapter assesses new evidence on observed recent and projected changes in the mountain cryosphere as well as associated impacts, risks and adaptation measures related to natural and human systems. Impacts in response to climate changes independently of changes in the cryosphere are not assessed in this chapter. Polar mountains are included in Chapter 3, except those in Alaska and adjacent Yukon, Iceland and Scandinavia, which are included in this chapter.

Observations of cryospheric changes, impacts, and adaptation in high mountain areas

Observations show general decline in low-elevation snow cover (*high confidence*) glaciers (*very high confidence*) and permafrost (*high confidence*) due to climate change in recent decades. Snow cover duration has declined in nearly all regions, especially at lower elevations, on average by 5 days per decade, with a *likely* range from 0–10 days per decade. Low elevation snow depth and extent have declined, although year-to-year variation is high. Mass change of glaciers in all mountain regions (excluding the Canadian and Russian Arctic, Svalbard, Greenland and Antarctica) was *very likely* –490 ± 100 kg m^{-2} yr^{-1} (–123 ± 24 Gt yr^{-1}) in 2006–2015. Regionally averaged mass budgets were *likely* most negative (less than –850 kg m^{-2} yr^{-1}) in the southern Andes, Caucasus and the European Alps/Pyrenees, and least negative in High Mountain Asia (–150 ± 110 kg m^{-2} yr^{-1}) but variations within regions are strong. Between 3.6–5.2 million km^2 are underlain by permafrost in the eleven high mountain regions covered in this chapter corresponding to 27–29% of the global permafrost area (*medium confidence*). Sparse and unevenly distributed measurements show an increase in permafrost temperature (*high confidence*), for example, by 0.19°C ± 0.05°C on average for about 28 locations in the European Alps, Scandinavia, Canada and Asia during the past decade. Other observations reveal decreasing permafrost thickness and loss of ice in the ground. {2.2.2, 2.2.3, 2.2.4, Figure TS.5}

Glacier, snow and permafrost decline has altered the frequency, magnitude and location of most related natural hazards (*high confidence*). Exposure of people and infrastructure to natural hazards has increased due to growing population, tourism and socioeconomic development (*high confidence*). Glacier retreat and permafrost thaw have decreased the stability of mountain slopes and the integrity of infrastructure (*high confidence*). The number and area of glacier lakes has increased in most regions in recent decades (*high confidence*), but there is only *limited evidence* that the frequency of glacier lake outburst floods (GLOF) has changed. In some regions, snow avalanches involving wet snow have increased (*medium confidence*), and rain-on-snow floods have decreased at low elevations in spring and increased at high elevations in winter (*medium confidence*). The number and extent of wildfires have increased in the Western USA partly due to early snowmelt (*medium confidence*). {2.3.2, 2.3.3}

Changes in snow and glaciers have changed the amount and seasonality of runoff in snow-dominated and glacier-fed river basins (*very high confidence*) with local impacts on water resources and agriculture (*medium confidence*). Winter runoff has increased in recent decades due to more precipitation falling as rain (*high confidence*). In some glacier-fed rivers, summer and annual runoff have increased due to intensified glacier melt, but decreased where glacier melt water has lessened as glacier area shrinks. Decreases were observed especially in regions dominated by small glaciers, such as the European Alps (*medium confidence*). Glacier retreat and snow cover changes have contributed to localized declines in agricultural yields in some high mountain regions, including the Hindu Kush Himalaya and the tropical Andes (*medium confidence*).

There is *limited evidence* of impacts on operation and productivity of hydropower facilities resulting from changes in seasonality and both increases and decreases in water input, for example, in the European Alps, Iceland, Western Canada and USA, and the tropical Andes. {2.3.1}

Species composition and abundance have markedly changed in high mountain ecosystems in recent decades (*very high confidence*), partly due to changes in the cryosphere (*high confidence*). Habitats for establishment by formerly absent species have opened up or been altered by reduced snow cover (*high confidence*), retreating glaciers (*very high confidence*), and thawing of permafrost (*medium confidence*). Reductions in glacier and snow cover have directly altered the structure of many freshwater communities (*high confidence*). Reduced snow cover has negatively impacted the reproductive fitness of some snow-dependent plant and animal species, including foraging and predator-prey relationships of mammals (*high confidence*). Upslope migration of individual species, mostly due to warming and to a lesser extent due to cryosphere-related changes, has often increased local species richness (*very high confidence*). Some cold-adapted species, including endemics, in terrestrial and freshwater communities have declined in abundance (*high confidence*). While the plant productivity has generally increased, the actual impact on provisioning, regulating and cultural ecosystem services varies greatly (*high confidence*). {2.3.3}

Tourism and recreation activities such as skiing, glacier tourism and mountaineering have been negatively impacted by declining snow cover, glaciers and permafrost (*medium confidence*). In several regions, worsening route safety has reduced mountaineering opportunities (*medium confidence*). Variability and decline in natural snow cover have compromised the operation of low-elevation ski resorts (*high confidence*). Glacier and snow decline have impacted aesthetic, spiritual and other cultural aspects of mountain landscapes (*medium confidence*), reducing the well-being of people (e.g., in the Himalaya, eastern Africa, and the tropical Andes). {2.3.5, 2.3.6}

Adaptation in agriculture, tourism and drinking water supply has aimed to reduce the impacts of cryosphere change (*medium confidence*), though there is *limited evidence* on their effectiveness owing to a lack of formal evaluations, or technical, financial and institutional barriers to implementation. In some places, artificial snowmaking has reduced the negative impacts on ski tourism (*medium confidence*). Release and storage of water from reservoirs according to sectoral needs (agriculture, drinking water, ecosystems) has reduced the impact of seasonal variability on runoff (*medium confidence*). {2.3.1, 2.3.5}

Future projections of cryospheric changes, their impacts and risks, and adaptation in high mountain areas

Snow cover, glaciers and permafrost are projected to continue to decline in almost all regions throughout the 21st century (*high confidence*). Compared to 1986–2005, low elevation snow depth will *likely* decrease by 10–40% for 2031–2050, regardless of Representative Concentration Pathway (RCP) and for 2081–2100, *likely* by 10–40 % for RCP2.6 and by 50–90% for RCP8.5. Projected glacier mass reductions between 2015–2100 are *likely* 22–44% for RCP2.6 and 37–57% for RCP8.5. In regions with mostly smaller glaciers and relatively little ice cover (e.g., European Alps, Pyrenees, Caucasus, North Asia, Scandinavia, tropical Andes, Mexico, eastern Africa and Indonesia), glaciers will lose more than 80% of their current mass by 2100 under RCP8.5 (*medium confidence*), and many glaciers will disappear regardless emission scenario (*very high confidence*). Permafrost thaw and degradation will increase during the 21st century (*very high confidence*) but quantitative projections are scarce. {2.2.2, 2.2.3, 2.2.4}

Most types of natural hazards are projected to change in frequency, magnitude and areas affected as the cryosphere continues to decline (*high confidence*). Glacier retreat and permafrost thaw are projected to decrease the stability of mountain slopes and increase the number and area of glacier lakes (*high confidence*). Resulting landslides and floods, and cascading events, will also emerge where there is no record of previous events (*high confidence*). Snow avalanches are projected to decline in number and runout distance at lower elevation, and avalanches involving wet snow even in winter will occur more frequently (*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, 2.3.3}

River runoff in snow dominated and glacier-fed river basins will change further in amount and seasonality in response to projected snow cover and glacier decline (*very high confidence*) with negative impacts on agriculture, hydropower and water quality in some regions (*medium confidence*). The average winter snowmelt runoff is projected to increase (*high confidence*), and spring peaks to occur earlier (*very high confidence*). Projected trends in annual runoff vary substantially among regions, and can even be opposite in direction, but there is *high confidence* that in all regions average annual runoff from glaciers will have reached a peak that will be followed by declining runoff at the latest by the end of the 21st century. Declining runoff is expected to reduce the productivity of irrigated agriculture in some regions (*medium confidence*). 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}

Current trends in cryosphere-related changes in high mountain ecosystems are expected to continue and impacts to intensify (*very high confidence*). While high mountains will provide new and greater habitat area, including refugia for lowland species, both range expansion and shrinkage are projected, and at high elevations this will lead to population declines (*high confidence*). The latter increases the risk of local extinctions, in particular for freshwater cold-adapted species (*medium confidence*). Without genetic plasticity and/or behavioural shifts, cryospheric changes will continue to negatively impact endemic and native species, such as some coldwater fish (e.g., trout) and species whose traits directly depend on snow (e.g., snowshoe hares) or many large mammals (*medium confidence*). The survival of such species will depend on appropriate conservation and adaptation measures (*medium confidence*). Many projected ecological changes will alter ecosystem services (*high confidence*), affecting ecological disturbances (e.g., fire, rock fall, slope erosion) with considerable impacts on people (*medium confidence*). {2.3.3}

Cultural assets, such as snow- and ice-covered peaks in many UNESCO World Heritage sites, and tourism and recreation activities, are expected to be negatively affected by future cryospheric change in many regions (*high confidence*). Current snowmaking technologies are projected to be less effective in a warmer climate in reducing risks to ski tourism in most parts of Europe, North America and Japan, in particular at 2°C global warming and beyond (*high confidence*). Diversification through year-round activities supports adaptation of tourism under future climate change (*medium confidence*). {2.3.5, 2.3.6}

Enablers and response options to promote adaptation and sustainable development in high mountain areas

The already committed and unavoidable climate change affecting all cryosphere elements, irrespective of the emission scenario, points to integrated adaptation planning to support and enhance water availability, access, and management (*medium confidence*). Integrated management approaches for water across all scales, in particular for energy, agriculture, ecosystems and drinking water supply, can be effective at dealing with impacts from changes in the cryosphere. These approaches also offer opportunities to support social-ecological systems, through the development and optimisation of storage and the release of water from reservoirs (*medium confidence*), while being cognisant of potential negative implications for some ecosystems. Success in implementing such management options depends on the participation of relevant stakeholders, including affected communities, diverse knowledge and adequate tools for monitoring and projecting future conditions, and financial and institutional resources to support planning and implementation (*medium confidence*). {2.3.1, 2.3.3, 2.4}

Effective governance is a key enabler for reducing disaster risk, considering relevant exposure factors such as planning, zoning, and urbanisation pressures, as well as vulnerability factors such as poverty, which can challenge efforts towards resilience and sustainable development for communities (*medium confidence*). Reducing losses to disasters depend on integrated and coordinated approaches to account for the hazards concerned, the degree of exposure, and existing vulnerabilities. Diverse knowledge that includes community and multi-stakeholder experience with past impacts complements scientific knowledge to anticipate future risks. {Cross-Chapter Box 2 in Chapter 1, 2.3.2, 2.4}

International cooperation, treaties and conventions exist for some mountain regions and transboundary river basins with potential to support adaptation action. However, there is *limited evidence* on the extent to which impacts and losses arising from changes in the cryosphere are specifically monitored and addressed in these frameworks. A wide range of institutional arrangements and practices have emerged over the past three decades that respond to a shared global mountain agenda and specific regional priorities. There is potential to strengthen them to also respond to climate-related cryosphere risks and open opportunities for development through adaptation (*limited evidence, high agreement*). The Sustainable Development Goals (SDGs), Sendai Framework and Paris Agreement have directed some attention in mountain-specific research and practice towards the monitoring and reporting on targets and indicators specified therein. {2.3.1, 2.4}

Figure TS.5 (next pages) | Synthesis of observed regional hazards and impacts in ocean[5] (top) and high mountain and polar land regions (bottom) assessed in SROCC. The same data are shown in different formats in **(a)** and **(b).** For each region, physical changes, impacts on key ecosystems, and impacts on human systems and ecosystem function and services are shown. For physical changes, yellow/green refers to an increase/decrease, respectively, in amount or frequency of the measured variable. For impacts on ecosystems, human systems and ecosystems services blue or red depicts whether an observed impact is positive (beneficial) or negative (adverse), respectively, to the given system or service. Cells assigned 'increase and decrease' indicate that within that region, both increase and decrease of physical changes are found, but are not necessarily equal; the same holds for cells showing 'positive and negative' attributable impacts. For ocean regions, the confidence level refers to the confidence in attributing observed changes to changes in greenhouse gas forcing for physical changes and to climate change for ecosystem, human systems, and ecosystem services. For high mountain and polar land regions, the level of confidence in attributing physical changes and impacts at least partly to a change in the cryosphere is shown. No assessment means: not applicable, not assessed at regional scale, or the evidence is insufficient for assessment. The physical changes in the ocean are defined as: Temperature change in 0–700 m layer of the ocean except for Southern Ocean (0–2000 m) and Arctic Ocean (upper mixed layer and major inflowing branches); Oxygen in the 0–1200 m layer or oxygen minimum layer; Ocean pH as surface pH (decreasing pH corresponds to increasing ocean acidification). Ecosystems in the ocean: Coral refers to warm-water coral reefs and cold-water corals. The 'upper water column' category refers to epipelagic zone for all ocean regions except Polar Regions, where the impacts on some pelagic organisms in open water deeper than the upper 200 m were included. Coastal wetland includes salt marshes, mangroves and seagrasses. Kelp forests are habitats of a specific group of macroalgae. Rocky shores are coastal habitats dominated by immobile calcified organisms such as mussels and barnacles. Deep sea is seafloor ecosystems that are 3000–6000 m deep. Sea-ice associated includes ecosystems in, on and below sea ice. Habitat services refer to supporting structures and services (e.g., habitat, biodiversity, primary production). Coastal Carbon Sequestration refers to the uptake and storage of carbon by coastal blue carbon ecosystems. Ecosystems on Land: Tundra refers to tundra and alpine meadows, and includes terrestrial Antarctic ecosystems. Migration refers to an increase or decrease in net migration, not to beneficial/adverse value. Impacts on tourism refer to the operating conditions for the tourism sector. Cultural services include cultural identity, sense of home, and spiritual, intrinsic and aesthetic values, as well as contributions from glacier archaeology. The underlying information is given for land regions in tables SM2.6, SM2.7, SM2.8, SM3.8, SM3.9, and SM3.10, and for ocean regions in tables SM5.10, SM5.11, SM3.8, SM3.9, and SM3.10. {2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.3.5, 2.3.6, 2.3.7, Figure 2.1, 3.2.1, 3.2.3, 3.2.4, 3.3.3, 3.4.1, 3.4.3, 3.5.2, Box 3.4, 4.2.2, 5.2.2, 5.2.3, 5.3.3, 5.4, 5.6, Figure 5.24, Box 5.3}

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[5] Marginal seas are not assessed individually as ocean regions in this report.

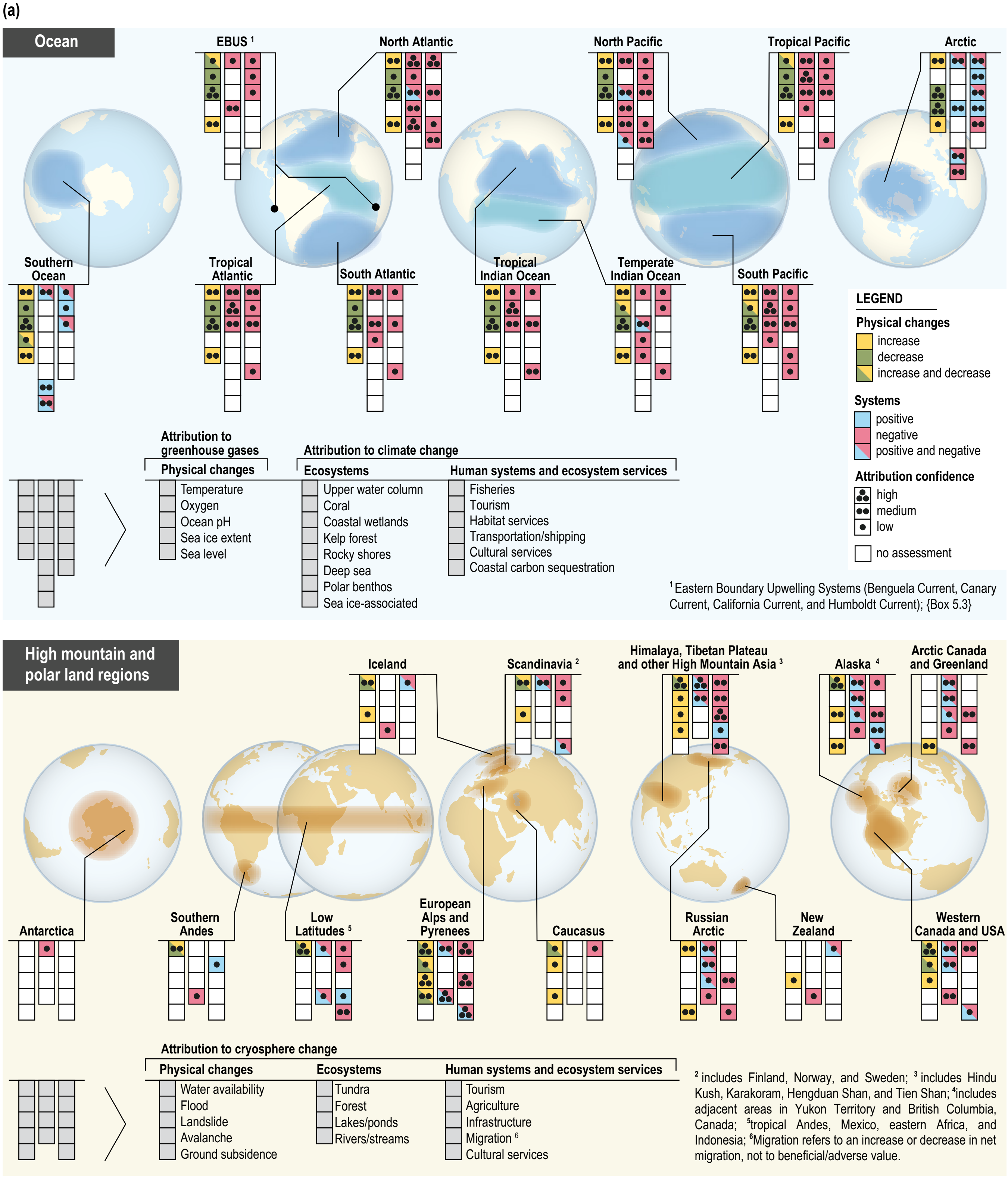
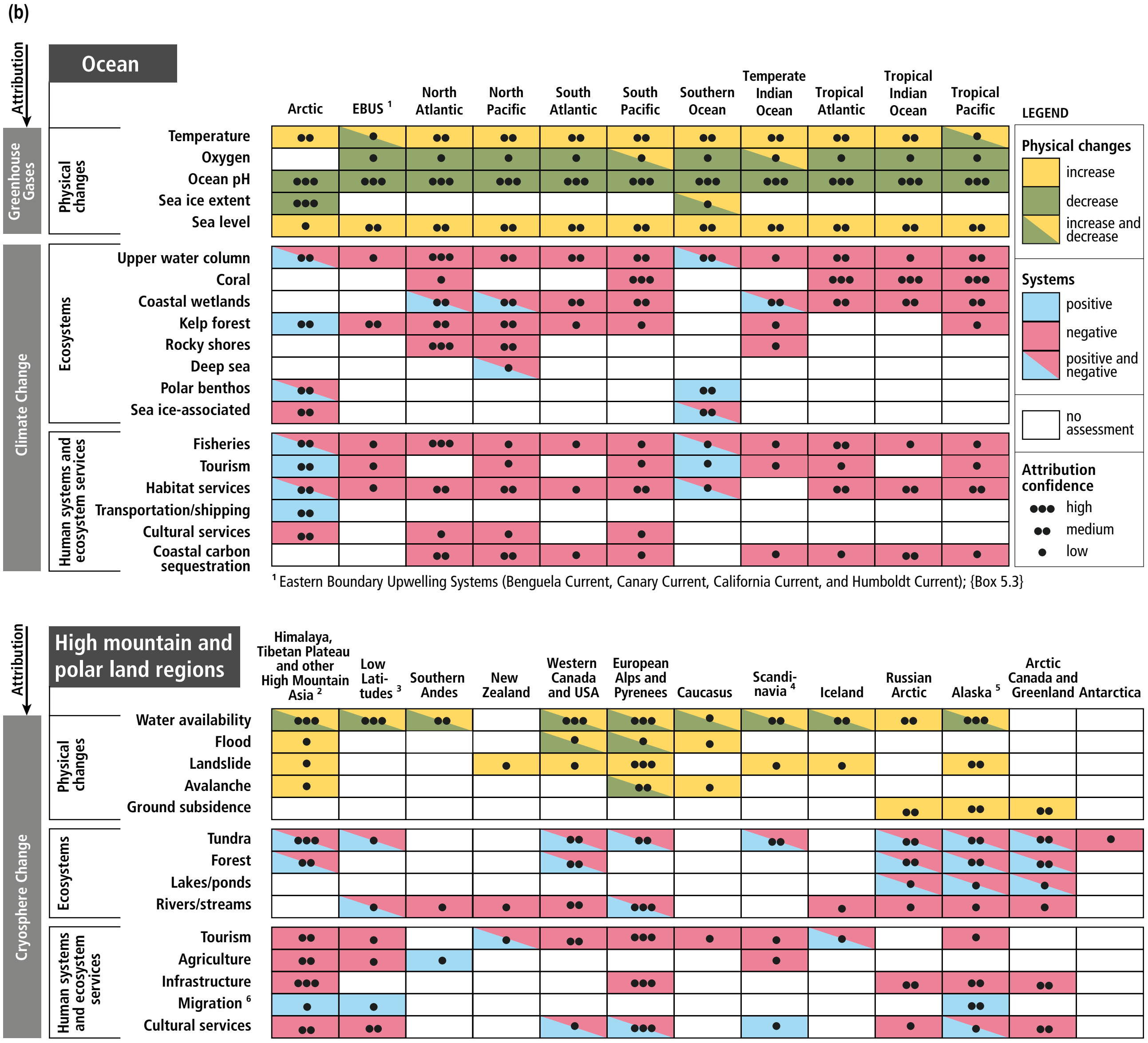

(a)
Ocean
EBUS ¹
North Atlantic
North Pacific
Tropical Pacific
Arctic
Southern Ocean
Tropical Atlantic
South Atlantic
Tropical Indian Ocean
Temperate Indian Ocean
South Pacific
LEGEND
Physical changes
increase
decrease
increase and decrease
Systems
positive
negative
positive and negative
Attribution confidence
high
medium
low
no assessment
Attribution to greenhouse gases
Attribution to climate change
Physical changes
Temperature
Oxygen
Ocean pH
Sea ice extent
Sea level
Ecosystems
Upper water column
Coral
Coastal wetlands
Kelp forest
Rocky shores
Deep sea
Polar benthos
Sea ice-associated
Human systems and ecosystem services
Fisheries
Tourism
Habitat services
Transportation/shipping
Cultural services
Coastal carbon sequestration
¹ Eastern Boundary Upwelling Systems (Benguela Current, Canary Current, California Current, and Humboldt Current); {Box 5.3}
High mountain and polar land regions
Iceland
Scandinavia ²
Himalaya, Tibetan Plateau and other High Mountain Asia ³
Alaska ⁴
Arctic Canada and Greenland
Antarctica
Southern Andes
Low Latitudes ⁵
European Alps and Pyrenees
Caucasus
Russian Arctic
New Zealand
Western Canada and USA
Attribution to cryosphere change
Physical changes
Water availability
Flood
Landslide
Avalanche
Ground subsidence
Ecosystems
Tundra
Forest
Lakes/ponds
Rivers/streams
Human systems and ecosystem services
Tourism
Agriculture
Infrastructure
Migration ⁶
Cultural services
² includes Finland, Norway, and Sweden; ³ includes Hindu Kush, Karakoram, Hengduan Shan, and Tien Shan; ⁴includes adjacent areas in Yukon Territory and British Columbia, Canada; ⁵tropical Andes, Mexico, eastern Africa, and Indonesia; ⁶Migration refers to an increase or decrease in net migration, not to beneficial/adverse value.

Figure TS.5 | a



[1] Eastern Boundary Upwelling Systems (Benguela Current, Canary Current, California Current, and Humboldt Current); {Box 5.3}

[2] includes Hindu Kush, Karakoram, Hengduan Shan, and Tien Shan; [3] tropical Andes, Mexico, eastern Africa, and Indonesia; [4] includes Finland, Norway, and Sweden; [5] includes adjacent areas in Yukon Territory and British Columbia, Canada; [6] Migration refers to an increase or decrease in net migration, not to beneficial/adverse value.

Figure TS.5 | b

TS.3 Polar Regions

This chapter assesses the state of physical, biological and social knowledge concerning the Arctic and Antarctic ocean and cryosphere, how they are affected by climate change, and how they will evolve in future. Concurrently, it assesses the local, regional and global consequences and impacts of individual and interacting polar system changes, and it assesses response options to reduce risk and build resilience in the polar regions. Key findings are:

The polar regions are losing ice, and their oceans are changing rapidly. The consequences of this polar transition extend to the whole planet, and are affecting people in multiple ways.

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. For each of the five years since the IPCC 5th Asesssment Report (AR5) (2014–2018), Arctic annual surface air temperature exceeded that of any year since 1900. During the winters (January to March) of 2016 and 2018, surface temperatures in the central Arctic were 6°C above the 1981–2010 average, contributing to unprecedented regional sea ice absence. These trends and extremes provide *medium evidence* with *high agreement* of the contemporary coupled atmosphere-cryosphere system moving well outside the 20th century envelope. {Box 3.1, 3.2.1.1}

The Arctic and Southern Oceans are continuing to remove carbon dioxide from the atmosphere and to acidify (*high confidence*). There is *medium confidence* that the amount of CO_2 drawn into the Southern Ocean from the atmosphere has experienced significant decadal variations since the 1980s. Rates of calcification (by which marine organisms form hard skeletons and shells) declined in the Southern Ocean by 3.9 ± 1.3% between 1998 and 2014. In the Arctic Ocean, the area corrosive to organisms that form shells and skeletons using the mineral aragonite expanded between the 1990s and 2010, with instances of extreme aragonite undersaturation. {3.2.1.2.4}

Both polar oceans have continued to warm in recent years, with the Southern Ocean being disproportionately and increasingly important in global ocean heat increase (*high confidence*). Over large sectors of the seasonally ice-free Arctic, summer upper mixed layer temperatures increased at around 0.5ºC per decade during 1982–2017, primarily associated with increased absorbed solar radiation accompanying sea ice loss, and the inflow of ocean heat from lower latitude increased since the 2000s (*high confidence*). During 1970–2017, the Southern Ocean south of 30ºS accounted for 35–43% of the global ocean heat gain in the upper 2000 m (*high confidence*), despite occupying ~25% of the global ocean area. In recent years (2005–2017), the Southern Ocean was responsible for an increased proportion of the global ocean heat increase (45–62%) (*high confidence*). {3.2.1.2.1, Figure TS.5}

Climate-induced changes in seasonal sea ice extent and thickness and ocean stratification are altering marine primary production (*high confidence*), with impacts on ecosystems (*medium confidence*). Changes in the timing, duration and intensity of primary production have occurred in both polar oceans, with marked regional or local variability (*high confidence*). In the Antarctic, such changes have been associated with locally-rapid environmental change, including retreating glaciers and sea ice change (*medium confidence*). In the Arctic, changes in primary production have affected regional species composition, spatial distribution, and abundance of many marine species, impacting ecosystem structure (*medium confidence*). {3.2.1, 3.2.3, 3.2.4}

In both polar regions, climate-induced changes in ocean and sea ice, together with human introduction of non-native species, have expanded the range of temperate species and contracted the range of polar fish and ice-associated species (*high confidence*). Commercially and ecologically important fish stocks like Atlantic cod, haddock and mackerel have expanded their spatial distributions northwards many hundreds of kilometres, and increased their abundance. In some Arctic areas, such expansions have affected the whole fish community, leading to higher competition and predation on smaller sized fish species, while some commercial fisheries have benefited. There has been a southward shift in the distribution of Antarctic krill in the South Atlantic, the main area for the krill fishery (*medium confidence*). These changes are altering biodiversity in polar marine ecosystems (*medium confidence*). {3.2.3, Box 3.4}

Arctic sea ice extent continues to decline in all months of the year (*very high confidence*); the strongest reductions in September (*very likely* –12.8 ± 2.3% per decade; 1979–2018) are unprecedented in at least 1000 years (*medium confidence*). 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% (*very high confidence*). Approximately half the observed sea ice loss is attributable to increased atmospheric greenhouse gas concentrations (*medium confidence*). Changes in Arctic sea ice have potential to influence mid-latitude weather on timescales of weeks to months (*low to medium confidence*). {3.2.1.1, Box 3.2}

It is *very likely* that Antarctic sea ice cover exhibits no significant trend over the period of satellite observations (1979–2018). While the drivers of historical decadal variability are known with *medium confidence,* there is currently *limited evidence* and *low agreement* concerning causes of the strong recent decrease (2016–2018), and *low confidence* in the ability of current-generation climate models to reproduce and explain the observations. {3.2.1.1}

Shipping activity during the Arctic summer increased over the past two decades in regions for which there is information, concurrent with reductions in sea ice extent (*high confidence*). Transit times across the Northern Sea Route have shortened due to lighter ice conditions, and while long-term, pan-Arctic datasets are incomplete, the distance travelled by ships in Arctic Canada nearly tripled during 1990–2015 (*high confidence*). Greater levels of Arctic ship-based transportation and tourism have socioeconomic and political implications for global trade, northern nations, and economies linked to traditional shipping corridors; they will also exacerbate region specific risks for marine ecosystems and coastal communities if further action to develop and adequately implement regulations does not keep pace with increased shipping (*high confidence*). {3.2.1.1, 3.2.4.2, 3.2.4.3, 3.4.3.3.2, 3.5.2.7}

Permafrost temperatures have increased to record high levels (*very high confidence*), but there is *medium evidence* and *low agreement* that this warming is currently causing northern permafrost regions to release additional methane and carbon dioxide. During 2007–2016, continuous-zone permafrost temperatures in the Arctic and Antarctic increased by 0.39 ± 0.15ºC and 0.37 ± 0.10ºC respectively. Arctic and boreal permafrost region soils contain 1460–1600 Gt organic carbon (*medium confidence*). Changes in permafrost influence global climate through emissions of carbon dioxide and methane released from the microbial breakdown of organic carbon, or the release of trapped methane. {3.4.1, 3.4.3}

Climate-related changes to Arctic hydrology, wildfire and abrupt thaw are occurring (*high confidence*), with impacts on vegetation and water and food security. Snow and lake ice cover has declined, with June snow extent decreasing 13.4 ± 5.4% per decade (1967–2018) (*high confidence*). Runoff into the Arctic Ocean increased for Eurasian and North American rivers by 3.3 ± 1.6% and 2.0 ± 1.8% respectively (1976–2017; *medium confidence*). Area burned and frequency of fires (including extreme fires) are unprecedented over the last 10,000 years (*high confidence*). There has been an overall greening of the tundra biome, but also browning in some regions of tundra and boreal forest, and changes in the abundance and distribution of animals including reindeer and salmon (*high confidence*). Together, these impact access to (and food availability within) herding, hunting, fishing, forage and gathering areas, affecting the livelihood, health and cultural identity of residents including Indigenous peoples (*high confidence*). {3.4.1, 3.4.3, 3.5.2}

Limited knowledge, financial resources, human capital and organisational capacity are constraining adaptation in many human sectors in the Arctic (*high confidence*). Harvesters of renewable resources are adjusting timing of activities to changes in seasonality and less safe ice travel conditions. Municipalities and industry are addressing infrastructure failures associated with flooding and thawing permafrost, and coastal communities and cooperating agencies are in some cases planning for relocation (*high confidence*). In spite of these adaptations, many groups are making decisions without adequate knowledge to forecast near- and long-term conditions, and without the funding, skills and institutional support to engage fully in planning processes (*high confidence*). {3.5.2, 3.5.4, Cross-Chapter Box 9}

It is *extremely likely* that the rapid ice loss from the Greenland and Antarctic ice sheets during the early 21st century has increased into the near present day, adding to the ice sheet contribution to global sea level rise. From Greenland, the 2012–2016 ice losses (–247 ± 15 Gt yr^{-1}) were similar to those from 2002 to 2011 (–263 ± 21 Gt yr^{-1}) and *extremely likely* greater than from 1992 to 2001 (–8 ± 82 Gt yr^{-1}). Summer melting of the Greenland Ice Sheet (GIS) has increased since the 1990s (*very high confidence*) to a level unprecedented over at least the last 350 years, and two-to-fivefold the pre-industrial level (*medium confidence*). From Antarctica, the 2012–2016 losses (–199 ± 26 Gt yr^{-1}) were *extremely likely* greater than those from 2002 to 2011 (–82 ± 27 Gt yr^{-1}) and *likely* greater than from 1992 to 2001 (–51 ± 73 Gt yr^{-1}). Antarctic ice loss is dominated by acceleration, retreat and rapid thinning of major West Antarctic Ice Sheet (WAIS) outlet glaciers (*very high confidence*), driven by melting of ice shelves by warm ocean waters (*high confidence*). The combined sea level rise contribution from both ice sheets for 2012–2016 was 1.2 ± 0.1 mm yr^{-1}, a 29% increase on the 2002–2011 contribution and a ~700% increase on the 1992–2001 period. {3.3.1}

Mass loss from Arctic glaciers (–212 ± 29 Gt yr^{-1}) during 2006–2015 contributed to sea level rise at a similar rate (0.6 ± 0.1 mm yr^{-1}) to the GIS (*high confidence*). Over the same period in Antarctic and subantarctic regions, glaciers separate from the ice sheets changed mass by –11 ± 108 Gt yr^{-1} (*low confidence*). {2.2.3, 3.3.2}

There is *limited evidence* and *high agreement* that recent Antarctic Ice Sheet (AIS) mass losses could be irreversible over decades to millennia. Rapid mass loss due to glacier flow acceleration in the Amundsen Sea Embayment (ASE) of West Antarctica and in Wilkes Land, East Antarctica, may indicate the beginning of Marine Ice Sheet Instability (MISI), but observational data are not yet sufficient to determine whether these changes mark the beginning of irreversible retreat. {3.3.1, Cross-Chapter Box 8 in Chapter 3, 4.2.3.1.2}

The polar regions will be profoundly different in future compared with today, and the degree and nature of that difference will depend strongly on the rate and magnitude of global climatic change*[6]*. This will challenge adaptation responses regionally and worldwide.

It is *very likely* that projected Arctic warming will result in continued loss of sea ice and snow on land, and reductions in the mass of glaciers. Important differences in the trajectories of loss emerge from 2050 onwards, depending on mitigation measures taken (*high confidence*). For stabilised global warming of 1.5°C, an approximately 1% chance of a given September being sea ice free at the end of century is projected; for stabilised warming at a 2°C increase, this rises to 10–35% (*high confidence*). The potential for reduced (further 5–10%) but stabilised Arctic autumn and spring snow extent by mid-century for Representative Concentration Pathway (RCP)2.6 contrasts with continued loss under RCP8.5 (a further 15–25% reduction to end of century) (*high confidence*). Projected mass reductions for polar glaciers between 2015 and 2100 range from 16 ± 7% for RCP2.6 to 33 ± 11% for RCP8.5 (*medium confidence*). {3.2.2, 3.3.2, 3.4.2, Cross-Chapter Box 6 in Chapter 2}

Both polar oceans will be increasingly affected by CO_2 uptake, causing conditions corrosive for calcium carbonate shell-producing organisms (*high confidence*), with associated impacts on marine organisms and ecosystems (*medium confidence*). It is *very likely* that both the Southern Ocean and the Arctic Ocean will experience year-round conditions of surface water undersaturation for mineral forms of calcium carbonate by 2100 under RCP8.5; under RCP2.6 the extent of undersaturated waters are reduced markedly. Imperfect representation of local processes and sea ice interaction in global climate models limit the ability to project the response of specific polar areas and the precise timing of undersaturation at seasonal scales. Differences in sensitivity and the scope for adaptation to projected levels of ocean acidification exist across a broad range of marine species groups. {3.2.1, 3.2.2.3, 3.2.3}

Future climate-induced changes in the polar oceans, sea ice, snow and permafrost will drive habitat and biome shifts, with associated changes in the ranges and abundance of ecologically important species (*medium confidence*). Projected shifts will include further habitat contraction and changes in abundance for polar species, including marine mammals, birds, fish, and Antarctic krill (*medium confidence*). Projected range expansion of subarctic marine species will increase pressure for high-Arctic species (*medium confidence*), with regionally variable impacts. Continued loss of Arctic multi-year sea ice will affect ice-related and pelagic primary production (*high confidence*), with impacts for whole ice-associated, seafloor and open ocean ecosystems. On Arctic land, projections indicate a loss of globally unique biodiversity as some high Arctic species will be outcompeted by more temperate species and very limited refugia exist (*medium confidence*). Woody shrubs and trees are projected to expand, covering 24–52% of the current tundra region by 2050. {3.2.2.1, 3.2.3, 3.2.3.1, Box 3.4, 3.4.2, 3.4.3}

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[6] Projections for ice sheets and glaciers in the polar regions are summarized in Chapters 4 and 2, respectively.

The projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial and subsistence fisheries with implications for regional economies, cultures and the global supply of fish, shellfish, and Antarctic krill (*high confidence*). Future impacts for linked human systems depend on the level of mitigation and especially the responsiveness of precautionary management approaches (*medium confidence*). Polar regions support several of the world's largest commercial fisheries. Specific impacts on the stocks and economic value in both regions will depend on future climate change and on the strategies employed to manage the effects on stocks and ecosystems (*medium confidence*). Under high emission scenarios current management strategies of some high-value stocks may not sustain current catch levels in the future (*low confidence*); this exemplifies the limits to the ability of existing natural resource management frameworks to address ecosystem change. Adaptive management that combines annual measures and within-season provisions informed by assessments of future ecosystem trends reduces the risks of negative climate change impacts on polar fisheries (*medium confidence*). {3.2.4, 3.5.2, 3.5.4}

Widespread disappearance of Arctic near-surface permafrost is projected to occur this century as a result of warming (*very high confidence*), with important consequences for global climate. By 2100, near-surface permafrost area will decrease by 2–66% for RCP2.6 and 30–99% for RCP8.5. This is projected to release 10s to 100s of billions of tons (Gt C), up to as much as 240 Gt C, of permafrost carbon as carbon dioxide and methane to the atmosphere with the potential to accelerate climate change. Methane will contribute a small proportion of these additional carbon emissions, on the order of 0.01–0.06 Gt CH_4 yr^{-1}, but could contribute 40–70% of the total permafrost-affected radiative forcing because of its higher warming potential. There is *medium evidence* but with *low agreement* whether the level and timing of increased plant growth and replenishment of soil will compensate these permafrost carbon losses. {3.4.2, 3.4.3}

Projected permafrost thaw and decrease in snow will affect Arctic hydrology and wildfire, with impacts on vegetation and human infrastructure (*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 (*medium confidence*). Fire is projected to increase for the rest of this century across most tundra and boreal regions, while interactions between climate and shifting vegetation will influence future fire intensity and frequency (*medium confidence*). By 2050, 70% of Arctic infrastructure is located in regions at risk from permafrost thaw and subsidence; 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*). {3.4.1, 3.4.2, 3.4.3, 3.5.2}

Response options exist that can ameliorate the impacts of polar change, build resilience and allow time for effective mitigation measures. Institutional barriers presently limit their efficacy.

Responding to climate change in polar regions will be more effective if attention to reducing immediate risks (short-term adaptation) is concurrent with long-term planning that builds resilience to address expected and unexpected impacts (*high confidence*). Emphasis on short-term adaptation to specific problems will ultimately not succeed in reducing the risks and vulnerabilities to society given the scale, complexity and uncertainty of climate change. Moving toward a dual focus of short- and long-term adaptation involves knowledge co-production, linking knowledge with decision making and implementing ecosystem-based stewardship, which involves the transformation of many existing institutions (*high confidence*). {3.5.4}

Innovative tools and practices in polar resource management and planning show strong potential in improving society's capacity to respond to climate change (*high confidence*). Networks of protected areas, participatory scenario analysis, decision support systems, community-based ecological monitoring that draws on local and indigenous knowledge, and self assessments of community resilience contribute to strategic plans for sustaining biodiversity and limit risk to human livelihoods and wellbeing. Such practices are most effective when linked closely to the policy process. Experimenting, assessing, and continually refining practices while strengthening the links with decision making has the potential to ready society for the expected and unexpected impacts of climate change (*high confidence*). {3.5.1, 3.5.2, 3.5.4}

Institutional arrangements that provide for strong multiscale linkages with Arctic local communities can benefit from including indigenous knowledge and local knowledge in the formulation of adaptation strategies (*high confidence*). The tightly coupled relationship of northern local communities and their environment provide an opportunity to better understand climate change and its effects, support adaptation and limit unintended consequences. Enabling conditions for the involvement of local communities in climate adaptation planning include investments in human capital, engagement processes for knowledge co-production and systems of adaptive governance. {3.5.3}

The capacity of governance systems in polar regions to respond to climate change has strengthened recently, but the development of these systems is not sufficiently rapid or robust to address the challenges and risks to societies posed by projected changes (*high confidence*). Human responses to climate change in the polar regions occur in a fragmented governance landscape. Climate change, new polar interests from outside the regions, and an increasingly active role played by informal organisations are compelling stronger coordination and integration between different levels and sectors of governance. The governance landscape is currently not sufficiently equipped to address cascading risks and uncertainty in an integrated and precautionary way within existing legal and policy frameworks (*high confidence*). {3.5.3, 3.5.4}

TS.4 Sea Level Rise and Implications for Low-lying Islands, Coasts and Communities

This chapter assesses past and future contributions to global, regional and extreme sea level changes, associated risk to low-lying islands, coasts, cities, and settlements, and response options and pathways to resilience and sustainable development along the coast.

Observations

Global mean sea level (GMSL) is rising (*virtually certain*) and accelerating (*high confidence*)[7]. The sum of glacier and ice sheet contributions is now the dominant source of GMSL rise (*very high confidence*). GMSL from tide gauges and altimetry observations increased from 1.4 mm yr^{-1} over the period 1901–1990 to 2.1 mm yr^{-1} over the period 1970–2015 to 3.2 mm yr^{-1} over the period 1993–2015 to 3.6 mm yr^{-1} over the period 2006–2015 (*high confidence*). The dominant cause of GMSL rise since 1970 is anthropogenic forcing (*high confidence*). {4.2.2.1.1, 4.2.2.2}

GMSL was considerably higher than today during past climate states that were warmer than pre-industrial, including the Last Interglacial (LIG; 129–116 ka), when global mean surface temperature was 0.5°C–1.0°C warmer, and the mid-Pliocene Warm Period (mPWP; ~3.3 to 3.0 million years ago), 2°C–4°C warmer. Despite the modest global warmth of the Last Interglacial, GMSL was *likely* 6–9 m higher, mainly due to contributions from the Greenland and Antarctic ice sheets (GIS and AIS, respectively), and *unlikely* more than 10m higher (*medium confidence*). Based on new understanding about geological constraints since the IPCC 5th Assessment Report (AR5), 25 m is a plausible upper bound on GMSL during the mPWP (*low confidence*). Ongoing uncertainties in palaeo sea level reconstructions and modelling hamper conclusions regarding the total magnitudes and rates of past sea level rise (SLR). Furthermore, the long (multi-millennial) time scales of these past climate and sea level changes, and regional climate influences from changes in Earth's orbital configuration and climate system feedbacks, lead to *low confidence* in direct comparisons with near-term future changes. {Cross-Chapter Box 5 in Chapter 1, 4.2.2, 4.2.2.1, 4.2.2.5, SM 4.1}

Non-climatic anthropogenic drivers, including recent and historical demographic and settlement trends and anthropogenic subsidence, have played an important role in increasing low-lying coastal communities' exposure and vulnerability to SLR and extreme sea level (ESL) events (*very high confidence*). In coastal deltas, for example, these drivers have altered freshwater and sediment availability (*high confidence*). In low-lying coastal areas more broadly, human-induced changes can be rapid and modify coastlines over short periods of time, outpacing the effects of SLR (*high confidence*). Adaptation can be undertaken in the short- to medium-term by targeting local drivers of exposure and vulnerability, notwithstanding uncertainty about local SLR impacts in coming decades and beyond (*high confidence*). {4.2.2.4, 4.3.1, 4.3.2.2, 4.3.2.3}

Coastal ecosystems are already impacted by the combination of SLR, other climate-related ocean changes, and adverse effects from human activities on ocean and land (*high confidence*). Attributing such impacts to SLR, however, remains challenging due to the influence of other climate-related and non-climatic drivers such as infrastructure development and human-induced habitat degradation (*high confidence*). Coastal ecosystems, including saltmarshes, mangroves, vegetated dunes and sandy beaches, can build vertically and expand laterally in response to SLR, though this capacity varies across sites (*high confidence*). These ecosystems provide important services that include coastal protection and habitat for diverse biota. However, as a consequence of human actions that fragment wetland habitats and restrict landward migration, coastal ecosystems progressively lose their ability to adapt to climate-induced changes and provide ecosystem services, including acting as protective barriers (*high confidence*). {4.3.2.3}

Coastal risk is dynamic and increased by widely observed changes in coastal infrastructure, community livelihoods, agriculture and habitability (*high confidence*). As with coastal ecosystems, attribution of observed changes and associated risk to SLR remains challenging. Drivers and processes inhibiting attribution include demographic, resource and land use changes and anthropogenic subsidence. {4.3.3, 4.3.4}

A diversity of adaptation responses to coastal impacts and risks have been implemented around the world, but mostly as a reaction to current coastal risk or experienced disasters (*high confidence*). Hard coastal protection measures (dikes, embankments, sea walls and surge barriers) are widespread, providing predictable levels of safety in northwest Europe, East Asia, and around many coastal cities and deltas. Ecosystem-based adaptation (EbA) is continuing to gain traction worldwide, providing multiple co-benefits, but there is still *low agreement* on its cost and long-term effectiveness. Advance, which refers to the creation of new land by building into the sea (e.g., land reclamation), has a long history in most areas where there are dense coastal populations. Accommodation measures, such as early warning systems (EWS) for ESL events, are widespread. Retreat is observed but largely restricted to small communities or carried out for the purpose of creating new wetland habitat. {4.4.2.3, 4.4.2.4, 4.4.2.5}

Projections

Future rise in GMSL caused by thermal expansion, melting of glaciers and ice sheets and land water storage changes, is strongly dependent on which Representative Concentration Pathway (RCP) emission scenario is followed. SLR at the end

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[7] Statements about uncertainty in Section 4.2 are contingent upon the RCP or other emissions assumptions that accompany them. In Section 4.4, the entirety of information facing a decision maker is taken into consideration, including the unknown path of future emissions, in assessing uncertainty. Depending on which perspective is chosen, uncertainty may or may not be characterised as 'deep'.

of the century is projected to be faster under all scenarios, including those compatible with achieving the long-term temperature goal set out in the Paris Agreement. GMSL will rise between 0.43 m (0.29–0.59 m, *likely* range; RCP2.6) and 0.84 m (0.61–1.10 m, *likely* range; RCP8.5) by 2100 (*medium confidence*) relative to 1986–2005. Beyond 2100, sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the GIS and AIS and will remain elevated for thousands of years (*high confidence*). Under RCP8.5, estimates for 2100 are higher and the uncertainty range larger than in AR5. Antarctica could contribute up to 28 cm of SLR (RCP8.5, upper end of *likely* range) by the end of the century (*medium confidence*). Estimates of SLR higher than the *likely* range are also provided here for decision makers with low risk tolerance. {SR1.5, 4.1, 4.2.3.2, 4.2.3.5}

Under RCP8.5, the rate of SLR will be 15 mm yr^{-1} (10–20 mm yr^{-1}, *likely* range) in 2100, and could exceed several cm yr^{-1} in the 22nd century. These high rates challenge the implementation of adaptation measures that involve a long lead time, but this has not yet been studied in detail. {4.2.3.2, 4.4.2.2.3}

Processes controlling the timing of future ice shelf loss and the spatial extent of ice sheet instabilities could increase Antarctica's contribution to SLR to values higher than the *likely* range on century and longer time scales (*low confidence*). Evolution of the AIS beyond the end of the 21st century is characterized by deep uncertainty as ice sheet models lack realistic representations of some of the underlying physical processes. The few model studies available addressing time scales of centuries to millennia indicate multi-metre (2.3–5.4 m) rise in sea level for RCP8.5 (*low confidence*). There is *low confidence* in threshold temperatures for ice sheet instabilities and the rates of GMSL rise they can produce. {Cross-Chapter Box 5 in Chapter 1, Cross-Chapter Box 8 in Chapter 3, and Sections 4.1, 4.2.3.1.1, 4.2.3.1.2, 4.2.3.6}

Sea level rise is not globally uniform and varies regionally. Thermal expansion, ocean dynamics and land ice loss contributions will generate regional departures of about ±30% around the GMSL rise. Differences from the global mean can be greater than ±30% in areas of rapid vertical land movements, including those caused by local anthropogenic factors such as groundwater extraction (*high confidence*). Subsidence caused by human activities is currently the most important cause of relative sea level rise (RSL) change in many delta regions. While the comparative importance of climate-driven RSL rise will increase over time, these findings on anthropogenic subsidence imply that a consideration of local processes is critical for projections of sea level impacts at local scales (*high confidence*). {4.2.1.6, 4.2.2.4}

Due to projected GMSL rise, ESLs that are historically rare (for example, today's hundred-year event) will become common by 2100 under all RCPs (*high confidence*). Many low-lying cities and small islands at most latitudes will experience such events annually by 2050. Greenhouse gas (GHG) mitigation envisioned in low-emission scenarios (e.g., RCP2.6) is expected to sharply reduce but not eliminate risk to low-lying coasts and islands from SLR and ESL events. Low-emission scenarios lead to slower rates of SLR and allow for a wider range of adaptation options. For the first half of the 21st century differences in ESL events among the scenarios are small, facilitating adaptation planning. {4.2.2.5, 4.2.3.4, Figure TS.6}

Non-climatic anthropogenic drivers will continue to increase the exposure and vulnerability of coastal communities to future SLR and ESL events in the absence of major adaptation efforts compared to today (*high confidence*). {4.3.4, Cross-Chapter Box 9}

The expected impacts of SLR on coastal ecosystems over the course of the century include habitat contraction, loss of functionality and biodiversity, and lateral and inland migration. Impacts will be exacerbated in cases of land reclamation and where anthropogenic barriers prevent inland migration of marshes and mangroves and limit the availability and relocation of sediment (*high confidence*). Under favourable conditions, marshes and mangroves have been found to keep pace with fast rates of SLR (e.g., >10 mm yr^{-1}), but this capacity varies significantly depending on factors such as wave exposure of the location, tidal range, sediment trapping, overall sediment availability and coastal squeeze (*high confidence*). {4.3.3.5.1}

In the absence of adaptation, more intense and frequent ESL events, together with trends in coastal development will increase expected annual flood damages by 2–3 orders of magnitude by 2100 (*high confidence*). However, well designed coastal protection is very effective in reducing expected damages and cost efficient for urban and densely populated regions, but generally unaffordable for rural and poorer areas (*high confidence*). Effective protection requires investments on the order of tens to several hundreds of billions of USD yr^{-1} globally (*high confidence*). While investments are generally cost efficient for densely populated and urban areas (*high confidence*), rural and poorer areas will be challenged to afford such investments with relative annual costs for some small island states amounting to several percent of GDP (*high confidence*). Even with well-designed hard protection, the risk of possibly disastrous consequences in the event of failure of defences remains. {4.3.4, 4.4.2.2, 4.4.3.2, Cross-Chapter Box 9}

Risk related to SLR (including erosion, flooding and salinisation) is expected to significantly increase by the end of this century along all low-lying coasts in the absence of major additional adaptation efforts (*very high confidence*). While only urban atoll islands and some Arctic communities are expected to experience moderate to high risk relative to today in a low emission pathway, almost high to very high risks are expected in all low-lying coastal settings at the upper end of the *likely* range for high emission pathways (*medium confidence*). However, the transition from moderate to high and from high to very high risk will vary from one coastal setting to another (*high confidence*). While a slower rate of SLR enables greater opportunities for adapting, adaptation benefits are also expected to vary between coastal settings. Although ambitious adaptation will not necessarily eradicate end-century SLR risk (*medium confidence*), it will help to buy time in many locations and therefore help to lay a robust foundation for adaptation beyond 2100. {4.1.3, 4.3.4, Box 4.1, SM4.2}

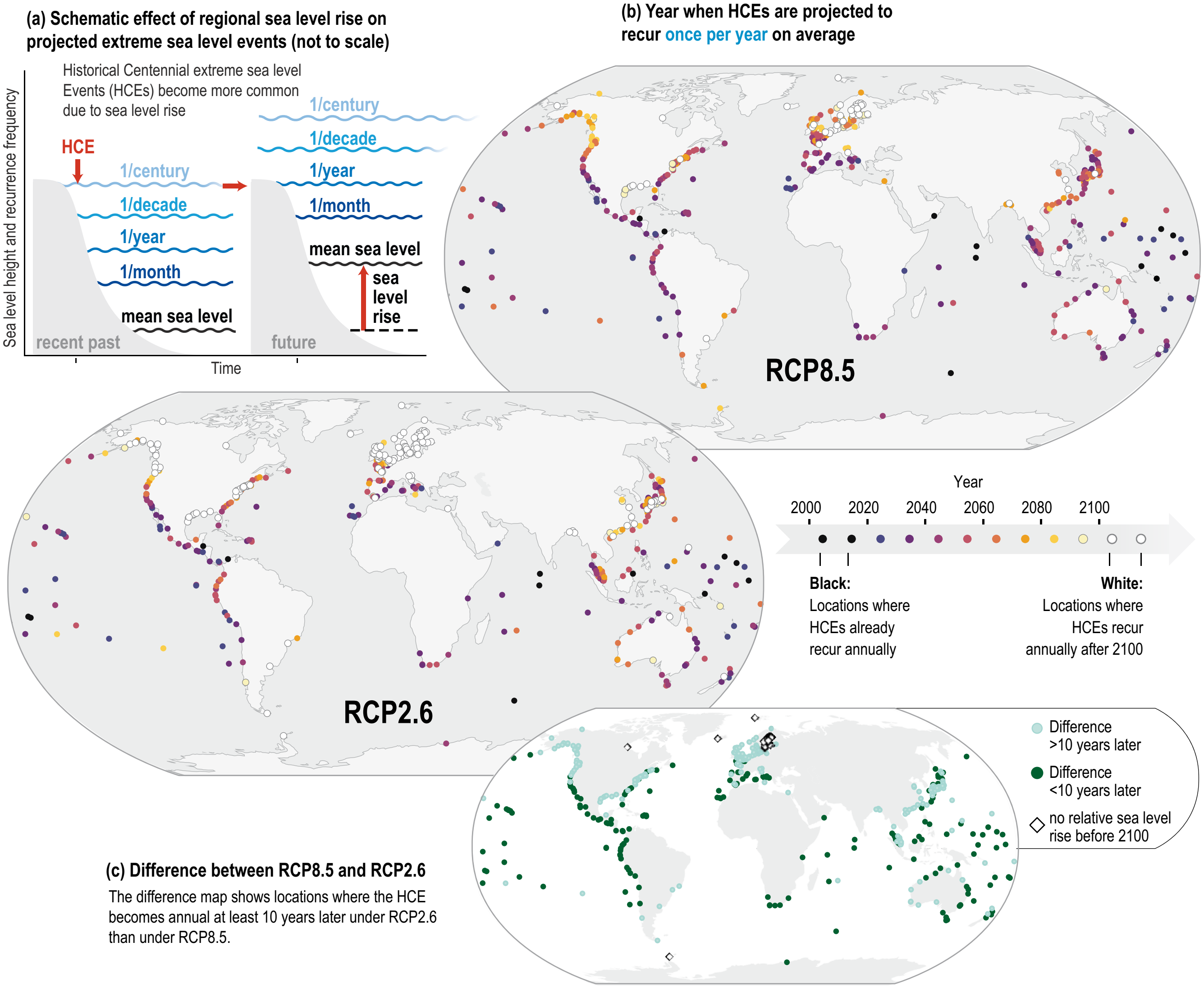


Figure TS.6 | The effect of regional sea level rise on extreme sea level events at coastal locations. Due to projected global mean sea level (GMSL) rise, local sea levels that historically occurred once per century (historical centennial events, HCEs) are projected to become at least annual events at most locations during the 21st century. The height of a HCE varies widely, and depending on the level of exposure can already cause severe impacts. Impacts can continue to increase with rising frequency of HCEs. **(a)** Schematic illustration of extreme sea level events and their average recurrence in the recent past (1986–2005) and the future. As a consequence of mean sea level rise, HCEs are projected to recur more frequently in the future. **(b)** The year in which HCEs are expected to recur once per year on average under RCP8.5 and RCP2.6, at the 439 individual coastal locations where the observational record is sufficient. The absence of a circle indicates an inability to perform an assessment due to a lack of data but does not indicate absence of exposure and risk. The darker the circle, the earlier this transition is expected. The likely range is ±10 years for locations where this transition is expected before 2100. White circles (33% of locations under RCP2.6 and 10% under RCP8.5) indicate that HCEs are not expected to recur once per year before 2100. **(c)** An indication at which locations this transition of HCEs to annual events is projected to occur more than 10 years later under RCP2.6 compared to RCP8.5. As the scenarios lead to small differences by 2050 in many locations results are not shown here for RCP4.5 but they are available in Chapter 4. {4.2.3, Figure 4.10, Figure 4.12}

Choosing and Implementing Responses

All types of responses to SLR, including protection, accommodation, EbA, advance and retreat, have important and synergistic roles to play in an integrated and sequenced response to SLR (*high confidence*). Hard protection and advance (building into the sea) are economically efficient in most urban contexts facing land scarcity (*high confidence*), but can lead to increased exposure in the long term. Where sufficient space is available, EbA can both reduce coastal risks and provide multiple other benefits (*medium confidence*). Accommodation such as flood proofing buildings and EWS for ESL events are often both low-cost and highly cost-efficient in all contexts (*high confidence*). Where coastal risks are already high, and population size and density are low, or in the aftermath of a coastal disaster, retreat may be especially effective, albeit socially, culturally and politically challenging. {4.4.2.2, 4.4.2.3, 4.4.2.4, 4.4.2.5, 4.4.2.6, 4.4.3}

Technical limits to hard protection are expected to be reached under high emission scenarios (RCP8.5) beyond 2100 (*high confidence*) and biophysical limits to EbA may arise during the 21st century, but economic and social barriers arise well before the end of the century (*medium confidence*). Economic challenges to hard protection increase with higher sea levels and will make adaptation unaffordable before technical limits are reached (*high confidence*). Drivers other than SLR are expected to contribute more to biophysical limits of EbA. For corals, limits may be reached during this century, due to ocean acidification and ocean warming, and for tidal wetlands due to pollution and infrastructure limiting their inland migration. Limits to accommodation are expected to occur well before limits to protection occur. Limits to retreat are uncertain, reflecting research gaps. Social barriers (including governance challenges) to adaptation are already encountered. {4.4.2.2, 4.4.2.3, 4.4.2.3.2, 4.4.2.5, 4.4.2.6, 4.4.3, Cross-Chapter Box 9}

Choosing and implementing responses to SLR presents society with profound governance challenges and difficult social choices, which are inherently political and value laden (*high confidence*). The large uncertainties about post 2050 SLR, and the substantial impact expected, challenge established planning and decision making practises and introduce the need for coordination within and between governance levels and policy domains. SLR responses also raise equity concerns about marginalising those most vulnerable and could potentially spark or compound social conflict (*high confidence*). Choosing and implementing responses is further challenged through a lack of resources, vexing trade-offs between safety, conservation and economic development, multiple ways of framing the 'sea level rise problem', power relations, and various coastal stakeholders having conflicting interests in the future development of heavily used coastal zones (*high confidence*). {4.4.2, 4.4.3}

Despite the large uncertainties about post 2050 SLR, adaptation decisions can be made now, facilitated by using decision analysis methods specifically designed to address uncertainty (*high confidence*). These methods favour flexible responses (i.e., those that can be adapted over time) and periodically adjusted decisions (i.e., adaptive decision making). They use robustness criteria (i.e., effectiveness across a range of circumstances) for evaluating alternative responses instead of standard expected utility criteria (*high confidence*). One example is adaptation pathway analysis, which has emerged as a low-cost tool to assess long-term coastal responses as sequences of adaptive decisions in the face of dynamic coastal risk characterised by deep uncertainty (*medium evidence, high agreement*). The range of SLR to be considered in decisions depends on the risk tolerance of stakeholders, with stakeholders whose risk tolerance is low also considering SLR higher than the *likely* range. {4.1, 4.4.4.3}

Adaptation experience to date demonstrates that using a locally appropriate combination of decision analysis, land use planning, public participation and conflict resolution approaches can help to address the governance challenges faced in responding to SLR (*high confidence*). Effective SLR responses depend, first, on taking a long-term perspective when making short-term decisions, explicitly accounting for uncertainty of locality-specific risks beyond 2050 (*high confidence*), and building governance capabilities to tackle the complexity of SLR risk (*medium evidence, high agreement*). Second, improved coordination of SLR responses across scales, sectors and policy domains can help to address SLR impacts and risk (*high confidence*). Third, prioritising consideration of 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 arenas for meaningful public deliberation and conflict resolution (*medium evidence, high agreement*). Finally, public awareness and understanding about SLR risks and responses can be improved by drawing on local, indigenous and scientific knowledge systems, together with social learning about locality-specific SLR risk and response potential (*high confidence*). {4.4.4.2, 4.4.5, Table 4.9, Figure TS.7}

Achieving the United Nations Sustainable Development Goals (SDGs) and charting Climate Resilient Development Pathways depends in part on ambitious and sustained mitigation efforts to contain SLR coupled with effective adaptation actions to reduce SLR impacts and risk (*medium evidence, high agreement*).

TS.5 Changing Ocean, Marine Ecosystems, and Dependent Communities

The ocean is essential for all aspects of human well-being and livelihood. It provides key services like climate regulation, through the energy budget, carbon cycle and nutrient cycle. The ocean is the home of biodiversity ranging from microbes to marine mammals that form a wide variety of ecosystems in open pelagic and coastal ocean.

Observations: Climate-related trends, impacts, adaptation

Carbon emissions from human activities are causing ocean warming, acidification and oxygen loss with some evidence of changes in nutrient cycling and primary production. The warming ocean is affecting marine organisms at multiple trophic levels, impacting fisheries with implications for food production and human communities. Concerns regarding the effectiveness of existing ocean and fisheries governance have already been reported, highlighting the need for timely mitigation and adaptation responses.

The ocean has warmed unabated since 2005, continuing the clear multi-decadal ocean warming trends documented in the IPCC Fifth Assessment Report (AR5). The warming trend is further confirmed by the improved ocean temperature measurements over the last decade. The 0–700 m and 700–2000 m layers of the ocean have warmed at rates of 5.31 ± 0.48 and 4.02 ± 0.97 ZJ yr^{-1} from 2005 to 2017. The long-term trend for 0–700 m and 700–2000 m layers have warmed 4.35 ± 0.8 and 2.25 ± 0.64 ZJ yr^{-1} from between the averages of 1971–1990 and 1998–2017 and is attributed to anthropogenic influences. It is *likely* the ocean warming has continued in the abyssal and deep ocean below 2000 m (southern hemisphere and Southern Ocean). {1.8.1, 1.2, 5.2.2}

It is *likely* that the rate of ocean warming has increased since 1993. The 0–700 m and 700–2000 m layers of the ocean have warmed by 3.22 ± 1.61 ZJ and 0.97 ± 0.64 ZJ from 1969 to 1993, and 6.28 ± 0.48 ZJ and 3.86 ± 2.09 ZJ from 1993 to 2017. This represents at least a two-fold increase in heat uptake. {Table 5.1, 5.2.2}

The upper ocean is *very likely* to have been stratifying since 1970. Observed warming and high-latitude freshening are making the surface ocean less dense over time relative to the deeper ocean (*high confidence*) and inhibiting the exchange between surface and deep waters. The upper 200 m stratification increase is in the *very likely* range of between 2.18–2.42% from 1970 to 2017. {5.2.2}

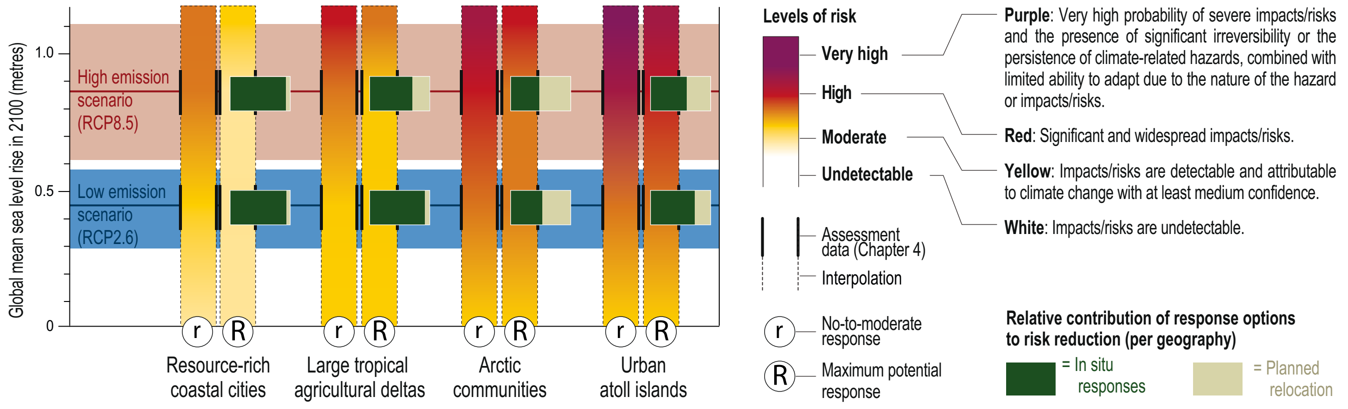
Multiple datasets and models show that the rate of ocean uptake of atmospheric CO_2 has continued to strengthen in the recent two decades in response to the increasing concentration of CO_2 in the atmosphere. The *very likely* range for ocean uptake is between 20–30% of total anthropogenic emissions in the recent two decades. Evidence is growing that the ocean carbon sink is dynamic on decadal timescales, especially in the Southern Ocean, which has affected the total global ocean carbon sink (*medium confidence*). {5.2.2.3}

The ocean is continuing to acidify in response to ongoing ocean carbon uptake. The open ocean surface water pH is observed to be declining (*virtually certain*) by a *very likely* range of 0.017–0.027 pH units per decade since the late 1980s across individual time series observations longer than 15 years. The anthropogenic pH signal is *very likely* to have emerged for three-quarters of the near-surface open ocean prior to 1950 and it is *very likely* that over 95% of the near surface open ocean has already been affected. These changes in pH have reduced the stability of mineral forms of calcium carbonate due to a lowering of carbonate ion concentrations, most notably in the upwelling and high-latitude regions of the ocean. {5.2.2.3, Box 5.1}

There is a growing consensus that the open ocean is losing oxygen overall with a *very likely* loss of 0.5–3.3% between 1970–2010 from the ocean surface to 1000 m (*medium confidence*). Globally, the oxygen loss due to warming is reinforced by

(a) Risk in 2100 under different sea level rise and response scenarios

Risk for illustrative geographies based on mean sea level changes (*medium confidence*)



Purple: Very high probability of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.

Red: Significant and widespread impacts/risks.

Yellow: Impacts/risks are detectable and attributable to climate change with at least medium confidence.

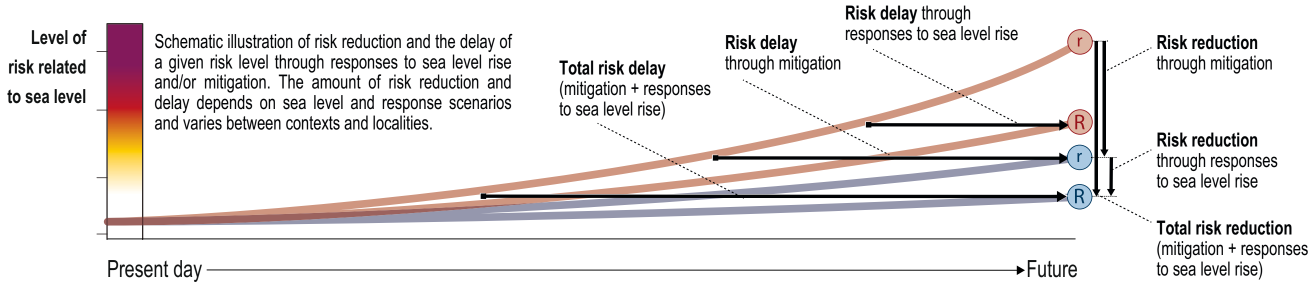
White: Impacts/risks are undetectable.

In this assessment, the term response refers to in situ responses to sea level rise (hard engineered coastal defenses, restoration of degraded ecosystems, subsidence limitation) and planned relocation. Planned relocation in this assessment refers to proactive managed retreat or resettlement only at a local scale, and according to the specificities of a particular context (e.g., in urban atoll islands: within the island, in a neighbouring island or in artificially raised islands). Forced displacement and international migration are not considered in this assessment.

The illustrative geographies are based on a limited number of case studies well covered by the peer reviewed literature. The realisation of risk will depend on context specifities.

Sea level rise scenarios: RCP4.5 and RCP6.0 are not considered in this risk assessment because the literature underpinning this assessment is only available for RCP2.6 and RCP8.5.

(b) Benefits of responses to sea level rise and mitigation



Schematic illustration of risk reduction and the delay of a given risk level through responses to sea level rise and/or mitigation. The amount of risk reduction and delay depends on sea level and response scenarios and varies between contexts and localities.

Figure TS.7 | a, b

(c) Responses to rising mean and extreme sea levels

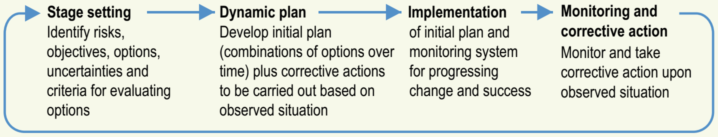
The table illustrates responses and their characteristics. It is not exhaustive. Whether a response is applicable depends on geography and context.

Confidence levels (assessed for effectiveness): ●●●● = Very High ●●● = High ●● = Medium ● = Low

Responses		**Potential effectiveness** in terms of reducing sea level rise (SLR) risks (technical/biophysical limits)	**Advantages** (beyond risk reduction)	**Co–benefits**	**Drawbacks**	**Economic efficiency**	**Governance challenges**
Hard protection		Up to multiple metres of SLR {4.4.2.2.4} ●●●	Predictable levels of safety {4.4.2.2.4}	Multifunctional dikes such as for recreation, or other land use {4.4.2.2.5}	Destruction of habitat through coastal squeeze,flooding & erosion downdrift, lock-in, disastrous consequence in case of defence failure {4.3.2.4, 4.4.2.2.5}	High if the value of assets behind protection is high, as found in many urban and densely populated coastal areas {4.4.2.2.7}	Often unaffordable for poorer areas. Conflicts between objectives (e.g., conservation, safety and tourism), conflicts about the distribution of public budgets, lack of finance {4.3.3.2, 4.4.2.2.6}
Sediment-based protection		Effective but depends on sediment availability {4.4.2.2.4} ●●●	High flexibility {4.4.2.2.4}	Preservation of beaches for recreation/ tourism {4.4.2.2.5}	Destruction of habitat, where sediment is sourced {4.4.2.2.5}	High if tourism revenues are high {4.4.2.2.7}	Conflicts about the distribution of public budgets {4.4.2.2.6}
Ecosystem based adaptation	**Coral conservation**	Effective up to 0.5 cm yr^{-1} SLR. ●● Strongly limited by ocean warming and acidification. Constrained at 1.5°C warming and lost at 2°C at many places. {4.3.3.5.2, 4.4.2.3.2, 5.3.4} ●●●	Opportunity for community involvement, {4.4.2.3.1}	Habitat gain, biodiversity, carbon sequestration, income from tourism, enhanced fishery productivity, improved water quality. Provision of food, medicine, fuel, wood and cultural benefits {4.4.2.3.5}	Long-term effectiveness depends on ocean warming, acidification and emission scenarios {4.3.3.5.2., 4.4.2.3.2}	Limited evidence on benefit-cost ratios; Depends on population density and the availability of land {4.4.2.3.7}	Permits for implementation are difficult to obtain. Lack of finance. Lack of enforcement of conservation policies. EbA options dismissed due to short-term economic interest, availability of land {4.4.2.3.6}
	Coral restoration						
	Wetland conservation (Marshes, Mangroves)	Effective up to 0.5–1 cm yr^{-1} SLR,●● decreased at 2°C {4.3.3.5.1, 4.4.2.3.2, 5.3.7} ●●●			Safety levels less predictable, development benefits not realized {4.4.2.3.5, 4.4.2.3.2}		
	Wetland restoration (Marshes, Mangroves)				Safety levels less predictable, a lot of land required, barriers for landward expansion of ecosystems has to be removed {4.4.2.3.5, 4.4.2.3.2}		
Coastal advance		Up to multiple metres of SLR {4.4.2.2.4} ●●●	Predictable levels of safety {4.4.2.2.4}	Generates land and land sale revenues that can be used to finance adaptation {4.4.2.4.5}	Groundwater salinisa–tion, enhanced erosion and loss of coastal ecosystems and habitat {4.4.2.4.5}	Very high if land prices are high as found in many urban coasts {4.4.2.4.7}	Often unaffordable for poorer areas. Social conflicts with regards to access and distribution of new land {4.4.2.4.6}
Coastal accommodation (Flood-proofing buildings, early warning systems for flood events, etc.)		Very effective for small SLR {4.4.2.5.4} ●●●	Mature technology; sediments deposited during floods can raise elevation {4.4.2.5.5}	Maintains landscape connectivity {4.4.2.5.5}	Does not prevent flooding/impacts {4.4.2.5.5}	Very high for early warning systems and building-scale measures {4.4.2.5.7}	Early warning systems require effective insti-tutional arrangements {4.4.2.6.6}
Retreat	**Planned relocation**	Effective if alternative safe localities are available {4.4.2.6.4} ●●●	Sea level risks at origin can be eliminated {4.4.2.6.4}	Access to improved services (health, education, housing), job opportunities and economic growth {4.4.2.6.5}	Loss of social cohesion, cultural identity and well-being. Depressed services (health, education, housing), job opportunities and economic growth {4.4.2.6.5}	Limited evidence [4.4.2.6.7}	Reconciling the divergent interests arising from relocating people from point of origin and destination {4.4.2.6.6}
	Forced displacement	Addresses only immediate risk at place of origin	Not applicable	Not applicable	Range from loss of life to loss of livelihoods and sovereignty {4.4.2.6.5}	Not applicable	Raises complex humanitarian questions on livelihoods, human rights and equity {4.4.2.6.6}

(d) Choosing and enabling sea level rise responses

Generic steps of adaptive decision making



Stage setting
Identify risks, objectives, options, uncertainties and criteria for evaluating options

Dynamic plan
Develop initial plan (combinations of options over time) plus corrective actions to be carried out based on observed situation

Implementation
of initial plan and monitoring system for progressing change and success

Monitoring and corrective action
Monitor and take corrective action upon observed situation

Enabling conditions

- Long-term perspective
- Cross-scale coordination
- Address vulnerability and equity
- Inclusive public participation
- Capability to address complexity

Figure TS.7 | c, d

Figure TS.7 | Sea level rise risks and responses. The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. **(a)** shows the combined risk of coastal flooding, erosion and salinization for illustrative geographies in 2100, due to changing mean and extreme sea levels under RCP2.6 and RCP8.5 and under two response scenarios. Risks under RCPs 4.5 and 6.0 were not assessed due to a lack of literature for the assessed geographies. The assessment does not account for changes in extreme sea level beyond those directly induced by mean sea level rise; risk levels could increase if other changes in extreme sea levels were considered (e.g., due to changes in cyclone intensity). Panel **(a)** considers a socioeconomic scenario with relatively stable coastal population density over the century. {SM4.3.2} Risks to illustrative geographies have been assessed based on relative sea level changes projected for a set of specific examples: New York City, Shanghai and Rotterdam for resource-rich coastal cities covering a wide range of response experiences; South Tarawa, Fongafale and Male' for urban atoll islands; Mekong and Ganges-Brahmaputra-Meghna for large tropical agricultural deltas; and Bykovskiy, Shishmaref, Kivalina, Tuktoyaktuk and Shingle Point for Arctic communities located in regions remote from rapid glacio-isostatic adjustment. {4.2, 4.3.4, SM4.2} The assessment distinguishes between two contrasting response scenarios. "No-to-moderate response" describes efforts as of today (i.e., no further significant action or new types of actions). "Maximum potential response" represents a combination of responses implemented to their full extent and thus significant additional efforts compared to today, assuming minimal financial, social and political barriers. The assessment has been conducted for each sea level rise and response scenario, as indicated by the burning embers in the figure; in-between risk levels are interpolated. {4.3.3} The assessment criteria include exposure and vulnerability (density of assets, level of degradation of terrestrial and marine buffer ecosystems), coastal hazards (flooding, shoreline erosion, salinization), in-situ responses (hard engineered coastal defenses, ecosystem restoration or creation of new natural buffers areas, and subsidence management) and planned relocation. Planned relocation refers to managed retreat or resettlement as described in Chapter 4, i.e., proactive and local-scale measures to reduce risk by relocating people, assets and infrastructure. Forced displacement is not considered in this assessment. Panel **(a)** also highlights the relative contributions of in-situ responses and planned relocation to the total risk reduction. **(b)** schematically illustrates the risk reduction (vertical arrows) and risk delay (horizontal arrows) through mitigation and/or responses to sea level rise. **(c)** summarizes and assesses responses to sea level rise in terms of their effectiveness, costs, co-benefits, drawbacks, economic efficiency and associated governance challenges. {4.4.2} **(d)** presents generic steps of an adaptive decision-making approach, as well as key enabling conditions for responses to sea level rise. {4.4.4, 4.4.5}

other processes associated with ocean physics and biogeochemistry, which cause the majority of the observed oxygen decline (*high confidence*). The oxygen minimum zones (OMZs) are expanding by a *very likely* range of 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*). {5.2.2.4, Figure TS.3, Figure TS.5}

In response to ocean warming and increased stratification, open ocean nutrient cycles are being perturbed and there is *high confidence* that this is having a regionally variable impact on primary producers. There is currently *low confidence* in appraising past open ocean productivity trends, including those determined by satellites, due to newly identified region-specific drivers of microbial growth and the lack of corroborating *in situ* time series datasets. {5.2.2.5, 5.2.2.6}

Ocean warming has contributed to observed changes in biogeography of organisms ranging from phytoplankton to marine mammals (*high confidence*), consequently changing community composition (*high confidence*), and in some cases, altering interactions between organisms (*medium confidence*). Observed rate of range shifts since the 1950s and *its very likely range* are estimated to be 51.5 ± 33.3 km per decade and 29.0 ± 15.5 km per decade for organisms in the epipelagic and seafloor ecosystems, respectively. The direction of the majority of the shifts of epipelagic organisms are consistent with a response to warming (*high confidence*). {5.2.3, 5.3}

Warming-induced range expansion of tropical species to higher latitudes has led to increased grazing on some coral reefs, rocky reefs, seagrass meadows and epipelagic ecosystems, leading to altered ecosystem structure (*medium confidence*). Warming, sea level rise (SLR) and enhanced loads of nutrients and sediments in deltas have contributed to salinisation and deoxygenation in estuaries (*high confidence*), and have caused upstream redistribution of benthic and pelagic species according to their tolerance limits (*medium confidence*). {5.3.4, 5.3.5, 5.3.6, 5.2.3}

Fisheries catches and their composition in many regions are already impacted by the effects of warming and changing primary production on growth, reproduction and survival of fish stocks (*high confidence*). Ocean warming and changes in primary production in the 20th century are related to changes in productivity of many fish stocks (*high confidence*), with an average decrease of approximately 3% per decade in population replenishment and 4.1% (*very likely range* of 9.0% decline to 0.3% increase) in maximum catch potential (*robust evidence, low agreement* between fish stocks, *medium confidence*). Species composition of fisheries catches since the 1970s in many shelf seas ecosystems of the world is increasing dominated by warm water species (*medium confidence*). {5.2.3, 5.4.1}

Warming-induced changes in spatial distribution and abundance of fish stocks have already challenged the management of some important fisheries and their economic benefits (*high confidence*). For existing international and national ocean and fisheries governance, there are concerns about the reduced effectiveness to achieve mandated ecological, economic, and social objectives because of observed climate impacts on fisheries resources (*high confidence*). {5.4.2, 5.5.2}

Coastal ecosystems are observed to be under stress from ocean warming and SLR that are exacerbated by non-climatic pressures from human activities on ocean and land (*high confidence*). Global wetland area has declined by nearly 50% relative to pre-industrial level as a result of warming, SLR, extreme climate events and other human impacts (*medium confidence*). Warming related mangrove encroachment into subtropical salt marshes has been observed in the past 50 years (*high confidence*). Distributions of seagrass meadows and kelp forests are contracting at low-latitudes that is attributable to warming (*high confidence*), and in some areas a loss of 36–43% following heat waves (*medium confidence*). Inundation, coastline erosion and salinisation are causing inland shifts in plant species distributions, which has been accelerating in the last decades (*medium confidence*). Warming has increased the frequency of large-scale coral bleaching events, causing worldwide reef degradation since 1997–1998 with cases of shifts to algal-dominated reefs (*high confidence*). Sessile calcified organisms (e.g., barnacles and 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*). Increased nutrient and organic matter loads in estuaries since the 1970s have exacerbated the effects of warming on bacterial respiration and eutrophication, leading to expansion of hypoxic areas (*high confidence*). {5.3.1, 5.3.2, 5.3.4, 5.3.6}

Coastal and near-shore ecosystems including salt marshes, mangroves and vegetated dunes in sandy beaches have a varying capacity to build vertically and expand laterally in response to SLR. These ecosystems provide important services including coastal protection, carbon sequestration and habitat for diverse biota (*high confidence*). The carbon emission associated with the loss of vegetated coastal ecosystems is estimated to be 0.04–1.46 Gt C yr^{-1} (*high confidence*). The natural capacity of ecosystems to adapt to climate impacts may be limited by human activities that fragment wetland habitats and restrict landward migration (*high confidence*). {5.3.2, 5.3.3, 5.4.1, 5.5.1}

Three out of the four major Eastern Boundary Upwelling Systems (EBUS) have shown large-scale wind intensification in the past 60 years (*high confidence*). However, the interaction of coastal warming and local winds may have affected upwelling strength, with the direction of changes varies between and within EBUS (*low confidence*). Increasing trends in ocean acidification in the California Current EBUS and deoxygenation in California Current and Humboldt Current EBUS are observed in the last few decades (*high confidence*), although there is *low confidence* to distinguish anthropogenic forcing from internal climate variability. The expanding California EBUS OMZ has altered ecosystem structure and fisheries catches (*medium confidence*). {Box 5.3}

Since the early 1980s, the occurrence of harmful algal blooms (HABs) and pathogenic organisms (e.g., *Vibrio*) has increased in coastal areas in response to warming, deoxygenation and eutrophication, with negative impacts on food provisioning, tourism, the economy and human health (*high confidence*). These impacts depend on species-specific responses to the interactive effects of climate change and other human drivers (e.g., pollution). Human communities in poorly monitored areas are among the most vulnerable to these biological hazards (*medium confidence*). {Box 5.4, 5.4.2}

Many frameworks for climate resilient coastal adaptation have been developed since AR5, with substantial variations in approach between and within countries, and across development status (*high confidence*). Few studies have assessed the success of implementing these frameworks due to the time-lag between implementation, monitoring, evaluation and reporting (*medium confidence*). {5.5.2}

Projections: scenarios and time horizons

Climate models project significant changes in the ocean state over the coming century. Under the high emissions scenario (Representative Concentration Pathway (RCP)8.5) the impacts by 2090 are substantially larger and more widespread than for the low emissions scenario (RCP2.6) throughout the surface and deep ocean, including: warming (*virtually certain*); ocean acidification (*virtually certain*); decreased stability of mineral forms of calcite (*virtually certain*); oxygen loss (*very likely*); reduced near-surface nutrients (*likely as not*); decreased net primary productivity (*high confidence*); reduced fish production (*likely*) and loss of key ecosystems services (*medium confidence*) that are important for human well-being and sustainable development. {5.2.2, Box 5.1, 5.2.3, 5.2.4, 5.4}

By 2100 the ocean is *very likely* to warm by 2 to 4 times as much for low emissions (RCP2.6) and 5 to 7 times as much for the high emissions scenario (RCP8.5) compared with the observed changes since 1970. The 0–2000 m layer of the ocean is projected to warm by a further 2150 ZJ (*very likely* range 1710–2790 ZJ) between 2017 and 2100 for the RCP8.5 scenario. The 0–2000 m layer is projected to warm by 900 ZJ (*very likely* range 650–1340 ZJ) by 2100 for the RCP2.6 scenario, and the overall warming of the ocean will continue this century even after radiative forcing and mean surface temperatures stabilise (*high confidence*). {5.2.2.2}

The upper ocean will continue to stratify. By the end of the century the annual mean stratification of the top 200 m (averaged between 60ºS–60ºN relative to the 1986–2005 period) is projected to increase in the *very likely* range of 1–9% and 12–30% for RCP2.6 and RCP8.5 respectively. {5.2.2.2}

It is *very likely* that the majority of coastal regions will experience statistically significant changes in tidal amplitudes over the course of the 21st century. The sign and amplitude of local changes to tides are *very likely* to be impacted by both human coastal adaptation measures and climate drivers. {5.2.2.2.3}

It is *virtually certain* that surface ocean pH will decline, by 0.036–0.042 or 0.287–0.29 pH units by 2081–2100, relative to 2006–2015, for the RCP2.6 or RCP8.5 scenarios, respectively. These pH changes are *very likely* to cause the Arctic and Southern Oceans, as well as the North Pacific and Northwestern Atlantic Oceans to become corrosive for the major mineral forms of calcium carbonate under RCP8.5, but these changes are *virtually certain* to be avoided under the RCP2.6 scenario. There is increasing evidence of an increase in the seasonal exposure to acidified conditions in the future (*high confidence*), with a *very likely* increase in the amplitude of seasonal cycle of hydrogen iron concentrations of 71–90% by 2100, relative to 2000 for the RCP8.5 scenario, especially at high latitudes. {5.2.2.3}

Oxygen is projected to decline further. Globally, the oxygen content of the ocean is *very likely* to decline by 3.2–3.7% by 2081–2100, relative to 2006–2015, for the RCP8.5 scenario or by 1.6–2.0% for the RCP2.6 scenario. The volume of the oceans OMZ is projected to grow by a *very likely* range of 7.0 ± 5.6% by 2100 during the RCP8.5 scenario, relative to 1850–1900. The climate signal of oxygen loss will *very likely* emerge from the historical climate by 2050 with a *very likely* range of 59–80% of ocean area being affected by 2031–2050 and rising with a *very likely* range of 79–91% by 2081–2100 (RCP8.5 emissions scenario). The emergence of oxygen loss is *very likely* smaller in area for the RCP2.6 scenario in the 21st century and by 2090 the emerged area is declining. {5.2.2.4, Box 5.1 Figure 1}

Overall, nitrate concentrations in the upper 100 m are *very likely* to decline by 9–14% across CMIP5 models by 2081–2100, relative to 2006–2015, in response to increased stratification for RCP8.5, with *medium confidence* in these projections due to the *limited evidence* of past changes that can be robustly understood and reproduced by models. There is *low confidence* regarding projected increases in surface ocean iron levels due to systemic uncertainties in these models. {5.2.2.5}

Climate models project that net primary productivity will *very likely* decline by 4–11% for RCP8.5 by 2081–2100, relative to 2006–2015. The decline is due to the combined effects of warming, stratification, light, nutrients and predation and will show regional variations between low and high latitudes (*low confidence*). The tropical ocean NPP will *very likely* decline by 7–16% for RCP8.5, with *medium confidence* as there are improved constraints from historical variability in this region. Globally, the sinking flux of organic matter from the upper ocean into the ocean interior is *very likely* to decrease by 9–16% for RCP8.5 in response to increased stratification and reduced nutrient supply, especially in tropical regions (*medium confidence*), which will reduce organic carbon supply to deep sea ecosystems (*high confidence*). The reduction in food supply to the deep sea is projected to lead to a 5–6% reduction in biomass of benthic biota over more than 97% of the abyssal seafloor by 2100 (*medium confidence*). {5.2.2.6, 5.2.4.2, Figure TS.8}

New ocean states for a broad suite of climate indices will progressively emerge over a substantial fractions of the ocean in the coming century (relative to past internal ocean variability), with Earth System Models (ESMs) showing an ordered emergence of first pH, followed by sea surface temperature (SST), interior oxygen, upper ocean nutrient levels and finally net primary production (NPP). The anthropogenic pH signal has *very likely* emerged for three quarters of the ocean prior to 1950, with little difference between scenarios. Oxygen changes will *very likely* emerge over 59–80% of the ocean area by 2031–2050 and rises to 79–91% by 2081–2100 (RCP8.5 emissions scenario). The projected time of emergence for five primary drivers of marine ecosystem change (surface warming and acidification, oxygen loss, nitrate content and net primary production change) are all prior to 2100 for over 60% of the ocean area under RCP8.5 and over 30% under RCP2.6 (*very likely*). {Box 5.1, Box 5.1 Figure 1}

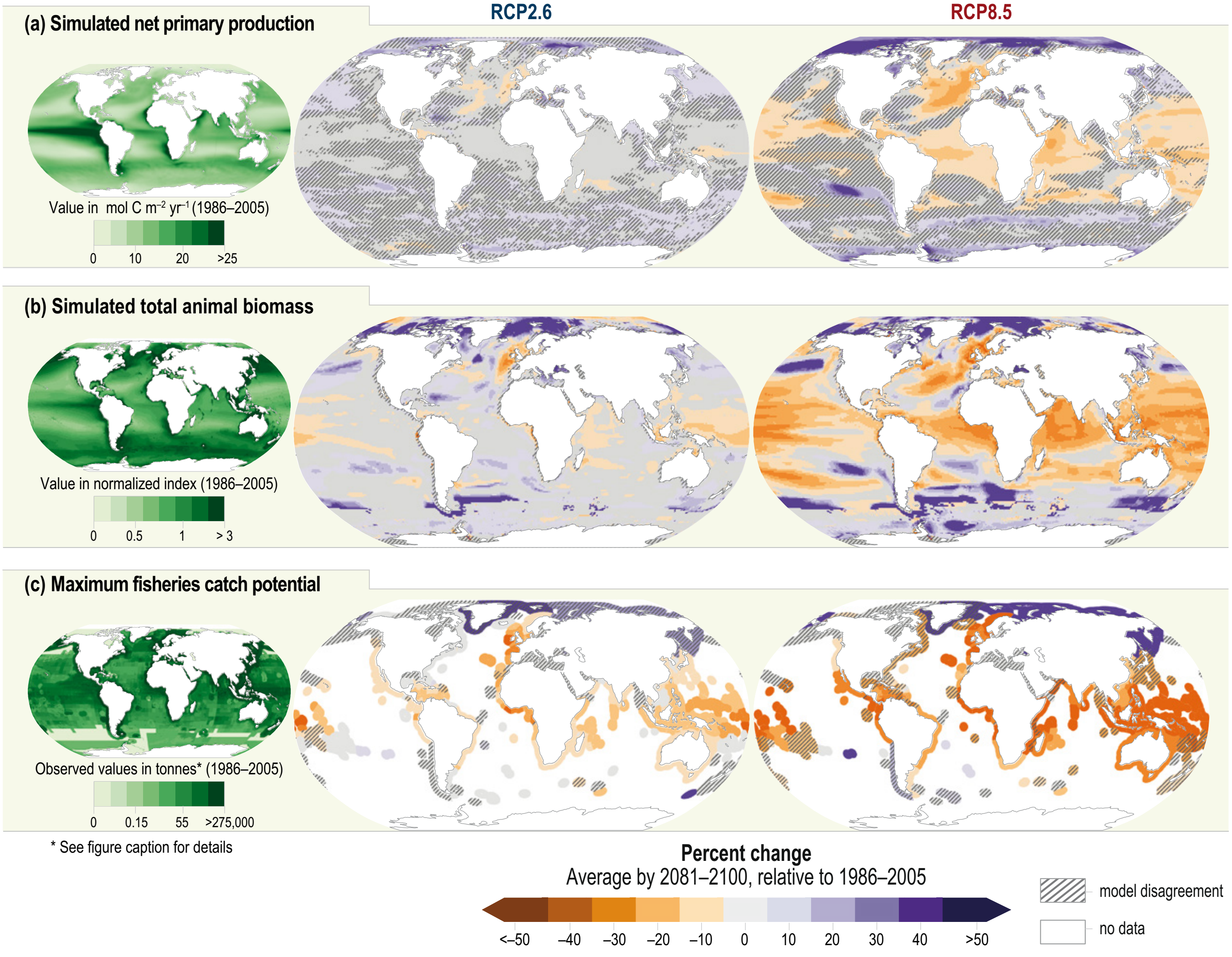


Figure TS.8 | a, b , c

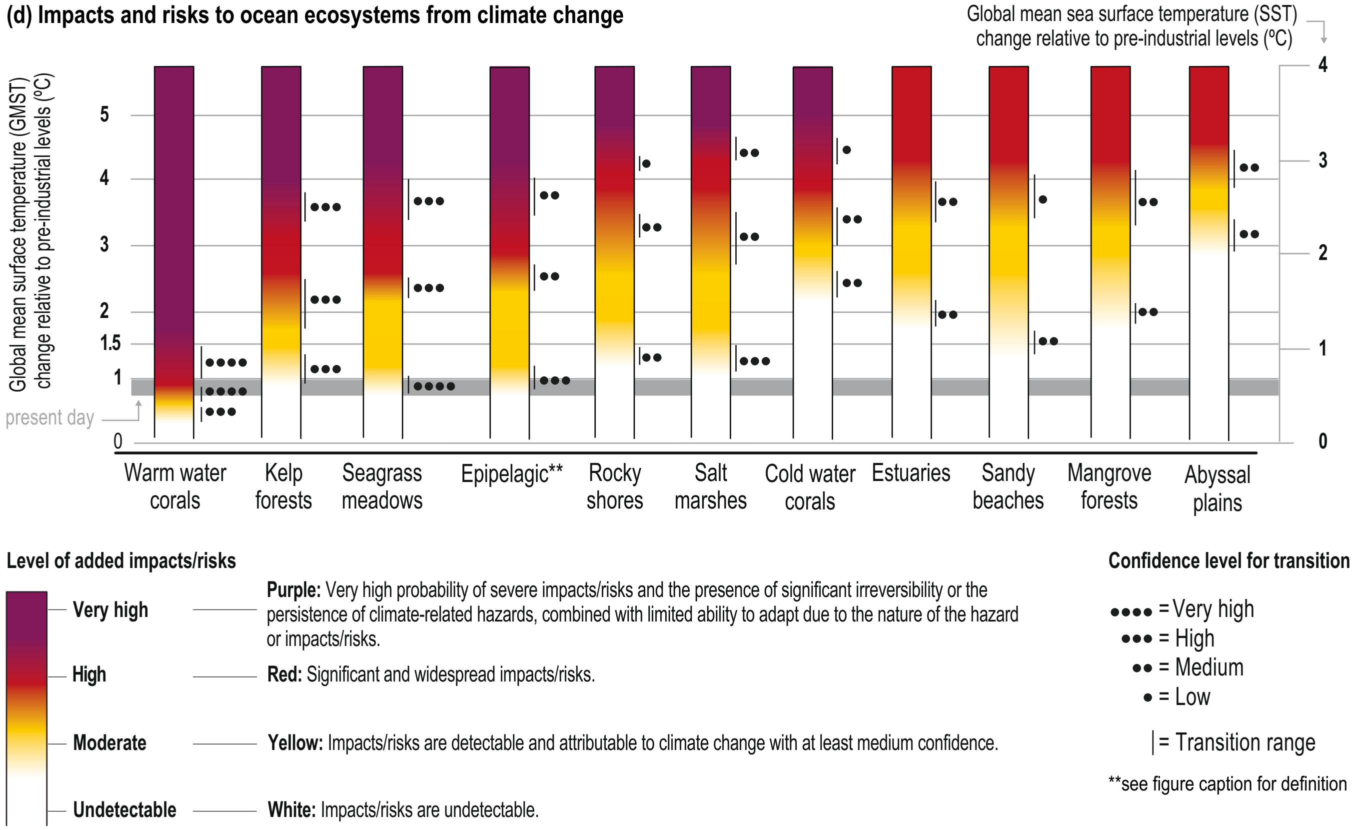

(d) Impacts and risks to ocean ecosystems from climate change

Figure TS.8 | Projected changes, impacts and risks for ocean regions and ecosystems. **(a)** depth integrated net primary production (NPP from CMIP5)[8], **(b)** total animal biomass (depth integrated, including fishes and invertebrates from FISHMIP)[9], **(c)** maximum fisheries catch potential and **(d)** impacts and risks for coastal and open ocean ecosystems. The three left panels represent the simulated **(a,b)** and observed **(c)** mean values for the recent past (1986–2005), the middle and right panels represent projected changes (%) by 2081–2100 relative to recent past under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenario (see Table TS.2), respectively. Total animal biomass in the recent past (b, left panel) represents the projected total animal biomass by each spatial pixel relative to the global average. **(c)** *Average observed fisheries catch in the recent past (based on data from the Sea Around Us global fisheries database); projected changes in maximum fisheries catch potential in shelf seas are based on the average outputs from two fisheries and marine ecosystem models. To indicate areas of model inconsistency, shaded areas represent regions where models disagree in the direction of change for more than: **(a)** and **(b)** 3 out of 10 model projections, and **(c)** one out of two models. Although unshaded, the projected change in the Arctic and Antarctic regions in **(b)** total animal biomass and **(c)** fisheries catch potential have low confidence due to uncertainties associated with modelling multiple interacting drivers and ecosystem responses. Projections presented in **(b)** and **(c)** are driven by changes in ocean physical and biogeochemical conditions e.g., temperature, oxygen level, and net primary production projected from CMIP5 Earth system models. **The epipelagic refers to the uppermost part of the ocean with depth <200 m from the surface where there is enough sunlight to allow photosynthesis. **(d)** Assessment of risks for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. Impacts and risks are shown in relation to changes in Global Mean Surface Temperature (GMST) relative to pre-industrial level. Since assessments of risks and impacts are based on global mean Sea Surface Temperature (SST), the corresponding SST levels are shown[10]. The assessment of risk transitions is described in Chapter 5 Sections 5.2, 5.3, 5.2.5 and 5.3.7 and Supplementary Materials SM5.3, Table SM5.6, Table SM5.8 and other parts of the underlying report. The figure indicates assessed risks at approximate warming levels and increasing climate-related hazards in the ocean: ocean warming, acidification, deoxygenation, increased density stratification, changes in carbon fluxes, sea level rise, and increased frequency and/or intensity of extreme events. The assessment considers the natural adaptive capacity of the ecosystems, their exposure and vulnerability. Impact and risk levels do not consider risk reduction strategies such as human interventions, or future changes in non-climatic drivers. Risks for ecosystems were assessed by considering biological, biogeochemical, geomorphological and physical aspects. Higher risks associated with compound effects of climate hazards include habitat and biodiversity loss, changes in species composition and distribution ranges, and impacts/risks on ecosystem structure and functioning, including changes in animal/plant biomass and density, productivity, carbon fluxes, and sediment transport. As part of the assessment, literature was compiled and data extracted into a summary table. A multi-round expert elicitation process was undertaken with independent evaluation of threshold judgement, and a final consensus discussion. Further information on methods and underlying literature can be found in Chapter 5, Sections 5.2 and 5.3 and Supplementary Material. {3.2.3, 3.2.4, 5.2, 5.3, 5.2.5, 5.3.7, SM5.6, SM5.8, Figure 5.16, Cross Chapter Box 1 in Chapter 1 Table CCB1}

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[8] NPP is estimated from the Coupled Models Intercomparison Project 5 (CMIP5).

[9] Total animal biomass is from the Fisheries and Marine Ecosystem Models Intercomparison Project (FISHMIP).

[10] The conversion between GMST and SST is based on a scaling factor of 1.44 derived from changes in an ensemble of RCP8.5 simulations; this scaling factor has an uncertainty of about 4% due to differences between the RCP2.6 and RCP8.5 scenarios. {Table SPM.1}

Simulated ocean warming and changes in NPP during the 21st century are projected to alter community structure of marine organisms (*high confidence*), reduce global marine animal biomass (*medium confidence*) and the maximum potential catches of fish stocks (*medium confidence*) with regional differences in the direction and magnitude of changes (*high confidence*). The global biomass of marine animals, including those that contribute to fisheries, is projected to decrease with a *very likely* range under RCP2.6 and RCP8.5 of 4.3 ± 2.0% and 15.0 ± 5.9%, respectively, by 2080–2099 relative to 1986–2005. The maximum catch potential is projected to decrease by 3.4% to 6.4% (RCP2.6) and 20.5% to 24.1% (RCP8.5) in the 21st century. {5.4.1}

Projected decreases in global marine animal biomass and fish catch potential could elevate the risk of impacts on income, livelihood and food security of the dependent human communities (*medium confidence*). Projected climate change impacts on fisheries also increase the risk of potential conflicts among fishery area users and authorities or between two different communities within the same country (*medium confidence*), exacerbated through competing resource exploitation from international actors and mal-adapted policies (*low confidence*). {5.2.3, 5.4, 5.5.3}

Projected decrease in upper ocean export of organic carbon to the deep seafloor is expected to result in a loss of animal biomass on the deep seafloor by 5.2–17.6% by 2090–2100 compared to the present (2006–2015) under RCP8.5 with regional variations (*medium confidence*). Some increases are projected in the polar regions, due to enhanced stratification in the surface ocean, reduced primary production and shifts towards small phytoplankton (*medium confidence*). The projected impacts on biomass in the abyssal seafloor are larger under RCP8.5 than RCP4.5 (*very likely*). The increase in climatic hazards beyond thresholds of tolerance of deep sea organisms will increase the risk of loss of biodiversity and impacts on functioning of deep water column and seafloor that is important to support ecosystem services, such as carbon sequestration (*medium confidence*). {5.2.4}

Structure and functions of all types of coastal ecosystems will continue to be at moderate to high risk under the RCP2.6 scenario (*medium confidence*) and will face high to very high risk under the RCP8.5 scenario (*high confidence*) by 2100. Seagrass meadows (*high confidence*) and kelp forests (*high confidence*) will face moderate to high risk at temperature above 1.5°C global sea surface warming. Coral reefs will face very high risk at temperatures 1.5°C of global sea surface warming (*very high confidence*). Intertidal rocky shores are also expected to be at very high risk (transition above 3°C) under the RCP8.5 scenario (*medium confidence*). These ecosystems have low to moderate adaptive capacity, as they are highly sensitive to ocean temperatures and acidification. The ecosystems with moderate to high risk (transition above 1.8°C) under future emissions scenarios are mangrove forests, sandy beaches, estuaries and salt marshes (*medium confidence*). Estuaries and sandy beaches are subject to highly dynamic hydrological and geomorphological processes, giving them more natural adaptive capacity to climate hazards. In these systems, sediment relocation, soil accretion and landward expansion of vegetation may initially mitigate against flooding and habitat loss, but salt marshes in particular will be at very high risk in the context of SLR and extreme climate-driven erosion under RCP8.5. {5.3, Figure 5.16}

Expected coastal ecosystem responses over the 21st century are habitat contraction, migration and loss of biodiversity and functionality. Pervasive human coastal disturbances will limit natural ecosystem adaptation to climate hazards (*high confidence*). Global coastal wetlands will lose between 20–90% of their area depending on emissions scenario with impacts on their contributions to carbon sequestration and coastal protection (*high confidence*). Kelp forests at low-latitudes and temperate seagrass meadows will continue to retreat as a result of intensified extreme temperatures, and their low dispersal ability will elevate the risk of local extinction under RCP8.5 (*high confidence*). Intertidal rocky shores will continue to be affected by ocean acidification, warming, and extreme heat exposure during low tide emersion, causing reduction of calcareous species and loss of ecosystem biodiversity and complexity shifting towards algae dominated habitats (*high confidence*). Salinisation and expansion of hypoxic conditions will intensify in eutrophic estuaries, especially in mid and high latitudes with microtidal regimes (*high confidence*). Sandy beach ecosystems will increasingly be at risk of eroding, reducing the habitable area for dependent organisms (*high confidence*). {5.3, 5.4.1}

Almost all coral reefs will degrade from their current state, even if global warming remains below 2°C (*very high confidence*), and the remaining shallow coral reef communities will differ in species composition and diversity from present reefs (*very high confidence*). These declines in coral reef health will greatly diminish 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}

Multiple hazards of warming, deoxygenation, aragonite undersaturation and decrease in flux of organic carbon from the surface ocean will decrease calcification and exacerbate the bioerosion and dissolution of the non-living component of cold water coral. Habitat-forming, cold water corals will be vulnerable where temperature and oxygen exceed the species' thresholds (*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 *very likely* range of 8.6 ± 2% biomass loss (*medium confidence*). {5.2.4, Box 5.2}

Anthropogenic changes in EBUS will emerge primarily in the second half of the 21st century (*medium confidence*). EBUS will be impacted by climate change in different ways, with strong regional variability with consequences for fisheries, recreation and climate regulation (*medium confidence*). The Pacific EBUS are projected to have calcium carbonate undersaturation in surface waters within a few decades under RCP8.5 (*high confidence*); combined with warming and decreasing oxygen levels, this will increase the impacts on shellfish larvae, benthic invertebrates and demersal fishes (*high confidence*) and related fisheries and aquaculture (*medium confidence*). The inherent natural variability of EBUS, together with uncertainties in present and future trends in the intensity and seasonality of upwelling, coastal warming and stratification, primary production and biogeochemistry of source waters poses large challenges in projecting the response of EBUS to climate change and to the adaptation of governance of biodiversity conservation and living marine resources in EBUS (*high confidence*). {Box 5.3}

Climate change impacts on ecosystems and their goods and services threatens key cultural dimensions of lives and livelihoods. These threats include erosion of Indigenous and non-indigenous culture, their knowledge about the ocean and knowledge transmission, reduced access to traditional food, loss of opportunities for aesthetic and spiritual appreciation of the ecosystems, and marine recreational activities (*medium confidence*). Ultimately, these can lead to the loss of part of people's cultural identity and values beyond the rate at which identify and values can be adjusted or substituted (*medium confidence*). {5.4.2}

Climate change increases the exposure and bioaccumulation of contaminants such as persistent organic pollutants and mercury (*medium confidence*), and their risk of impacts on marine ecosystems and seafood safety (*high agreement, medium evidence, medium confidence*). Such risks are particularly large for top predators and for human communities that have high consumption on these organisms, including coastal Indigenous communities (*medium confidence*). {5.4.2}

Shifting distributions of fish stocks between governance jurisdictions will increase the risk of potential conflicts among fishery area users and authorities or between two different communities within the same country (*medium confidence*). These fishery governance related risks are widespread under high emissions scenarios with regional hotspots (*medium confidence*), and highlight the limits of existing natural resource management frameworks for addressing ecosystem change (*high confidence*). {5.2.5, 5.4.2.1.3, 5.5, 5.5.2}

Response options to enhance resilience

There is clear evidence for observed climate change impacts throughout the ocean with consequences for human communities and require options to reduce risks and impacts. Coastal blue carbon can contribute to mitigation for many nations but its global scope is modest (offset of <2% of current emissions) (*likely*). Some ocean indices are expected to emerge earlier than others (e.g., warming, acidification and effects on fish stocks) and could therefore be used to prioritise planning and building resilience. The survival of some keystone ecosystems (e.g., coral reefs) are at risk, while governance structures are not well-matched to the spatial and temporal scale of climate change impacts on ocean systems. Ecosystem restoration may be able to locally reduce climate risks (*medium confidence*) but at relatively high cost and effectiveness limited to low emissions scenarios and to less sensitive systems (*high confidence*). {5.2, 5.3, 5.4, 5.5}

Coastal blue carbon ecosystems, such as mangroves, salt marshes and seagrasses, can help reduce the risks and impacts of climate change, with multiple co-benefits. Some 151 countries around the world contain at least one of these coastal blue carbon ecosystems and 71 countries contain all three. Below-ground carbon storage in vegetated marine habitats can be up to 1000 tC ha^{-1}, much higher than most terrestrial ecosystems (*high confidence*). Successful implementation of measures to maintain and promote carbon storage in such coastal ecosystems could assist several countries in achieving a balance between emissions and removals of greenhouse gases (*medium confidence*). Conservation of these habitats would also sustain the wide range of ecosystem services they provide and assist with climate adaptation through improving critical habitats for biodiversity, enhancing local fisheries production, and protecting coastal communities from SLR and storm events (*high confidence*). The climate mitigation effectiveness of other natural carbon removal processes in coastal waters, such as seaweed ecosystems and proposed non-biological marine CO_2 removal methods, are smaller or currently have higher associated uncertainties. Seaweed aquaculture warrants further research attention. {5.5.1.1, 5.5.1.1, 5.5.1, 5.5.2, 5.5.1.1.3, 5.5.1.1.4}

The potential climatic benefits of blue carbon ecosystems can only be a very modest addition to, and not a replacement for, the very rapid reduction of greenhouse gas emissions. The maximum global mitigation benefits of cost-effective coastal wetland restoration is *unlikely* to be more than 2% of current total emissions from all sources. Nevertheless, the protection and enhancement of coastal blue carbon can be an important contribution to both mitigation and adaptation at the national scale. The feasibility of climate mitigation by open ocean fertilisation of productivity is limited to negligible, due to the likely decadal-scale return to the atmosphere of nearly all the extra carbon removed, associated difficulties in carbon accounting, risks of unintended side effects and low acceptability. Other human interventions to enhance marine carbon uptake, for example, ocean alkalinisation (enhanced weathering), would also have governance challenges, with the increased risk of undesirable ecological consequences (*high confidence*). {5.5.1.2}

Socioinstitutional adaptation responses are more frequently reported in the literature than ecosystem-based and built infrastructure approaches. Hard engineering responses are more effective when supported by ecosystem-based adaptation (EbA) approaches (*high agreement*), and both approaches are enhanced by combining with socioinstitutional approaches for adaptation (*high confidence*). Stakeholder engagement is necessary (*robust evidence, high agreement*). {5.5.2}

EbA is a cost-effective coastal protection tool that can have many co-benefits, including supporting livelihoods, contributing to carbon sequestration and the provision of a range of other valuable ecosystem services (*high confidence*). Such adaptation does, however, assume that the climate can be stabilised. Under changing climatic conditions there are limits to the effectiveness of ecosystem-based adaptation, and these limits are currently difficult to determine. {5.5.2.1}

Socioinstitutional adaptation responses, including community-based adaptation, capacity-building, participatory processes, institutional support for adaptation planning and support mechanisms for communities are important tools to address climate change impacts (*high confidence*). For fisheries management, improving coordination of integrated coastal management and marine protected areas (MPAs) have emerged in the literature as important adaptation governance responses (*robust evidence, medium agreement*). {5.5.2.2, 5.5.2.6}

Observed widespread decline in warm water corals has led to the consideration of alternative restoration approaches to enhance climate resilience. Approaches, such as 'coral reef gardening' have been tested, and ecological engineering and other approaches such as assisted evolution, colonisation and chimerism are being researched for reef restoration. However, the effectiveness of these approaches to increase resilience to climate stressors and their large-scale implementation for reef restoration will be limited unless warming and ocean acidification are rapidly controlled (*high confidence*). {Box 5.5, 5.5.2}

Existing ocean governance structures are already facing multi-dimensional, scale-related challenges because of climate change. This trend of increasing complexity will continue (*high confidence*). The mechanisms for the governance of marine Areas Beyond National Jurisdiction (ABNJ), such as ocean acidification, would benefit from further development (*high confidence*). There is also scope to increase the overall effectiveness of international and national ocean governance regimes by increasing cooperation, integration and widening participation (*medium confidence*). Diverse adaptations of ocean related governance are being tried, and some are producing promising results. However, rigorous evaluation is needed of the effectiveness of these adaptations in achieving their goals. {5.5.3}

There are a broad range of identified barriers and limits for adaptation to climate change in ecosystems and human systems (*high confidence*). Limitations include the space that ecosystems require, non-climatic drivers and human impacts that need to be addressed as part of the adaptation response, the lowering of adaptive capacity of ecosystems because of climate change, and the slower ecosystem recovery rates relative to the recurrence of climate impacts, availability of technology, knowledge and financial support and existing governance structures (*medium confidence*). {5.5.2}

TS.6 Extremes, Abrupt Changes and Managing Risks

This chapter assesses extremes and abrupt or irreversible changes in the ocean and cryosphere in a changing climate, to identify regional hot spots, cascading effects, their impacts on human and natural systems, and sustainable and resilient risk management strategies. It is not comprehensive in terms of the systems assessed and some information on extremes, abrupt and irreversible changes, in particular for the cryosphere, may be found in other chapters.

Ongoing and Emerging Changes in the Ocean and Cryosphere, and their Impacts on Ecosystems and Human Societies

Anthropogenic climate change has increased observed precipitation (*medium confidence*), winds (*low confidence*), and extreme sea level events (*high confidence*) associated with some tropical cyclones, which has increased intensity of multiple extreme events and associated cascading impacts (*high confidence*). Anthropogenic climate change may have contributed to a poleward migration of maximum tropical cyclone intensity in the western North Pacific in recent decades related to anthropogenically-forced tropical expansion (*low confidence*). There is emerging evidence for an increase in the annual global proportion of Category 4 or 5 tropical cyclones in recent decades (*low confidence*). {6.3, Table 6.2, Figure 6.2, Box 6.1}

Changes in Arctic sea ice have the potential to influence mid-latitude weather (*medium confidence*), but there is *low confidence* in the detection of this influence for specific weather types. {6.3}

Extreme wave heights, which contribute to extreme sea level events, coastal erosion and flooding, have increased in the Southern and North Atlantic Oceans by around 1.0 cm yr^{-1} and 0.8 cm yr^{-1} over the period 1985–2018 (*medium confidence*). Sea ice loss in the Arctic has also increased wave heights over the period 1992–2014 (*medium confidence*). {6.3}

Marine heatwaves (MHWs), periods of extremely high ocean temperatures, have negatively impacted marine organisms and ecosystems in all ocean basins over the last two decades, including critical foundation species such as corals, seagrasses and kelps (*very high confidence*). Globally, marine heat related events have increased; marine heatwaves, defined when the daily sea surface temperature exceeds the local 99th percentile over the period 1982 to 2016, have doubled in frequency and have become longer-lasting, more intense and more extensive (*very likely*). It is *very likely* that between 84–90% of marine heatwaves that occurred between 2006 and 2015 are attributable to the anthropogenic temperature increase. {6.4, Figures 6.3, 6.4}

Both palaeoclimate and modern observations suggest that the strongest El Niño and La Niña events since the pre-industrial period have occurred during the last fifty years (*medium confidence*). There have been three occurrences of extreme El Niño events during the modern observational period (1982–1983, 1997–1998, 2015–2016), all characterised by pronounced rainfall in the normally dry equatorial East Pacific. There have been two occurrences of extreme La Niña (1988–1989, 1998–1999). El Niño and La Niña variability during the last 50 years is unusually high compared with average variability during the last millennium. {6.5, Figure 6.5}

The equatorial Pacific trade wind system experienced an unprecedented intensification during 2001–2014, resulting in enhanced ocean heat transport from the Pacific to the Indian

Ocean, influencing the rate of global temperature change (*medium confidence*). In the last two decades, total water transport from the Pacific to the Indian Ocean by the Indonesian Throughflow (ITF), and the Indian Ocean to Atlantic Ocean has increased (*high confidence*). Increased ITF has been linked to Pacific cooling trends and basin-wide warming trends in the Indian Ocean. Pacific sea surface temperature (SST) cooling trends and strengthened trade winds have been linked to an anomalously warm tropical Atlantic. {6.6, Figure 6.7}

Observations, both in situ (2004–2017) and based on sea surface temperature reconstructions, indicate that the Atlantic Meridional Overturning Circulation (AMOC) has weakened relative to 1850–1900 (*medium confidence*). There is insufficient data to quantify the magnitude of the weakening, or to properly attribute it to anthropogenic forcing due to the limited length of the observational record. Although attribution is currently not possible, CMIP5 model simulations of the period 1850–2015, on average, exhibit a weakening AMOC when driven by anthropogenic forcing. {6.7, Figure 6.8}

Climate change is modifying multiple types of climate-related events or hazards in terms of occurrence, intensity and periodicity. It increases the likelihood of compound hazards that comprise simultaneously or sequentially occurring events to cause extreme impacts in natural and human systems. Compound events in turn trigger cascading impacts (*high confidence*). Three case studies are presented in the chapter, (i) Tasmania's Summer of 2015–2016, (ii) The Coral Triangle and (ii) Hurricanes of 2017. {6.8, Box 6.1}

Projections of Ocean and Cryosphere Change and Hazards to Ecosystems and Human Society Under Low and High Emission Futures

The average intensity of tropical cyclones, the proportion of Category 4 and 5 tropical cyclones and the associated average precipitation rates are projected to increase for a 2°C global temperature rise above any baseline period (*medium confidence*). Rising mean sea levels will contribute to higher extreme sea levels associated with tropical cyclones (*very high confidence*). Coastal hazards will be exacerbated by an increase in the average intensity, magnitude of storm surge and precipitation rates of tropical cyclones. There are greater increases projected under RCP8.5 than under RCP2.6 from around mid-century to 2100 (*medium confidence*). There is *low confidence* in changes in the future frequency of tropical cyclones at the global scale. {6.3.1}

Significant wave heights (the average height from trough to crest of the highest one-third of waves) are projected to increase across the Southern Ocean and tropical eastern Pacific (*high confidence*) and Baltic Sea (*medium confidence*) and decrease over the North Atlantic and Mediterranean Sea under RCP8.5 (*high confidence*). Coastal tidal amplitudes and patterns are projected to change due to sea level rise and coastal adaptation measures (*very likely*). Projected changes in waves arising from changes in weather patterns, and changes in tides due to sea level rise, can locally enhance or ameliorate coastal hazards (*medium confidence*). {6.3.1, 5.2.2}

Marine heatwaves are projected to further increase in frequency, duration, spatial extent and intensity (maximum temperature) (*very high confidence*). Climate models project increases in the frequency of marine heatwaves by 2081–2100, relative to 1850–1900, by approximately 50 times under RCP8.5 and 20 times under RCP2.6 (*medium confidence*). The largest increases in frequency are projected for the Arctic and the tropical oceans (*medium confidence*). The intensity of marine heatwaves is projected to increase about 10-fold under RCP8.5 by 2081–2100, relative to 1850–1900 (*medium confidence*). {6.4}

Extreme El Niño and La Niña events are projected to *likely* increase in frequency in the 21st century and to *likely* intensify existing hazards, with drier or wetter responses in several regions across the globe. Extreme El Niño events are projected to occur about as twice as often under both RCP2.6 and RCP8.5 in the 21st century when compared to the 20th century (*medium confidence*). Projections indicate that extreme Indian Ocean Dipole events also increase in frequency (*low confidence*). {6.5, Figures 6.5, 6.6}

Lack of long-term sustained Indian and Pacific Ocean observations, and inadequacies in the ability of climate models to simulate the magnitude of trade wind decadal variability and the inter-ocean link, mean there is *low confidence* in future projections of the trade wind system. {6.6, Figure 6.7}

The AMOC will *very likely* weaken over the 21st century (*high confidence*), although a collapse is *very unlikely* (*medium confidence*). Nevertheless, a substantial weakening of the AMOC remains a physically plausible scenario. Such a weakening would strongly impact natural and human systems, leading to 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 TCs in the Atlantic, and an increase in regional sea level around the Atlantic especially along the northeast coast of North America (*medium confidence*). Such impacts would be superimposed on the global warming signal. {6.7, Figure 6.8}

Impacts from further changes in TCs and ETCs, MHWs, extreme El Niño and La Niña events and other extremes will exceed the limits of resilience and adaptation of ecosystems and people, leading to unavoidable loss and damage (*medium confidence*). {6.9.2}

Strengthening the Global Responses in the Context of Sustainable Development Goals (SDGs) and Charting Climate Resilient Development Pathways for Oceans and Cryosphere

There is *medium confidence* that including extremes and abrupt changes, such as AMOC weakening, ice sheet collapse (West Antarctic Ice Sheet (WAIS) and Greenland Ice Sheet (GIS)), leads to a several-fold increase in the cost of carbon emissions

(*medium confidence*). If carbon emissions decline, the risk of extremes and abrupt changes are reduced, creating co-benefits. {6.8.6}

For TCs and ETCs, investment in disaster risk reduction, flood management (ecosystem and engineered) and early warning systems decreases economic loss (*medium confidence*), but such investments may be hindered by limited local capacities, such as increased losses and mortality from extreme winds and storm surges in less developed countries despite adaptation efforts. There is emerging evidence of increasing risks for locations impacted by unprecedented storm trajectories (*low confidence*). Managing the risk from such changing storm trajectories and intensity proves challenging because of the difficulties of early warning and its receptivity by the affected population (*high confidence*). {6.3, 6.9}

Limiting global warming would reduce the risk of impacts of MHWs, but critical thresholds for some ecosystems (e.g., kelp forests, coral reefs) will be reached at relatively low levels of future global warming (*high confidence*). Early warning systems, producing skillful forecasts of MHWs, can further help to reduce the vulnerability in the areas of fisheries, tourism and conservation, but are yet unproven at large scale (*medium confidence*). {6.4}

Sustained long-term monitoring and improved forecasts can be used in managing the risks of extreme El Niño and La Niña events associated with human health, agriculture, fisheries, coral reefs, aquaculture, wildfire, drought and flood management (*high confidence*). {6.5}

Extreme change in the trade wind system and its impacts on global variability, biogeochemistry, ecosystems and society have not been adequately understood and represent significant knowledge gaps. {6.6}

By 2300, an AMOC collapse is *as likely as not* for high emission pathways and *very unlikely* for lower ones, highlighting that an AMOC collapse can be avoided in the long term by CO_2 mitigation (*medium confidence*). Nevertheless, the human impact of these physical changes have not been sufficiently quantified and there are considerable knowledge gaps in adaptation responses to a substantial AMOC weakening. {6.7}

The ratio between risk reduction investment and reduction of damages of extreme events varies. Investing in preparation and prevention against the impacts from extreme events is *very likely* less than the cost of impacts and recovery (*medium confidence*). Coupling insurance mechanisms with risk reduction measures can enhance the cost-effectiveness of adapting to climate change (*medium confidence*). {6.9}

Climate change adaptation and disaster risk reduction require capacity building and an integrated approach to ensure trade-offs between short- and long-term gains in dealing with the uncertainty of increasing extreme events, abrupt changes and cascading impacts at different geographic scales (*high confidence*). {6.9}

Limiting the risk from the impact of extreme events and abrupt changes leads to successful adaptation to climate change with the presence of well-coordinated climate-affected sectors and disaster management relevant agencies (*high confidence*). Transformative governance inclusive of successful integration of disaster risk management (DRM) and climate change adaptation, empowerment of vulnerable groups, and accountability of governmental decisions promotes climate-resilient development pathways (*high confidence*). {6.9}

TS.7 Low-lying Islands and Coasts (Integrative Cross-Chapter Box)

Ocean and cryosphere changes already impact Low-Lying Islands and Coasts (LLIC), including Small Island Developing States (SIDS), with cascading and compounding risks. Disproportionately higher risks are expected in the course of the 21st century. Reinforcing the findings of the IPCC Special Report on Global Warming of 1.5ºC, vulnerable human communities, especially those in coral reef environments and polar regions, may exceed adaptation limits well before the end of this century and even in a low greenhouse gas emission pathway (*high confidence*). Depending on the effectiveness of 21st century mitigation and adaptation pathways under all emission scenarios, most of the low-lying regions around the world may face adaptation limits beyond 2100, due to the long-term commitment of sea level rise (*medium confidence*). LLIC host around 11% of the global population, generate about 14% of the global Gross Domestic Product and comprise many world cultural heritage sites. LLIC already experience climate-related ocean and cryosphere changes (*high confidence*), and they share both commonalities in their exposure and vulnerability to climate change (e.g., low elevation, human disturbances to terrestrial and marine ecosystems), and context-specificities (e.g., variable ecosystem climate sensitivities and risk perceptions by populations). Options to adapt to rising seas, e.g., range from hard engineering to ecosystem-based measures, and from securing current settings to relocating people, built assets and activities. Effective combinations of measures vary across geographies (cities and megacities, small islands, deltas and Arctic coasts), and reflect the scale of observed and projected impacts, ecosystems' and societies' adaptive capacity, and the existence of transformational governance (*high confidence*) {Sections 3.5.3, 4.4.2 to 4.4.5, 5.5.2, 6.8, 6.9, Cross-Chapter Box 2 in Chapter 1}.