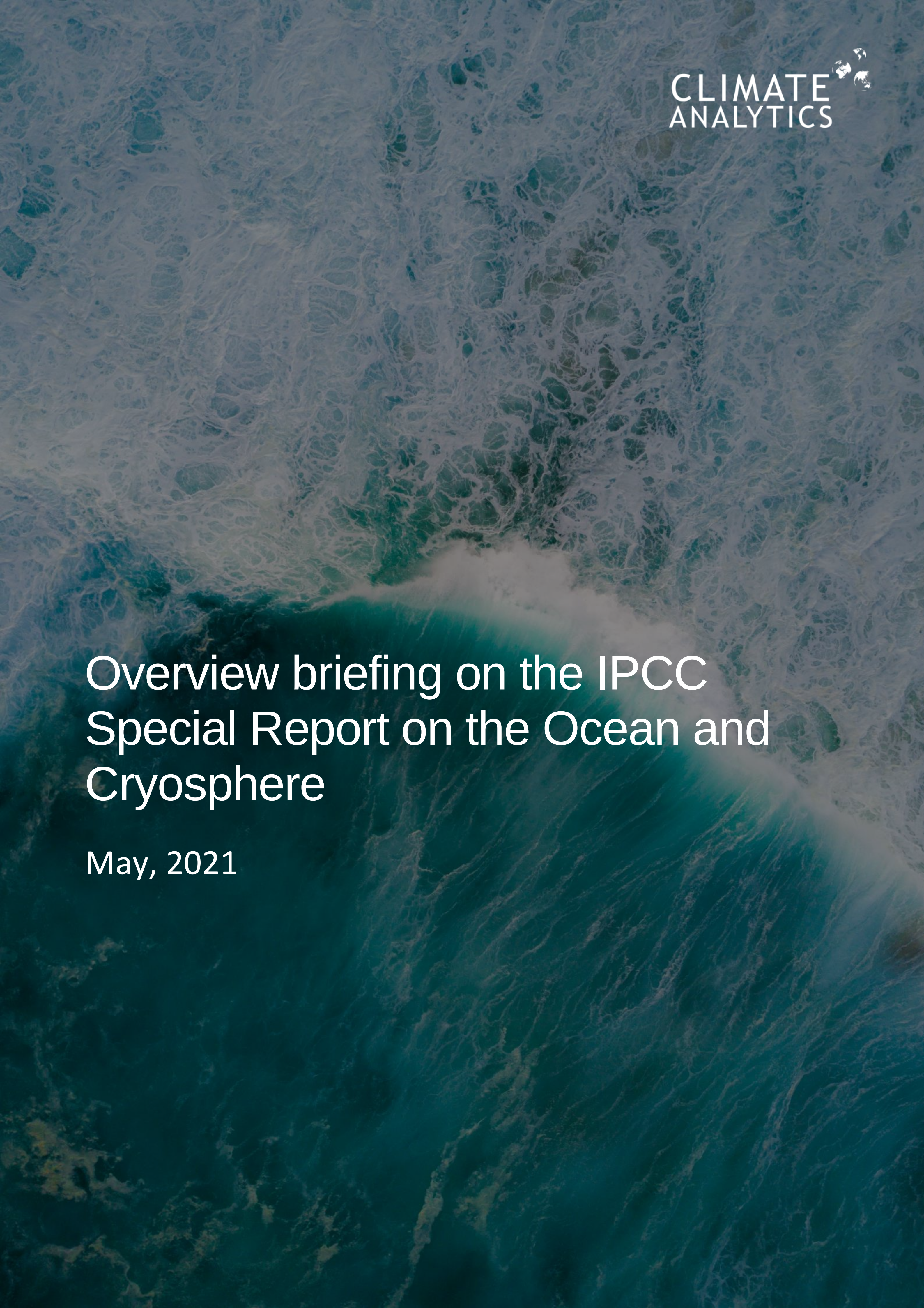

CLIMATE ANALYTICS

Overview briefing on the IPCC Special Report on the Ocean and Cryosphere

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Executive summary

The ocean remembers - the new dimension of climate legacy

The IPCC Special Report on Global Warming of 1.5°C sent a message of urgency. The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate re-emphasises it and adds the dimensions of legacy of our actions. It shows how changes in ocean and ⇒cryosphere will continue for centuries and millennia even after emissions have seized. Sea levels in 2300 might exceed 3.5m under very high emission scenarios, and only achieving the Paris Agreement temperature goal would give a good chance to hold 2300 sea level rise below 1m.

The climate reality to date

Impacts of climate change on ocean and cryosphere are already unequivocal today; marine heatwaves' frequency has doubled in forty years and caused irreversible loss, such as for the Great Barrier Reef that has already lost 50% of its shallow-water corals. Limiting warming to 1.5°C would lead to a decline by a further 70-90% at 1.5°C with larger losses (>99%) at 2°C at the end of the century, emphasizing the need for urgent action but also the loss and damage inferred by climate change to these unique and precious systems already.

Changes are pervasive and observed from high mountains, to the polar regions, to coasts, and into the deep ocean, strongly exposing communities who live in connection to these environments. Loss and damage is already a reality for vulnerable coastal communities, some of them being forced to migrate.

Achieving the goals of the Paris Agreement would substantial reduce climate change impacts

The IPCC assessment reveals the benefits of ambitious mitigation and effective adaptation for sustainable development and, conversely, the escalating costs and risks of delayed action.
It also establishes how adaptation can only delay impacts in ocean and cryosphere, and not be a 'solution'. Limits to adaptation can be reached and exceeded if warming exceeds 1.5°C; adaption costs for coastal adaptation alone for some small island states can amount to several percent of GDP.

Under a high greenhouse gas emission scenario (RCP8.5[1]), at the end of the century, the ocean will have taken up 5-7 times more heat compared to the observed accumulated ocean heat uptake since 1970; marine heatwaves will be 50 times more frequent; sea level rise will reach around 0.84 m with respect to 1986-2005; the global-scale biomass of marine animals across the food-web will decrease by 15%, the ⇒maximum catch potential of fisheries by 20%. Millions of people are and will continue to be threatened by sea-level rise, even under a low emission scenario (RCP2.6[2]).

Post-IPCC science re-emphasizes the importance of limiting warming to below 2°C to avoid tipping points

Recent science has found that at 2°C warming, the West Antarctic Ice Sheet would reach a ⇒tipping point. In addition, emissions implied by present day NDCs would commit the world to sea level rise above 1m in 2300 with the NDCs of the biggest five emitters (China, US, EU, India, Russia) alone contributing about 12cm. In addition, new elevation data has revealed that three times more people might be vulnerable to sea-level rise and coastal flooding than previously thought.

[1] cf Technical note
[2] cf Technical note

New science on permafrost release reveals how abrupt permafrost thaw can lead to increased rates of greenhouse gas emissions.

Impacts on the marine biosphere continue to emerge. In 2020, the Great Barrier Reef has experienced its worst mass bleaching event since 1998 and this in a year without an ⇒El Niño. February 2020 had the highest monthly sea surface temperatures ever recorded on the Great Barrier Reef, and for the first time, severe bleaching has struck all three regions of the Great Barrier Reef – the northern, central and now large parts of the southern sectors.

Selected information on d*ifferential impacts between a Paris Agreement scenario (RCP2.6) and a no-policy high warming scenario (RCP8.5) from the IPCC Special Report*:

Projected impacts and risks	**RCP 2.6**	**RCP 8.5**
Global glacier mass reduction between 2015 and 2100	18 ± 7%	36 ± 11%
Heat uptake by 2100 (compared to the observed accumulated ocean heat uptake since 1970)	2-4 times more heat uptake	5-7 times more heat uptake
Frequency of marine heatwaves by 2081–2100, relative to 1850–1900	20 times more frequent	50 times more frequent
Global mean sea level rise in 2100 with respect to 1986–2005	0.43 m (0.29–0.59 m)	0.84 m (0.61–1.10 m)
Rate of global mean sea level rise in 2100	4 mm yr^{-1} (2-6 mm yr^{-1})	15 mm yr^{-1} (10-20 mm yr^{-1})
Rise in sea level by 2300	0.6–1.07 m	2.3–5.4 m
Ocean oxygen content decline by 2081-2100 relative to 2006–2015	1.6-2.0%	3.2–3.7%
Open ocean surface pH decrease by 2081–2100 relative to 2006–2015	0.036–0.042 pH units	0.287–0.290 pH units
Decrease of the global-scale biomass of marine animals across the food-web by 2080–2099 relative to 1986–2005	4.3 ± 2.0%	15.0 ± 5.9%
Decrease of the maximum catch potential of fisheries by 2100 relative to 1986–2005	3.4–6.4%	20.5–24.1%
Decrease in marine fisheries maximum revenue potential by 2050 relative to 2000	7.1 ± 3.5%	10.4 ± 4.2%

1 Observed changes and impacts

1.1 Observed physical changes and impacts on natural ecosystems

- Physical changes have already been observed in both the ocean and ⇒cryosphere: frequency of marine heatwaves has doubled, the Greenland Ice Sheet lost ice mass at an average rate of 278 ± 11 Gt yr^{-1}; 2.5 million km^2 of Artic June snow cover was lost;
- Sea level rise (+0.16m for 1902-2015) and other climate change impacts strongly threaten coastal ecosystems;
- Shifts in species composition, abundance and biomass production of ecosystems have been observed, with an overall decrease in the maximum catch potential of fisheries (-4.1%).

1.1.1 Observed physical changes

Ocean

The global ocean has warmed unabated since 1970 and has been assessed with *high confidence* to have taken up more than 90% of the excess heat in the climate system. Marine heatwaves have *very likely* doubled in frequency since 1982 and have become longer-lasting, more intense and more extensive. Moreover, the ocean has taken up between 20–30% of total anthropogenic CO2 emissions since the 1980s causing further ⇒ocean acidification, leading open ocean surface pH to decline by a range of 0.017–0.027 pH units per decade. The increasing ⇒ocean stratification, alongside the changing ventilation and biogeochemistry, leads to a loss of oxygen by a range of 0.5-3.3% over the upper 1000m between 1970 and 2010. In addition to that, there is *medium confidence* that the ⇒Atlantic Meridional Overturning Circulation (AMOC) has weakened relative to 1850–1900.

Cryosphere

Ice sheets and glaciers worldwide have lost mass. Between 2006 and 2015, the Greenland Ice Sheet lost ice mass at an average rate of 278 ± 11 Gt yr^{-1} (equivalent to 0.77 ± 0.03 mm yr^{-1} of global sea level rise), the Antarctic Ice Sheet lost mass at an average rate of 155 ± 19 Gt yr^{-1} (0.43 ± 0.05 mm yr^{-1}), and glaciers worldwide outside Greenland and Antarctica lost mass at an average rate of 220 ± 30 Gt yr^{-1} (equivalent to 0.61 ± 0.08 mm yr^{-1} sea level rise). From 1967 to 2018, approximately 2.5 million km^2 of Artic June snow cover was lost. In nearly all high mountain areas, the depth, extent, and duration of snow cover have declined over recent decades. Moreover, there is *very high confidence* that permafrost temperatures have increased to record high levels (1980s-present) including the recent increase by 0.29°C ± 0.12°C from 2007 to 2016 averaged across polar and high-mountain regions globally. Between 1979 and 2018, Arctic sea ice extent has *very likely* decreased for all months of the year; a decline of the areal proportion of multi-year ice at least five years old of approximately 90% has been assessed with *very high confidence*. In the Artic, there is *high confidence* that area burned and frequency of fires (including extreme fires) are unprecedented over the last 10,000 years: an estimated 80,000 km^2 of boreal area was burned globally per year from 1997 to 2011.

Sea level rise

Total Global Mean Sea Level (GMSL) rise for 1902–2015 is 0.16 m (*likely* range 0.12–0.21 m), and there is *high confidence* that the rate of 3.6 mm yr^{-1} ((3.1–4.1 mm yr–1, *very likely* range) is unprecedented over the last century, mostly because of the ice sheets' loss but also because of the thermal expansion of the water. It is *extremely likely* that sea level rise has accelerated due to the combined increased ice loss from the Greenland and Antarctic ice sheets (it is *likely* that mass loss from the Antarctic ice sheet over the period 2007–2016 tripled relative to 1997–2006, and doubled for Greenland) and acceleration of ice flow and retreat in Antarctica, which has the potential to lead to sea level rise of several meters within a few centuries, is observed in West and East Antarctica. It has been assessed with *medium confidence* that 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. Furthermore, there is *high confidence* that increases in tropical cyclone winds and rainfall, and increases in extreme waves, combined with relative sea level rise, exacerbate extreme sea level events and coastal hazards.

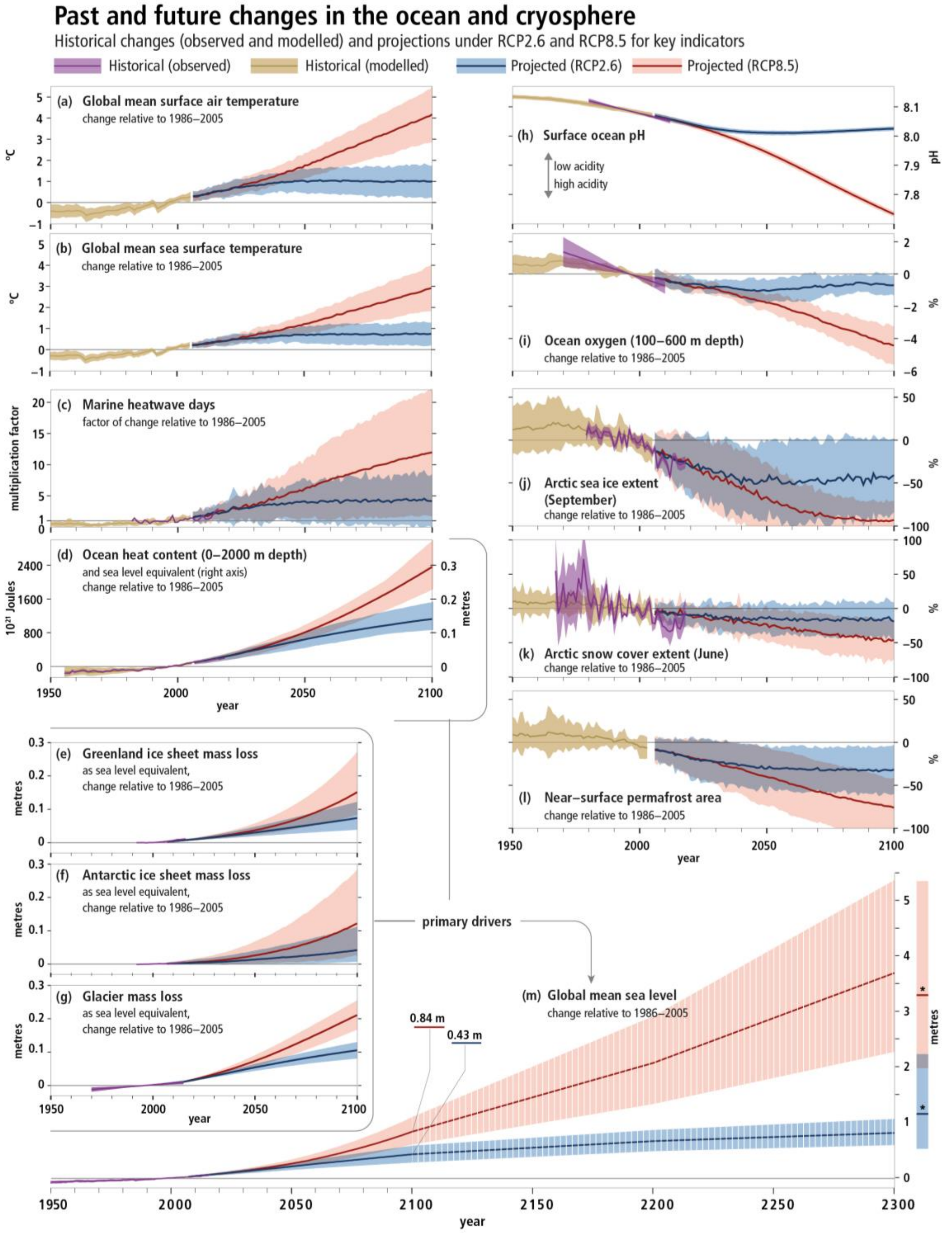

Figure 1: (fig SPM.1) Observed and modelled historical changes in the ocean and cryosphere since 1950, and projected future changes under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios. Changes are shown for: (a) Global mean surface air temperature change with likely range. Ocean-related changes with very likely ranges for (b) Global mean sea surface temperature change; (c) Change factor in surface ocean marine heatwave days; (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 (ε ≈ 0.125 m per 1024 Joules) for observed warming since 1970; (h) Global mean surface pH (on the total scale). Assessed observational trends are compiled from open ocean time series sites longer than 15 years; and (i) Global mean ocean oxygen change (100–600 m depth). Assessed observational trends span 1970–2010 centered on 1996. 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; and components from (e,f) Greenland and Antarctic ice sheet mass loss {3.3.1}; and (g) Glacier mass loss. Further cryosphere-related changes with very likely ranges for (j) Arctic sea ice extent change for September13; (k) Arctic snow cover change for June (land areas north of 60oN); and (l) Change in near-surface (within 3–4 m) permafrost area in the Northern Hemisphere.

1.1.2 Observed impacts on ecosystems

Through the appearance of land previously covered by ice, changes in snow cover, and thawing permafrost, ⇒cryospheric and associated hydrological changes have impacted terrestrial and freshwater species and ecosystems in high mountain and polar regions. Observed rates of range shifts since the 1950s 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.

Shifts in species composition, abundance and biomass production of ecosystems

There is *high confidence* that since about 1950 many marine species across various groups have undergone shifts in geographical range and seasonal activities in response to ocean warming, sea ice change and biogeochemical changes (such as oxygen loss) to their habitats. This has resulted in shifts in species composition, abundance and biomass production of ecosystems, from the equator to the poles. Ocean warming in the 20th century and beyond, along with intensive fishing, has contributed with *medium confidence* to an overall decrease in ⇒maximum catch potential, and in many regions, to reduced fisheries catches, 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 from 1930 to 2010. In some areas, the contribution of changing ocean conditions to the expansion of suitable habitat and/or increases in the abundance of some species, such as in the ice-free waters of the Artic because of sea ice changes, have been assessed with *high confidence*. Nevertheless, these changes are also linked to the habitat contraction of marine mammals and seabirds.

Coastal ecosystems

Coastal ecosystems are among the most affected by ocean warming, and there is *high confidence* that it is in combination with adverse effects from human activities on ocean and land. Habitat contraction, geographical shift of associated species, loss of biodiversity and ecosystem functionality, large-scale coral bleaching events causing worldwide reef degradation since 1997, large-scale mangrove mortality, have already been observed. There is *high confidence* that nearly 50% of coastal wetlands have been lost over the last 100 years, as a result of the combined effects of localised human pressures, sea level rise, warming and ⇒extreme climate events. There is *high confidence* that distributions of seagrass meadows and kelp forests are contracting at low-latitudes and a loss of 36–43% following heat waves has been observed in some areas. Moreover, as vegetated coastal ecosystems are important carbon stores, their loss is responsible for the current release of 0.04–1.46 GtC yr^{-1}.

1.2 Observed impacts on People and Ecosystem services

- Food security and human health have already been negatively impacted by climate change;
- Cultural aspects (local culture, tourism, aesthetics) are also affected;
- Coastal communities are the most exposed to climate-related hazards, some even plan for relocation.

1.2.1 Food security & health

Since the mid-20th century, the shrinking cryosphere in the Arctic and high-mountain areas, along with the increasing frequency of wildfires, has led to predominantly negative impacts on food security, water resources, water quality, livelihoods and health, with costs and benefits being unequally distributed across populations and regions. In the Artic, there is *high confidence* that changes in snow cover, lake and river ice, and permafrost have disrupted access to and the availability of food, livestock, hunting, fishing and gathering areas. Glacier retreat and snow cover changes have contributed to localized declines in agricultural yields in some high mountain regions, including with *medium confidence* the Hindu Kush Himalaya, and the tropical Andes. Moreover, ⇒peak water has been reached before 2019 for 82–95% of the glacier area in the tropical Andes, 40-49% in Western Canada and USA, and 55-67% in Central Europe (including European Alps and Pyrenees) and the Caucasus.

Moreover, negative impacts of cryosphere change on human health have included increased risk of food- and waterborne diseases, malnutrition, injury, and mental health challenges especially among Indigenous peoples. There is *medium confidence* that stored anthropogenic legacy pollutants contaminants (such as mercury) released from melting glaciers and thawing permafrost have affected water quality; an estimated 2.5 tonnes has been released by glaciers to downstream ecosystems across the Tibetan Plateau over the last 40 years. Furthermore, since the early 1980s, there is *high confidence* that the occurrence of harmful algal blooms 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; human communities in poorly monitored areas are among the most vulnerable to these biological hazards.

1.2.2 Cultural aspects

Negative consequences of warming-induced changes in the spatial distribution and abundance of some fish and shellfish have been assessed with *high confidence* for Indigenous peoples and local communities that are dependent on fisheries. Catches, economic benefits, livelihoods, and local culture are affected. Furthermore, there is *medium confidence* that in many mountain regions, tourism and recreation activities (skiing, glacier tourism, mountaineering) have been negatively impacted, alongside the degradation of aesthetic aspects of high mountains (e.g. in the Himalaya, East Africa, the tropical Andes).

1.2.3 Coastal communities

In addition to that, there is *high confidence* that coastal communities are among the most exposed to multiple climate-related hazards, including tropical cyclones, extreme sea levels and flooding, marine heatwaves, sea ice loss, and permafrost thaw. There is *high confidence* that some coastal communities have planned for relocation, even if a diversity of responses has been implemented worldwide, mostly after ⇒extreme events, but also some in anticipation of future sea level rise.

2 Projected changes and risks

2.1 Projected physical changes and risks for ecosystems

- Impacts on the ocean and cryosphere are projected to become greater, leading to some irreversible changes and in some cases to crossing of a ⇒tipping point; under RCP8.5, by the end of the century, a decrease in the open ocean surface pH by around 0.3 pH units, a 10-fold increase in marine heatwaves' frequency and a decrease in global-scale marine biomass across the food-web by 15.0 ± 5.9% are projected.
- Sea level rise is projected to continue to increase under all RCP scenarios (0.84m under RCP8.5 in 2100), with many low-lying megacities and small islands projected to experience historical centennial events at least annually by 2050.

2.1.1 Projected physical changes

Oceans

Over the 21st century the ocean is projected to transition to unprecedented conditions. It is *virtually certain* that it will continue to warm, taking up 5-7 times more heat by 2100 under RCP8.5 than the observed accumulated ocean heat uptake since 1970. The upper ⇒ocean stratification is *very likely* projected to increase, therefore inhibiting vertical nutrient, carbon and oxygen fluxes. Moreover, by 2081–2100 under RCP8.5, ocean oxygen content, upper ocean nitrate content, net primary production and carbon export are projected to decline globally by *very likely* ranges of 3–4%, 9–14%, 4–11% and 9–16% respectively, relative to 2006–2015. In addition to this, it is *virtually certain* that continued carbon uptake by the ocean is projected to decrease the open ocean surface pH by around 0.3 pH units by 2081–2100, relative to 2006–2015, under RCP8.5. Under RCP8.5, oxygen loss between 100 and 600 m depth is projected to *very likely* emerge over 59–80% of the ocean area by 2031–2050 and over 79–91% by 2081-2100.

Furthermore, marine heatwaves are projected to further increase in frequency (notably in the Arctic and the tropical oceans), duration, spatial extent and intensity with *very high confidence*, the latter being projected to increase about 10-fold under RCP8.5 by 2081–2100, relative to 1850–1900 (*medium confidence*). Extreme ⇒El Niño and ⇒La Niña events are projected to *likely* increase in frequency in the 21[st] century and to likely intensify existing hazards, with drier or wetter responses in several regions across the globe. Besides, the ⇒AMOC is projected to *very likely* weaken in the 21st century under all RCPs, causing a decrease in marine productivity in the North Atlantic, more storms in Northern Europe, less Sahelian summer rainfall and South Asian summer rainfall, a reduced number of tropical cyclones in the Atlantic, and an increase in regional sea level along the northeast coast of North America.

Cryosphere

There is *high confidence* that global-scale glacier mass loss, permafrost thaw, and decline in snow cover and Arctic sea ice extent are projected to continue in the near-term (2031–2050), contributing to sea level rise and leading to river run-off, with increases in average winter runoff and earlier spring peaks. There is *medium confidence* that regions with mostly smaller glaciers (e.g., Central Europe, Caucasus, North Asia, Scandinavia, tropical Andes, Mexico, eastern Africa and Indonesia) are projected to lose more than 80% of their current ice mass by 2100 under RCP8.5. In addition to that, there is *high confidence* that Arctic autumn and spring snow cover are projected to decrease, so is low elevation mean winter snow depth in high mountains areas. Moreover, widespread permafrost thaw is projected for this century and beyond (*very high confidence*). The rates and magnitudes of these ⇒cryospheric changes are projected to increase further in the second half of the 21st century in a high greenhouse gas emissions scenario (**Error! Reference source not found.**).

The permafrost region represents a large, climate sensitive reservoir of organic carbon with the potential for some of this pool to be rapidly decayed and transferred to the atmosphere as CO2 and methane as permafrost thaws in a warming climate, thus accelerating the pace of climate change; the potential carbon release from the permafrost zone is estimated at 92 ± 17 Pg C (1 Pg = 1 billion metric tonnes) by 2100 under high emission climate warming trajectories. On the other hand, permafrost thaw gives more potential for stimulated plant growth (the summer growing season is a period of net carbon uptake into terrestrial ecosystems) to offset some CO2.

Sea level rise

The Global Mean Sea Level (GMSL) continues to rise at an increasing rate: in 2100 under RCP8.5, it is projected to have risen by 0.84m (0.61-1.10 m, *likely* range) and to increase by 15 mm yr^{-1} (10–20 mm yr^{-1}, *likely* range) (with regional differences); sea level rise is projected to continue beyond 2100 in all RCP scenarios (mean sea level rise projections are higher by 0.1 m compared to AR5 under RCP8.5 in 2100, and the likely range extends beyond 1 m in 2100 due to a larger projected ice loss from the Antarctic Ice Sheet). Consequently, there is *high confidence* that local sea levels that historically occurred once per century (historical centennial events) are projected to occur at least annually at most locations by 2100 under all RCP scenarios. Many low-lying megacities and small islands (including ⇒SIDS) are projected to experience historical centennial events at least annually by 2050 under RCP2.6, RCP4.5 and RCP8.5. Moreover, there is *high confidence* that an increase in the average intensity and magnitude of storm surges and precipitation rates of tropical cyclones will exacerbate coastal hazards.

2.1.2 *Projected risks for ecosystems*

Oceans

Projected ocean warming and changes in net primary production alter biomass, production and community structure of marine ecosystems. The global-scale biomass of marine animals across the food web is projected to decrease by 15.0 ± 5.9% and, with *medium confidence*, the ⇒maximum catch potential of fisheries by 20.5-24.1% by the end of the 21st century relative to 1986–2005 under RCP8.5. The rate and magnitude of decline is projected to be highest in the tropics, whereas impacts remain diverse in polar regions where ocean warming and sea ice changes are projected to increase marine net primary production. Moreover, ocean warming and acidification (among others) threaten species such as the Antarctic krill, a key prey species for penguins, seals and whales, or corals, which support high biodiversity. There is *high confidence* that almost all warm-water coral reefs are projected to suffer significant losses in their extent and local extinctions, even if global warming is limited to 1.5°C. Furthermore, there is *high confidence* that ocean warming, sea level rise and tidal changes are projected to expand salinization and ⇒hypoxia in estuaries with high risks for some biota leading to migration, reduced survival, and local extinction under high emission scenarios.

Cryosphere

There is *medium confidence* that future land ⇒cryosphere changes will continue to alter terrestrial and freshwater ecosystems in high mountain and polar regions with major shifts in species distributions resulting in changes in ecosystem structure and functioning, such as further upslope migration by lower-elevation species, range contractions, or forest expansion. A loss of globally unique biodiversity is also projected with *medium confidence*. Particularly on Arctic land where there is limited refugia for some High-Arctic species and they are hence outcompeted by more temperate species. Additionally, permafrost thaw and decrease in snow will affect Arctic and mountain hydrology and wildfire, with impacts on vegetation and wildlife: about 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is projected to increase small lake area by over 50% by 2100 for RCP8.5 (*medium confidence*). Furthermore, there is *medium confidence* that wildfire will increase for the rest of this century across most tundra and boreal regions, as well as in some mountain regions.

2.1.3 Tipping points & irreversible changes

The specific trajectories that will materialise crucially depend on if and when certain climate system thresholds or ⇒tipping points are reached. Critical in this ⇒cryospheric context and very uncertain is the tipping point when Greenland ice loss becomes irreversible and the threshold for ice shelf stability in West Antarctica, which depend on surface melt and sub-ice melt, combined with uncertainties surrounding marine ice sheet instability and/or marine ice cliff instability. For Greenland, with more than 2.0°C of summer warming, it becomes *more likely than not* that the Greenland ice sheet crosses a tipping point, entering a long-term state of decline with the potential loss of most or all of the ice sheet over thousands of years. If the warming is sustained, ice loss could become irreversible due to the reinforced surface melt (as the ice sheet surface lowers into warmer elevations) and the ⇒albedo-melt feedback associated with darkening of the ice surface. There is deep uncertainty[1] about whether and when a tipping point will be passed. The chance of passing a tipping-point is substantially higher for RCP8.5 than for RCP2.6. With the prospect of multiple interacting tipping points, the present social cost of carbon increases from 15 to 116 USD per tonne of CO2.

Some irreversible phenomena related to the ocean and cryosphere have been assessed, with low to very high confidence: ocean deoxygenation and ⇒hypoxic events (*medium confidence)*, as well as ⇒ocean acidification (*very high confidence)*, are reversible at surface, but irreversible for centuries to millennia at depth; the partial West Antarctic Ice Sheet collapse is irreversible for decades to millennia (*low confidence)*; the Greenland ice sheet decay is irreversible for millennia (*high confidence)*; ice-shelf collapses are possibly irreversible for centuries (*low confidence)*; changes in warm coral reefs are irreversible due to irreversible changes in habitat composition (*very high confidence)*.

Critical thresholds have been studied for some species. There is *medium confidence* that the most widely distributed, habitat-forming species in deep water (e.g., Lophelia pertusa, a cold-water coral) cannot survive with warming above water temperatures of 14°C-15°C or oxygen concentrations below 1.6 ml l^{-1} in the Gulf of Mexico, 3.3 ml l^{-1} in the north Atlantic, 2 ml l^{-1} in the Mediterranean, and 0.5–1.5 ml l^{-1} in the south-east Atlantic. Rocky shore species (e.g., barnacles, mussels) have been assessed with *high confidence* to be extremely sensitive to extreme temperature events and to acidification, critical thresholds being expected to be reached at warming of 1.5°C and above. The same goes for kelp forests, which are already experiencing large-scale changes, and are projected with *very high*

[1] A situation of deep uncertainty exists when experts or stakeholders do not know or cannot agree on: (1) appropriate conceptual models that describe relationships among key driving forces in a system; (2) the probability distributions used to represent uncertainty about key variables and parameters; and/or (3) how to weigh and value desirable alternative outcomes.

confidence to experience higher frequency of mass mortality events as the exposure to extreme temperature rises.

2.2 Projected risks for People and Ecosystem services

- Food security, as well as human health, are projected to become increasingly affected by climate change. In some regions there is a projected decrease in maximum fisheries catch potential of -50%;
- Climate change impacts on marine ecosystems and their services is projected to continue putting key cultural dimensions of lives and livelihoods at risk, particularly for Indigenous communities;
- Increased mean and extreme sea level, alongside ocean warming and ⇒acidification, are projected to exacerbate risks for human communities in low-lying coastal areas.

2.2.1 Food security

There is *medium confidence* that future shifts in fish distribution and decreases in their abundance and fisheries catch potential due to climate change affect food security of marine resource-dependent communities, as well as marine fisheries maximum revenue potential, which are projected to be negatively impacted in 89% of the world's fishing countries under the RCP8.5 scenario by the 2050s relative to the current status. There is *medium confidence* that many populations that are already facing challenges in food insecurity reside in low-latitude regions such as in the Pacific Islands and West Africa where maximum fisheries catch potential is projected to decrease by -50% in some regions, and where land-based food production is also at risk. These populations are also estimated to have the highest proportion of their micronutrient intake relative to the total animal sourced food, which increases their vulnerability. Moreover, sea level rise will affect agriculture mainly through land submergence, soil and fresh groundwater resources salinisation, and land loss due to permanent coastal erosion, with consequences for production, livelihood diversification and food security, especially in heavily coastal agriculture-dependent countries such as Bangladesh.

There is *medium confidence* that range shifts under ocean warming will alter the distribution of fish stocks across political boundaries. This redistribution between countries could destabilise existing international fisheries agreements and increase the risk of international conflicts.

2.2.2 Health

There is *medium confidence* that global warming compromises seafood safety through human exposure to elevated bioaccumulation of persistent organic pollutants (POPs) and mercury in marine plants and animal: in the northeastern Pacific, concentrations of MeHg (methylmercury) and polychlorinated biphenyls (PCBs) in top predators could increase by 8% and 3%, respectively, by 2100 under RCP8.5 relative to current levels. This accumulation causes long-term contamination of traditional seafoods, particularly affecting Arctic ecosystems and their associated indigenous communities. Moreover, there is *medium confidence* that projected conditions of increased coastal flooding from storm surges and sea level rise will increase exposure to waterborne disease, such as Vibrio, whose suitable area is projected to be nearly multiplied by two between 2015 and 2050 in the Baltic Sea for both RCP4.5 and RCP8.5 scenarios. Besides, the occurrence of harmful algal blooms, their toxicity and risk on natural and human systems (water discolouration and foam accumulation, anoxia, contamination of seafood with toxins, disruption of food-webs and massive large-scale mortality of marine biota) are projected to continue to increase with warming and rising CO2 in the 21st century *(high confidence)*.

There is *medium confidence* that glacier decline is projected to accelerate the release of stored anthropogenic legacy pollutants; projections indicate that all scenarios of future climate change will enhance the mobilisation of metals, such as mercury, in metamorphic mountain catchments. Glacier dissolved organic carbon (DOC) losses are expected to accelerate as they shrink, leading to a cumulative annual loss of roughly 15 Tera gC yr^{-1} of glacial DOC by 2050 from melting glaciers and ice sheets. Permafrost degradation is also a major and increasing source of bioavailable DOC.

2.2.3 Cultural aspects

There is *medium confidence* that disaster risks to human settlements and livelihood options in high mountain areas and the Arctic are expected to increase, due to future changes in hazards such as floods, fires, landslides, avalanches, unreliable ice and snow conditions, and increased exposure of people and infrastructure. Indeed, permafrost thaw-induced subsidence of the land surface is projected to impact overlying urban and rural communication and transportation infrastructure in the Arctic and in high mountain areas, provided that the majority of Arctic infrastructure is located in regions where permafrost thaw is projected to intensify by mid-century. Furthermore, the decline in warm-water coral reefs is projected to greatly compromise the services they provide to society, such as coastal services or tourism (*high confidence)*. Moreover, there is *high confidence* that high mountain tourism, recreation and cultural assets are projected to be negatively affected by future ⇒cryospheric changes.

There is *medium confidence* that climate change impacts on marine ecosystems and their services put key cultural dimensions of lives and livelihoods at risk, particularly for Indigenous communities. This includes potentially rapid and irreversible loss of culture and local knowledge and Indigenous knowledge (for example, the shape of shores in many low-lying islands in the Pacific, leading to modification or disappearance of geomorphological features that represent gods and mythological ancestors), as well as the degradation of aesthetic and inspirational values of marine biodiversity and ecosystems that are important to the psychological and spiritual well-being of people, including film, literature, art and recreation.

2.2.4 Human communities in low-lying coastland areas

There is *high confidence* that increased mean and extreme sea level, alongside ocean warming and ⇒acidification, are projected to exacerbate risks for human communities in low-lying coastal areas. In the absence of more ambitious adaptation efforts compared to today and under current trends of increasing exposure and vulnerability of coastal communities, there is *very high confidence* that impacts such as erosion, land loss, flooding, salinization, and cascading impacts due to mean sea level rise and extreme events are projected to significantly increase throughout this century under all greenhouse gas emissions scenarios. Under the same assumptions, annual coastal flood damages are projected to increase by the order of magnitude of 2 to 3 by 2100 compared to today. Some island nations are therefore likely to become uninhabitable, though habitability thresholds remain extremely difficult to assess. While ambitious adaptation has the potential to reduce risks in many locations (which does not prevent residual risks and associated losses from occurring), there is *high confidence* that rural and poorer areas may be challenged to afford such investments with relative annual costs for some small island states amounting to several percent of GDP.

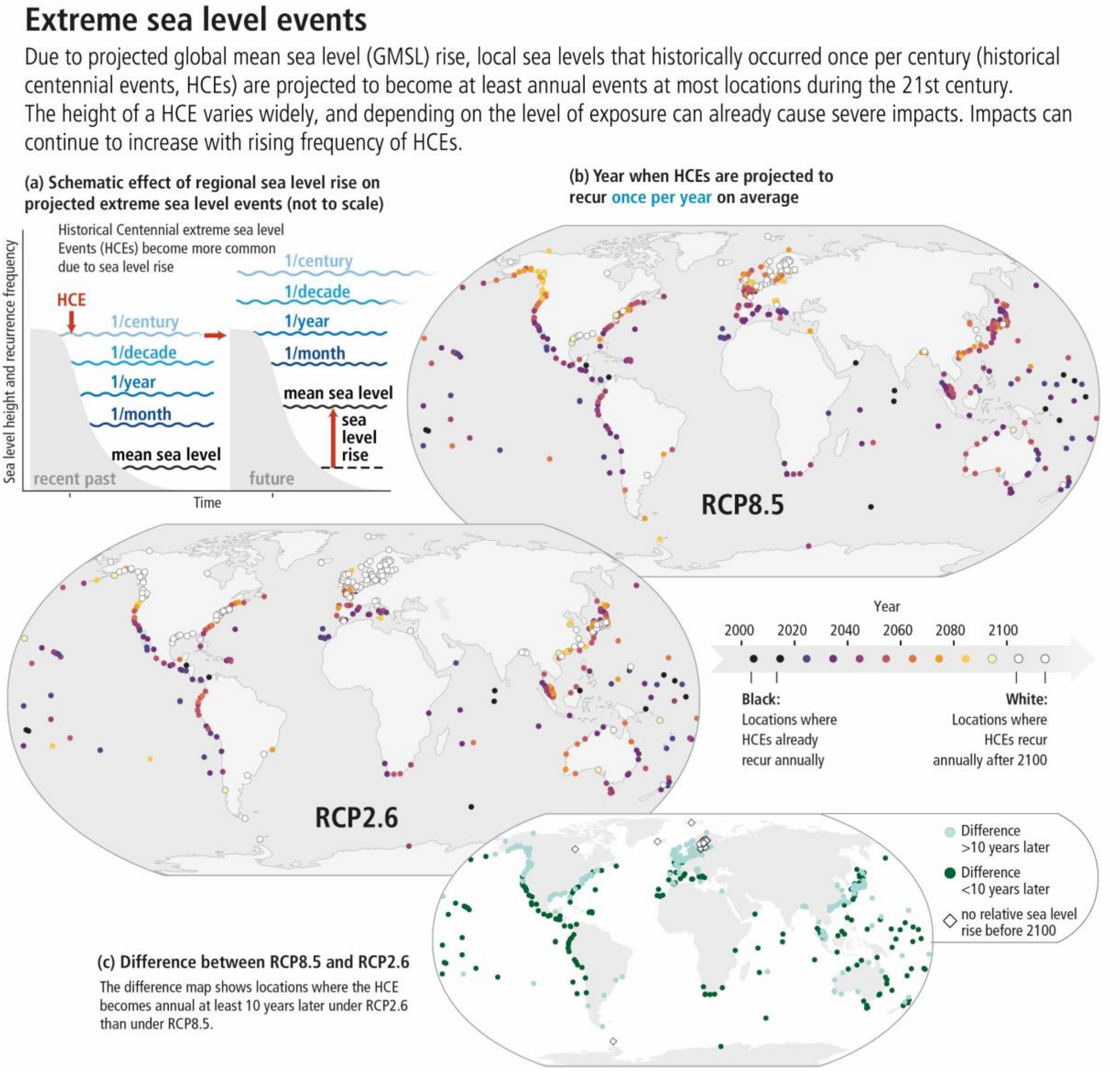

Figure 2: (fig SPM.4) The effect of regional sea level rise on extreme sea level events at coastal locations. (a) Schematic illustration of extreme sea level events and their average recurrence in the recent past (1986–2005) and the future. As a consequence of mean sea level rise, local sea levels that historically occurred once per century (historical centennial events, 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.

2.3 Avoidable risks by limiting warming to likely below 2°C

- Limiting warming to likely below 2°C is expected to substantially reduce the probability and magnitude of most of global warming impacts on the ocean and cryosphere: in 2100, under RCP2.6, compared to RCP8.5, the rise in sea level is projected to be half as high, the frequency of marine heatwaves two and a half times lower, the decrease in ⇒maximum catch potential four times lower.
- People and ecosystems services would be less affected by these impacts, such as extreme events;
- The capacity of organisms and ecosystems to adjust and adapt is higher at lower emissions scenarios.

2.3.1 RCP2.6 vs RCP8.5

Limiting global warming to likely below 2°C is expected to substantially reduce the probability and magnitude of most of global warming impacts on the ocean and cryosphere. The following table brings together some projected impacts and risks under RCP2.6 and RCP8.5:

Projected impacts and risks	**RCP 2.6**	**RCP 8.5**
Glacier mass reduction between 2015 and 2100	18 ± 7%	36 ± 11%
Sea level contribution of glacier mass reduction	94 ± 25 mm	200 ± 44 mm
Arctic autumn and spring snow cover decrease relative to 1986–2005	5–10% in the near-term + no further losses	5–10% in the near-term + additional 15–25% loss by 2100
Decreases in low elevation mean winter snow depth in high mountains areas for 2081-2100 compared to 1986–2005	10–40%	50-90%
Near-surface (within 3–4 m) permafrost area shrinking by 2100	24 ± 16%	69 ± 20%
Heat uptake by 2100 (compared to the observed accumulated ocean heat uptake since 1970)	2-4 times more heat uptake	5-7 times more heat uptake
Frequency of marine heatwaves by 2081–2100, relative to 1850–1900	20 times more frequent	50 times more frequent
Global mean sea level rise in 2100 with respect to 1986–2005	0.43 m (0.29–0.59 m)	0.84 m (0.61–1.10 m)
Rate of global mean sea level rise in 2100	4 mm yr^{-1} (2-6 mm yr^{-1})	15 mm yr^{-1} (10-20 mm yr^{-1})
Rise in sea level by 2300	0.6–1.07 m	2.3–5.4 m
Ocean oxygen content decline by 2081-2100 relative to 2006–2015	1.6-2.0%	3.2–3.7%
Open ocean surface pH decrease by 2081–2100 relative to 2006–2015	0.036–0.042 pH units	0.287–0.290 pH units
Decrease of the global-scale biomass of marine animals across the foodweb by 2080–2099 relative to 1986–2005	4.3 ± 2.0%	15.0 ± 5.9%
Decrease of the maximum catch potential of fisheries by 2100 relative to 1986–2005	3.4–6.4%	20.5–24.1%
Declines in zooplankton biomass in the 21st century relative to 1990–1999	6.4 ± 0.79%	13.6 ± 1.70%
Decrease in marine fisheries maximum revenue potential by 2050 relative to 2000	7.1 ± 3.5%	10.4 ± 4.2%

Table 1: Selected projected impacts and risks on the ocean, cryosphere and sea level rise under RCP2.6 and RCP8.5. Data is given with likely ranges.

2.3.2 Biodiversity and structure of ecosystems

Risks of severe impacts on biodiversity, structure and functioning of coastal ecosystems are higher for elevated temperatures under high compared to low emissions scenarios in the 21st century and beyond. And, there is *high confidence* that the capacity of organisms and ecosystems to adjust and adapt is higher at lower emissions scenarios. All coastal ecosystems assessed are projected to face increasing risk level, from moderate[1] to high risk[2] under RCP2.6 and high to very high risk[3] under RCP8.5 by 2100. The ecosystems expected to be at very high risk under the high emission scenario are coral reefs (transition from high to very high risk 0.6°C–1.2°C), seagrasses meadows (2.2°C–3.0°C), kelp forests (2.2°C–2.8°C) and rocky shores (2.9°C– 3.4°C). The ecosystems at moderate to high risk under future emission scenarios are mangrove forests (transition from moderate to high risk at 2.5°C–2.7°C of global sea surface warming), estuaries and sandy beaches (2.3°C–3.0°C), and salt marshes (transition from moderate to high risk at 1.8°C–2.7°C and from high to very high risk at 3.0°C–3.4°C). Whilst no changes in kelp species richness are projected under RCP2.6, more than 50% richness loss is projected under RCP8.5 in some areas. In all coastal ecosystems, multiple climate hazards will emerge from historical variability in the 21st century under RCP8.5, while the time of emergence will *very likely* be later and with less climate hazard under RCP2.6.

2.3.3 People and ecosystem services

As shown above in **Error! Reference source not found.**, limiting warming to likely below 2°C could reduce sea level rise by 0.4m compared to RCP8.5, thus significantly limiting risks for coastal areas. Figure 2 highlights that what used to be a historical centennial sea level event is projected to become an annual event, with increased delay under RCP2.6 which gives more time for communities to adapt. Moreover, under RCP2.6, the global biomass of marine animals, including those that contribute to fisheries, is projected to *very likely* decrease three times less than under RCP8.5, and four times less for the maximum catch potential, limiting food security risks.

Furthermore, avoidable risks on the biodiversity and structure of ecosystems are avoidable risks for the well-being and identity of local communities, as highlighted in previous paragraphs. Coastal ecosystems such as mangroves or coral reefs also provide significant protection against sea-level rise, this protection being much more efficient at a level of warming below 2°C.

3 Implementing Responses to Ocean and Cryosphere Change

3.1 The need for stringent mitigation to limit ocean and cryosphere impacts

- Urgent and ambitious emission reductions are required to reduce the need and cost of adaptation, and to reduce the risks of surpassing limits to adaptation.
- International and intergenerational increased ambition and justice are needed.

[1] Impacts/risks are detectable and attributable to climate change with at least medium confidence.
[2] Significant and widespread impacts/risks.
[3] Very high probability of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.

- People with the highest exposure and vulnerability are often those with the lowest capacity to respond.

Societies will be exposed 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, confronting them with the unavoidable need to adapt. For example, although ambitious adaptation will not eradicate end-of-century sea level rise risk (*medium confidence*), it will help to buy time in many locations and therefore help to lay a robust foundation for adaptation beyond 2100.

There is *very high confidence* that enabling climate resilience and sustainable development depends critically on urgent and ambitious emission reductions. Indeed, effective mitigation at a global scale will reduce the need and cost of adaptation and reduce the risks of surpassing limits to adaptation. The more and earlier mitigation is implemented, the less severe adaptation measures are needed; the higher the sea levels rise, the more challenging is coastal protection.

There is *high confidence* that the scale and cross-boundary dimensions of changes challenge the ability of communities, cultures and nations to respond effectively within existing governance frameworks. For example, the temporal scales of climate change impacts and their societal consequences operate on time horizons which are longer than those of governance arrangements (e.g., planning cycles, public and corporate decision-making cycles, and financial instruments vs long-term changes including shifts in the frequency and intensity of extreme events). Examples include changing landslides and floods in high mountain regions and risks to important species and ecosystems in the Arctic, as well as to low-lying nations and islands, small island nations, other coastal regions, and to coral reef ecosystems.

There is *high confidence* that the capacity of governance systems in polar and ocean regions to respond to climate change impacts has strengthened recently, but this development is not sufficiently rapid or robust to adequately address the scale of increasing projected risks. In high mountains, coastal regions and small islands, it has been assessed that difficulties remain in coordinating climate adaptation responses, due to the many interactions of climatic and non-climatic risk drivers (such as inaccessibility, demographic and settlement trends, or land subsidence caused by local activities) across scales, sectors and policy domains (*high confidence)*. People with the highest exposure and vulnerability are often those with the lowest capacity to respond. Thus, profound economic and institutional transformations are needed if climate-resilient development is to be achieved. Urgent and ambitious emission reductions coupled with coordinated sustained and increasingly ambitious adaptation actions are essential.

3.2 Adaptation

- Several adaptation options exist, such as hard engineering or ecosystem-based adaptation;
- Nevertheless, most of them face many barriers, such as financial, technological, ecological, institutional, governance barriers, but also limited effectiveness (e.g., ineffectiveness beyond 1.5°C warming for coral reefs), side effects, etc.
- Under a warming of 1.5°C adaptation and accommodation needs would be lower and communities would have more time to respond to climate change impacts.

3.2.1 Protection, accommodation, socioinstitutional responses

In the coming decades, there is *high confidence* that reducing local drivers of exposure and vulnerability such as coastal urbanization and human-induced subsidence constitute effective responses. Coastal accommodation and protection against sea level rise include hard protection (e.g., dikes), sediment-based protection, early warning systems for flood events or flood-proofing of buildings, coastal advance, ecosystem-based adaptation (coral conservation/restoration, wetland conservation/restoration), and retreat (planned or forced, which can be described as a response rather than accommodation) (Table 2). At a global scale, coastal protection can reduce flood risk by 2-3 orders of magnitude during the 21st century, with effects being very disparate between regions (*high confidence)*.

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.

3.2.2 Ecosystem-based adaptation and its limits

Ecosystem-based adaptation (EbA) uses the range of opportunities for sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. The cost-effectiveness of EbA approaches varies between marine ecosystem types; for example, coral reefs and salt-marshes performed best at reducing wave heights, whilst salt marshes and mangroves were two to five times cheaper than submerged breakwaters for wave heights of less than half a meter.

There is *high confidence* that 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. Such adaptation does, however, assume that the climate can be stabilised, which limits its effectiveness under changing climatic conditions, these limits being currently difficult to determine.

Coastal EbA faces many barriers (Table 2): physical constraints (space requirements and coastal squeeze), recovery periods of natural systems, poor condition of ecosystems inhibiting their performance, and the fast pace of climate change, which lead to the the exceedance of the adaptive capacity of ecosystems. Moreover, social and cultural norms with conflicting and competing values, lack of public knowledge on climate change and distrust of information sources, as well as populations increasingly distanced from and unconcerned about nature, may constrain ecosystem-based adaptation response.

3.2.3 Blue Carbon

Coastal blue carbon ecosystems, such as mangroves, salt marshes and seagrasses, can help reduce the risks and impacts of climate change, with many co-benefits in terms of biodiversity, fisheries production, coastal protection (Table 2**Error! Reference source not found.**); some 151 countries around the world contain at least one of these coastal blue carbon ecosystems. Nevertheless, the maximum global mitigation benefits of cost-effective coastal wetland restoration are *unlikely* to be more than 2% of current total emissions from all sources. The climate mitigation effectiveness of other natural carbon removal processes in coastal waters, such as seaweed ecosystems and proposed nonbiological marine CO_2 removal methods, are smaller or currently have higher associated uncertainties. In particular, the feasibility of climate mitigation by open ⇒ocean fertilisation 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 (such as ⇒ocean acidification) and low acceptability.

3.2.4 Sea level rise: costs, benefits and trade-offs of available options

Responses to sea-level rise often have many co-benefits, as can be seen in Table 2. When implemented together, hard and soft engineering responses provide social and ecological co-benefits with reduced damage costs. For example, without reefs, damage from flooding and costs from frequent storms would double and triple respectively, while countries from Southeast Asia, East Asia and Central America could each save an excess of 400 million USD through good reef management. However, coral reef restoration options may be ineffective if global warming exceeds 1.5°C, because corals are already at high risk at current levels of warming, which is one of many limits to adaptation. Moreover, there is *high confidence* that responses to sea level rise and associated risk reduction present society with profound governance challenges, resulting from the uncertainty about the magnitude and rate of future sea level rise, vexing trade-offs between societal goals (e.g., safety, conservation, economic development, intra- and inter-generational equity), limited resources, and conflicting interests and values among diverse stakeholders.

Table 2 summarizes and assesses responses to sea level rise in terms of their effectiveness, costs, co-benefits, drawbacks, economic efficiency, and associated governance challenges:

(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 expan–sion 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}

Table 2: (fig SPM.5c) Summary and assessment of responses to sea level rise in terms of their effectiveness, costs, co-benefits, drawbacks, economic efficiency and associated governance challenges.

3.2.5 Barriers for adaptation to climate change

There is *high confidence* that adaptation comes with financial, technological, ecological, institutional, and governance barriers. For example, fishery adaptation (increasing resilience of habitats, providing refugia for species with shifting distributions, conserving biodiversity, cooperative international fisheries arrangements) faces increasing occurrence and severity of storms which limits fishing time, technologically poor boats and fishing equipment, and lack of access to credit and markets, among others. Conflicting interests and values of stakeholders, the path-dependent nature of organisations, resistance to change, and inadequate collaboration and public awareness have been reported as socioinstitutional barriers (*high confidence*).

Moreover, there is *high confidence* that the temporal scales of climate change impacts in ocean and cryosphere and their societal consequences operate on time horizons which are longer than those of governance arrangements (e.g., planning cycles, public and corporate decision making cycles, and financial instruments), thus challenging the ability of societies to adequately prepare for and respond to long-term changes including shifts in the frequency and intensity of extreme events (e.g., changing landslides and floods in high mountain regions).

There is *high confidence* that people with the highest exposure and vulnerability are often also those with the lowest adaptive capacity, particularly in low-lying islands and coasts, and Arctic and high mountain regions with development challenges. Coastal protection depends on investments on the order of tens to several hundreds of billions of US$ per year, rural and poorer areas may thus be challenged to afford such investments with relative annual costs for some small island states assessed to amount to several percent of GDP (*high confidence)*. In Pacific Islands and Coastal Territories, fisheries adaptation will require adaptation costs considered beyond the means of most of these countries. In West African fisheries, loss of coastal ecosystems and productivity are estimated to require 5–10% of countries' GDP in adaptation costs.

3.2.6 Co-benefits associated with near-term action in line with 'likely below 2°C'

Near-term action in line with warming of 1.5°C will limit climate change impacts and risks, as highlighted above. Under all pathways, historical centennial sea level events are projected to become annual events, but with increased delay under RCP2.6. Moreover, it allows to protect coastal ecosystems such as mangroves or coral reefs while preserving their protection effect against sea-level rise. Thus, not only would adaptation and accommodation needs be lower, but communities would have more time to respond to climate change impacts.

3.3 Loss and Damage

- Natural and human loss and damage have already occurred and are projected for the future even with major adaptation efforts;
- In some places, limits to adaptation have been/will be reached: for vulnerable systems, particularly for Artic communities and urban atoll islands, a sizeable part of the risk reduction is achieved through relocation.

3.3.1 Limits to adaptation, maximum potential response

There is *medium confidence* that even with major adaptation efforts, residual risks and associated losses are projected to occur. For example, the increase in frequency of extreme ⇒El Niño continues for up to a century even after global mean temperature has stabilised at 1.5°C, thereby challenging the limits to adaptation. Figure 3 shows that for vulnerable systems, particularly for Artic communities and urban atoll islands, a sizeable part of the risk reduction is achieved through relocation even when considering the maximum potential response[1]: retreat, planned or forced, may not be considered to be adaptation, and testifies that we have already reached a point of no return with regard to the impact of climate change on some coastal areas. The 'potential effectiveness' column of Table 2 shows that ecosystem-based adaptation options are in fact effective only for low rates of sea level rise, thus strongly limited. Hence, not only loss and damage have already been experienced in the last decades, but more are projected due to inertia and adaptation limits, even when limiting global warming to 1.5°C.

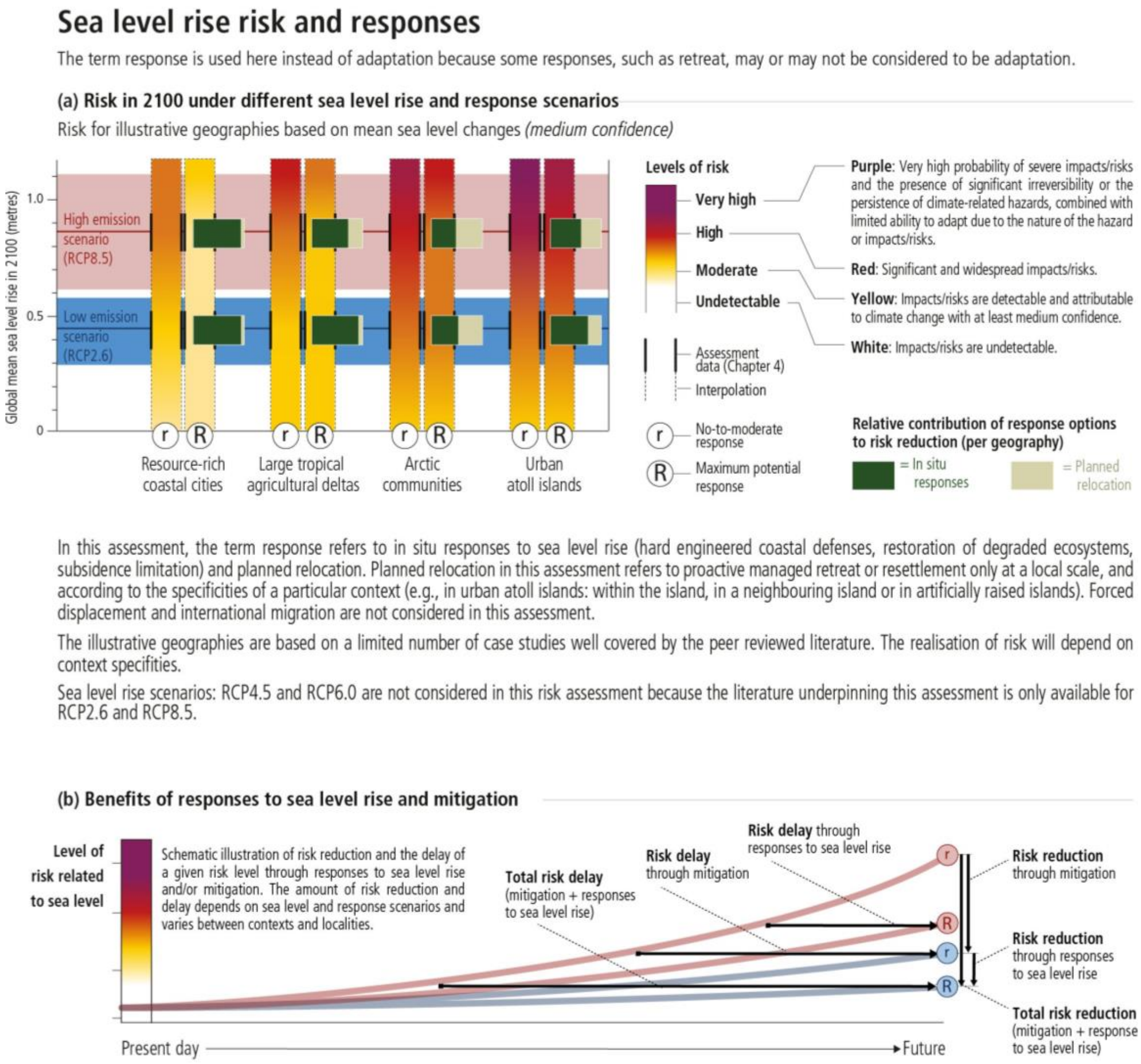

Figure 3: (fig SPM.5ab) (a) shows the combined risk of coastal flooding, erosion and salinization for illustrative geographies in 2100, due to changing mean and extreme sea levels under RCP2.6 and RCP8.5 and under two response scenarios. The assessment does not account for changes in extreme sea level beyond those directly

[1] Combination of responses implemented to their full extent and thus significant additional efforts compared to today, assuming minimal financial, social and political barriers.

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. 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. 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. 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, 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.

3.3.2 Loss and damage in natural systems

Corals are among the most affected by climate change and have already suffered severe degradation and loss. Mass bleaching events have become more frequent and more intense, as experienced in 2017 when 94.3% of corals were bleached in the Gulf. There is *high confidence* that if recovery occurs, it is slow (more than 15 years). The Great Barrier Reef has already lost 50% of shallow-water corals. Projections show future massive loss and damage: there is *very high confidence* that almost all coral reefs will degrade from their current state, even if global warming remains below 2°C, and the remaining shallow coral reef communities will differ in species composition and diversity from present reefs. Coral reefs are projected to decline by a further 70-90% at 1.5°C with larger losses (>99%) at 2°C. Any coral reefs that do survive to the end of the century will not be the same because of irreversible changes in habitat structure and functioning, including species extinctions and food-web disruptions.

In high mountains areas, terrestrial and freshwater biota has already experienced several changes and losses. There is *medium evidence* and *high agreement* that many mountain animals have been observed to change their behaviour in a subtle manner, for example, foraging or hunting behaviour, with negative impacts on reproductive fitness for some species such as for reindeers. There is *robust evidence* that winter-white animals for which coat or plumage color is cued by day length have confronted more days with brown snowless ground, which has already contributed to range contractions for several species, including hares and ptarmigan. A number of cold-adapted species have decreased in abundance below a threshold of watershed glacier cover varying from 19-32%. Reduced production of large copepods and euphausiids have been observed in the southeastern Bering Sea, as well as a declining benthic biomass in the northern Bering Sea and southern Chukchi Sea. Increased mortality rates of walrus calves and of ice-breeding seals have occurred. Changes in sea ice patterns are driving demographic changes in polar bears, including declines in some populations, e.g. because of less ice driving them to travel over greater distances and swim more than previously both in offshore and in coastal areas.

3.3.3 Loss and damage in human systems

Natural loss and damage can lead to cultural (identity, traditions, customs) loss and damage. Degradation and loss of biodiversity and habitats negatively impact the ecosystem features that are currently appreciated by human communities, such as coral reefs, mangroves, charismatic species (such as some marine mammals and seabirds) and geomorphological features (e.g., sandy beaches), leading to a deterioration of the sense of place, pride, identity and opportunities for inspiration, spirituality, recreation and well-being; this is being experienced in the Great Barrier Reef, affecting 8 300 people across multiple cultural groups.

There is robust evidence of planned relocation taking place worldwide in low-lying zones exposed to the impacts of coastal hazards: in 2017, 18.8 million people were displaced by disasters, of which 18 million were displaced by weather-related events including 8.6 million people displaced by floods and 7.5 million by storms, with hundreds of millions more at risk. Costs of retreat vary, e.g. 10,000 US$ in Fiji or 100,000 US$ per person in Alaska and in the Isle of Jean Charles in the USA. Relocated communities have often become further impoverished, because they are removed from cultural and material resources on which they rely, compounded by poor implementation processes that may fail to ensure fairness, social and environmental justice and well-being.

Environmentally driven migration and displacement gained major attention over the last decade in the international policy community, with programs such as the Nansen Initiative or the Platform on Disaster Displacement. Governments are further encouraged by civil society to relocate people at risk and displaced populations out of disaster-prone areas to avoid potential casualties. Globally, about 6,000 to 17,000 km^2 of land is expected to be lost during the 21^{st} century due to enhanced coastal erosion associated with sea level rise, in combination with other drivers. This could lead to displacement of 1.6-5.3 million people and associated cumulative costs of 300 to 1000 billion US$.

4 Hot topics since the SROCC and beyond

This section summarizes relevant studies, some of which have been published after the Special Report, that provide further relevant context on the IPCC's findings.

Sea-level rise and the need for a longer-term perspective in the political discourse: Sea-level commitment as a gauge for climate policy, Clark et al., 2018[1]

In this paper, the authors argue that a well-defined relationship between global mean sea-level rise (GMSLR) and cumulative carbon emissions can be used to inform policy about emission limits to prevent dangerous and essentially permanent anthropogenic interference with the climate system. Response time of GMSLR to climate change due to CO2 emissions is much longer than that of temperature. Due to contributions from glaciers, deep-ocean warming and ice-sheet melting, GMSLR will continue for many millennia. Clark et al. find that the < 2°C scenario would result in a rise of 0.9 m (0.5 to 1.2 m) in 2300 and 7.4 m (6.0 to 8.8 m) in 9000, whereas the < 1.5°C scenario would result in 0.6 m (0.4 to 0.9 m) in 2300 and 3.7 m (2.8 to 4.7 m) in 9000. Thus, even if we successfully limit temperature changes, the long-term sea-level impacts may argue for more restrictive emission quotas during the twenty-first century, continued reductions in quotas beyond the twenty first century or other long-term policies to mitigate or adapt to continuing sea level rise.

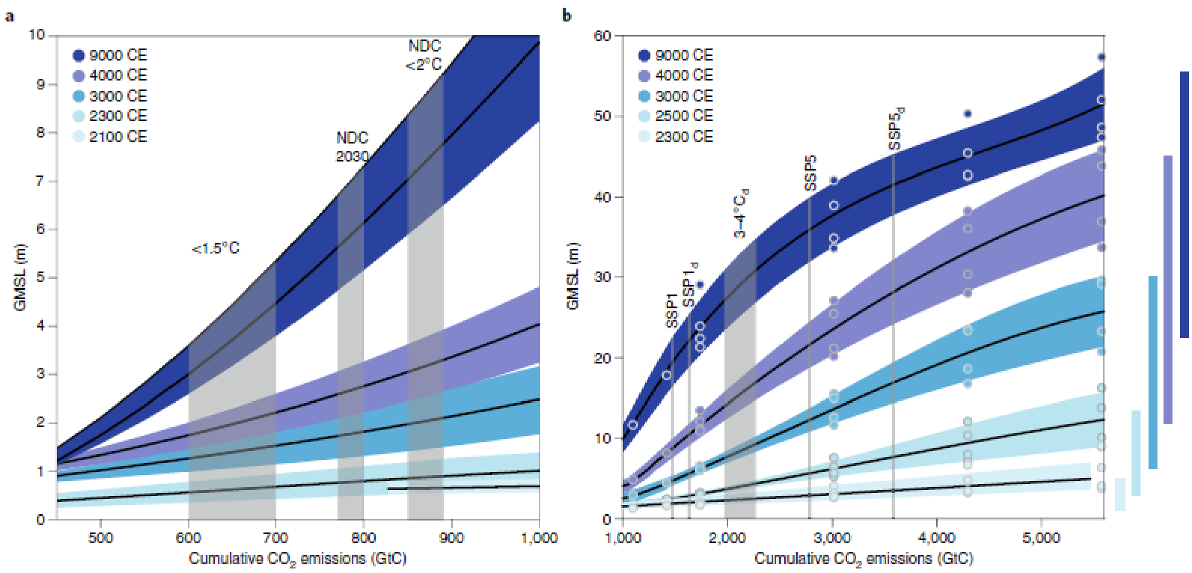

*Figure 4: **GMSL as a function of cumulative carbon emissions**. **a:** GMSL at five future time points for cumulative carbon emissions (relative to the pre-industrial) of between 450 and 1000 GtC. The black line and colour envelope represent mean sea level and 1s.d.*[2] *uncertainties. **b**: GMSL at five future time points for cumulative carbon emissions (relative to the pre-industrial) of between 1000 and 5600 GtC. The black line and colour envelope represent mean sea level and 1σ uncertainty. Coloured circles represent model results from a previous study (Clark, P. U. et al. Nat. Clim. Change 6, 360–369 (2016)). Vertical grey bars identify cumulative emissions for several scenarios from the literature. Vertical bars to the right of **b** show the spread in GMSLR for the two simulations with the Bern3D-LPX model for uncertainty in Equilibrium Climate Sensitivity values ranging from 1.5 to 4.5 °C, which the IPCC assessed as the likely range (66–100% probability).*

[1] Clark, P. U., Mix, A. C., Eby, M., Levermann, A., Rogelj, J., Nauels, A., & Wrathall, D. J. (2018). Sea-level commitment as a gauge for climate policy. *Nature Climate Change*, *8*(8), 653–655. https://doi.org/10.1038/s41558-018-0226-6

[2] Standard deviation: measure of the amount of variation or dispersion of a set of values

Sea level rise commitment and the long-term sea-level rise costs of near-term GHG emissions: Attributing long-term sea-level rise to Paris Agreement emission pledges, Nauels et al., 2019[1]

In this study, the authors claim that a focus on the 21st century fails to provide a complete picture of the consequences of anthropogenic greenhouse gas emissions on future sea-level rise and its long-term impacts. For example, they find that ⇒Nationally Determined Contributions' (NDCs') emissions from 2016 to 2030 will correspond to around 1/5 of global mean sea level rise (GMSLR) by 2300; 12cm of the projected sea level rise commitment in 2300 can be attributed to emissions from the top 5 emitting countries (China, United States of America, European Union, India, and Russia) over the same period. Hence, global and individual countries' emissions over the first decades of the 21st century alone will cause substantial long-term sea-level rise. Only stringent near-term emission reductions in line with achieving the 1.5 °C long-term temperature goal of the Paris Agreement would provide a chance of limiting long-term sea-level rise to below 1 m.

Sea-level rise vulnerability: New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding, Kulp & Strauss, 2019[2]

In this study, the authors use a new digital elevation model (DEM), CoastalDEM, to assess sea-level rise projections and coastal exposure projections (number of people on land that may be exposed to coastal inundation). They find values considerably higher than those previously calculated that were based on the SRTM, the Shuttle Radar Topography Mission. For the present day, CoastalDEM estimates a global total of 110 million people on land below the current high ⇒tide line and 230 million on land below annual flood levels (SRTM-based estimates were of 28M and 65M). Under RCP2.6, 4.5 and 8.5 and assuming a mostly stable Antarctic, sea levels projected by 2050 are high enough to threaten land currently home to a total of 150 million (40 million marginal exposure) people to a future permanently below the high tide line. This number rises by another 40/50/80 million (RCP2.6/4.5/8.5) people by end of century. A total of 340/360/390 million people are on land threatened by annual flood events in 2100, or an extra 90/110/140 million beyond the contemporary baseline.

[1] Nauels, A., Gütschow, J., Mengel, M., Meinshausen, M., & Clark, P. U. (2019). *Attributing long-term sea-level rise to Paris Agreement emission pledges*. 1–6. https://doi.org/10.1073/pnas.1907461116

[2] Kulp, S. A., & Strauss, B. H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-12808-z

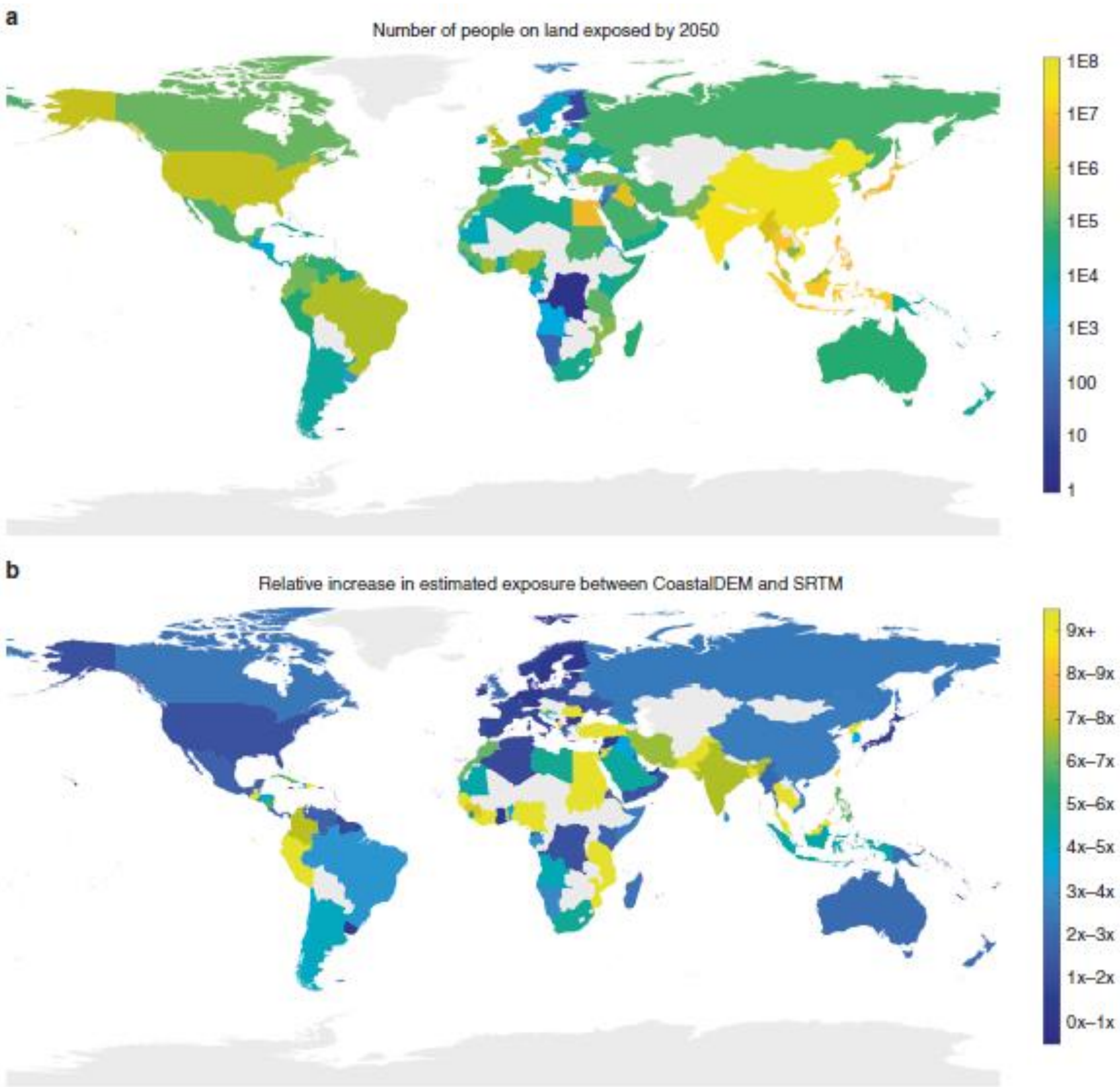

*Figure 5: **Total populations on vulnerable land**. **a** Current population on land below projected mean higher high water level in 2100 assuming intermediate carbon emissions (RCP 4.5) and relatively stable Antarctic ice sheets (sea level model K14). Estimates based on CoastalDEM. **b** Factor by which CoastalDEM increases estimates of people on vulnerable land over SRTM in each country under K14/RCP 4.5. Countries wholly north of 60 degrees N are excluded because CoastalDEM is undefined at those latitudes.*

In the case of Antarctic instability and under RCP2.6/4.5/8.5, a total of 290/300/300 million people today live on land indicated as vulnerable to an annual flood event by mid-century, rising to as many as 350/400/480 million by 2100. As this analysis combines future water level projections with contemporary population densities, it reflects the portion of presently developed land at risk in the future, which the authors interpret as a threat indicator. They also underline that marginal exposure highlights new populations of concern, while leaving out populations in areas that may be defended at present, and thus may be more likely to be defended in the future. “If our findings stand, coastal communities worldwide must prepare themselves for much more difficult futures than may be currently anticipated.”

Mass bleaching event in 2020 on the Great Barrier Reef, Hughes & Pratchett, 2020[1]

The Great Barrier Reef has recently experienced a severe and the most widespread bleaching ever recorded, the third in just five years. Indeed, February 2020 had the highest monthly sea surface temperatures ever recorded on the Great Barrier Reef, which led to 25.1% of reefs that were severely affected (that is, on each reef more than 60% of corals were bleached), and a further 35% that had more modest levels of bleaching. For the first time, severe bleaching has struck all three regions of the Great Barrier Reef – the northern, central and now large parts of the southern sectors. 2020 is the second-worst mass bleaching event of the five experienced by the Great Barrier Reef since 1998. "The Great Barrier Reef will continue to lose corals from heat stress, until global emissions of greenhouse gasses are reduced to net zero, and sea temperatures stabilise."

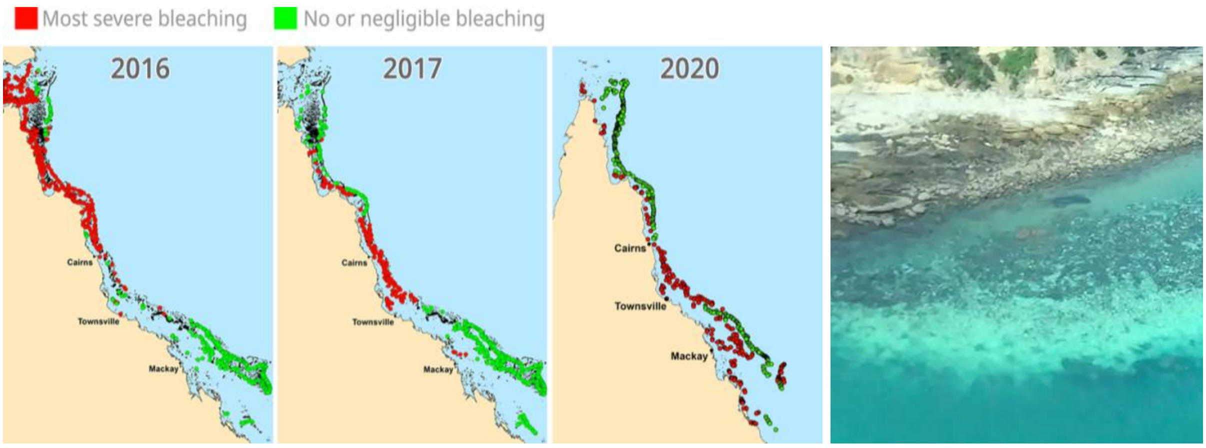

Figure 6: (left) Severity of the last three mass bleaching events on the Great Barrier Reef. (right) Severe bleaching on the Great Barrier Reef. (Hughes & Pratchett, 2020)

Carbon release through abrupt permafrost thaw, Turetsky et al., 2020[2]

This study addresses the issue of an abrupt permafrost thaw, that could release much more carbon than gradual changes in seasonally thawed soil through collapsing ground, rapid erosion and landslides. Abrupt thaw will probably occur in <20% of the permafrost zone, with carbon losses being equivalent to approximately 40% of the mean net emissions attributed to gradual thaw. The authors state that regrowing vegetation reduces total carbon emissions by around 20%, most of this biomass offset (85%) occurring in stabilized thaw lakes and wetlands. Despite this, they found that under RCP4.5, while gradual thaw may lead to net ecosystem carbon increase, abrupt thaw emissions are likely to offset this potential carbon sink, changing the carbon behavior from net uptake to net release.

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[1] Hughes, Terry; Pratchett, M. (2020). *We just spent two weeks surveying the Great Barrier Reef. What we saw was an utter tragedy*. The Conversation. https://theconversation.com/we-just-spent-two-weeks-surveying-the-great-barrier-reef-what-we-saw-was-an-utter-tragedy-135197%0D

[2] Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M., Gibson, C., Sannel, A. B. K., & McGuire, A. D. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*. https://doi.org/10.1038/s41561-019-0526-0

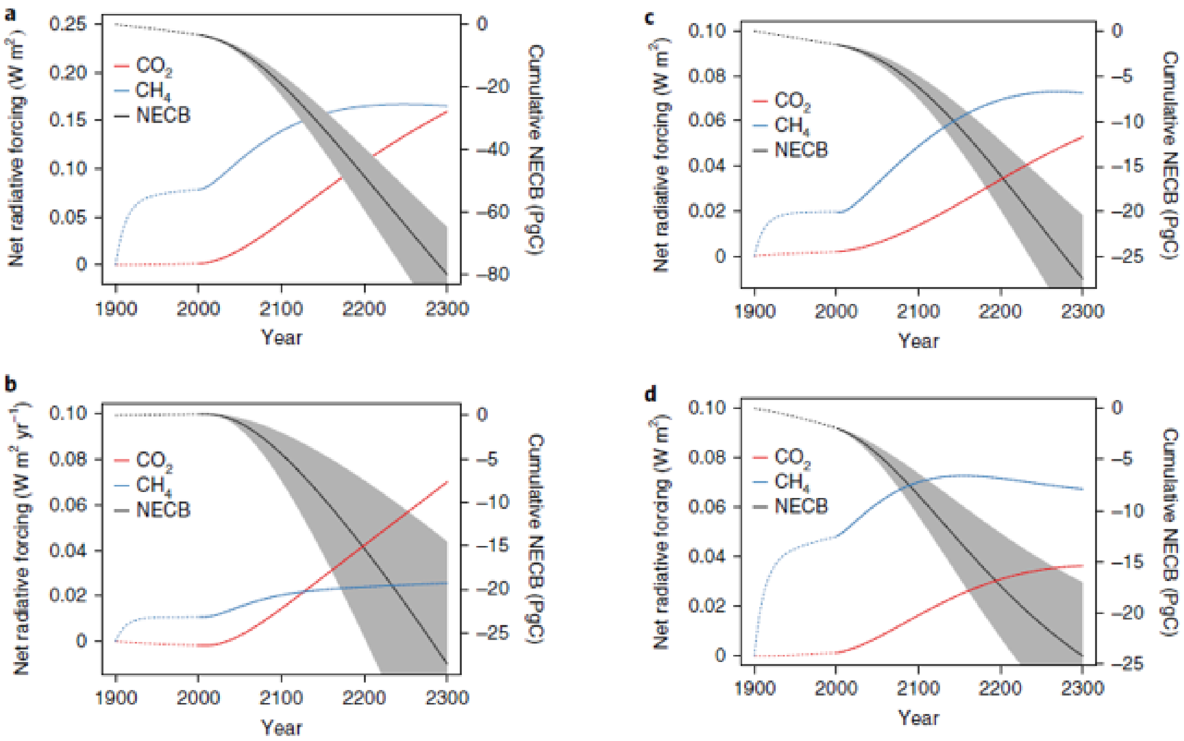

*Figure 7: **Simulated carbon release due to abrupt thaw**. **a–d**, Simulated cumulative changes in net ecosystem carbon balance (NECB) (means ± s.d.) and the radiative greenhouse gas forcing of CO_2 relative to CH_4 for: total abrupt thaw across the permafrost region (**a**); and abrupt thaw in hillslope landscapes leading to slumps, gullies or active layer detachments (**b**), lowland mineral landscapes leading to thermokarst lake formation (**c**) and lowland organic landscapes leading to thaw wetland or lake formation (**d**). Positive NECB values represent ecosystem carbon uptake, whereas negative values represent ecosystem carbon loss. Radiative forcing data are cumulative values, whereby positive forcing denotes incoming energy exceeding outgoing energy.*

The hysteresis of the Antarctic Ice Sheet, Garbe et al.[1], 2020

The Antarctic Ice Sheet represents the largest potential source for sea-level rise under global warming. Due to feedbacks between ice, oceans, atmosphere and the solid Earth, the response of the ice sheet to higher temperatures is non-linear. In this study, the authors show that there are many temperature thresholds beyond which the ice loss is irreversible, leading to long-term sea-level rise. They argue that "if the Paris Agreement to limit global warming to well below 2 °C above pre-industrial temperatures is not met, one or more critical thresholds might be subsequently crossed in Antarctica, committing us to long-term, possibly irreversible, sea-level rise of up to dozens of metres." They find that at warming levels between 1 °C and 2.5 °C above pre-industrials levels, retreats in West Antarctica could result in long-term mass losses equivalent to more than 2 m of sea-level rise. Between 2°C and 6°C, each degree results in 2.4m of sea-level rise. Between 6°C and 9°C of warming, the loss of more than 70% of the present-day ice volume is triggered, with a sensitivity of 10m of sea-level equivalent per degree of warming. At more than 10°C of warming above pre-industrial levels, Antarctica is committed to become virtually ice-free. Each of these thresholds gives rise to hysteresis behaviour: that is, the currently observed ice-sheet configuration is not regained even if temperatures are reversed to

[1] Garbe, J., Albrecht, T., Levermann, A., Donges, J. F., & Winkelmann, R. (2020). The hysteresis of the Antarctic Ice Sheet. Nature. https://doi.org/10.1038/s41586-020-2727-5

present-day levels. In particular, the West Antarctic Ice Sheet does not regrow to its modern extent until temperatures are at least 1°C lower than pre-industrial levels.

Technical note

Representative Concentration Pathways

In the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), assessments of projected future changes largely refer to Representative Concentration Pathways (RCPs). RCPs are scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs), ⇒aerosols and chemically active gases, as well as land use / land cover.
Each RCP is named after the ⇒radiative forcing they have at the end of the 2100. For example, RCP2.6 describes a pathway where ⇒radiative forcing peaks at 3W/m2 and then declines to around 2.6W/m2 in 2100. Each RCP is only one of many possible scenarios that would lead to the specific ⇒radiative forcing characteristics.

SROCC uses mainly RCP2.6 and RCP8.5 in its assessment, reflecting the available literature. RCP2.6 represents a low greenhouse gas emission, high mitigation future, that in simulations gives a two in three chance of limiting global warming to below 2ºC by 2100. By contrast, RCP8.5 is a high greenhouse gas emissions scenario in the absence of policies to combat climate change, leading to continued and sustained growth in atmospheric greenhouse gas concentrations. SROCC also references other scenarios, including RCP4.5 and RCP6.0 that have intermediate levels of greenhouse gas emissions and result in intermediate levels of warming.

Due to uncertainties in feedback processes in the earth system, the response of the climate system to anthropogenic CO_2 emissions is subject to considerable uncertainty. The IPCC Fifth' Assessment Report estimates the ⇒transient climate response to cumulative CO_2 emissions to be between 0.2-0.7°C per 1000 Gt CO_2. Table 3 provides the ranges of estimates of total warming since the pre-industrial period under these four different RCPs. The uncertainty of ⇒the transient climate response is included in the uncertainty ranges.

	Near-term: 2031–2050		End-of-century: 2081–2100	
Scenario	Mean (°C)	*Likely* range (°C)	Mean (°C)	*Likely* range (°C)
RCP2.6	1.6	1.1 to 2.0	1.6	0.9 to 2.4
RCP4.5	1.7	1.3 to 2.2	2.5	1.7 to 3.3
RCP6.0	1.6	1.2 to 2.0	2.9	2.0 to 3.8
RCP8.5	2.0	1.5 to 2.4	4.3	3.2 to 5.4

Table 3: (table SPM.1) Projected global mean surface temperature change relative to 1850–1900 for two time periods under four RCPs.

IPCC's calibrated language

SROCC uses IPCC calibrated language for the communication of confidence in the assessment process. This 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 8 details how to understand this language:

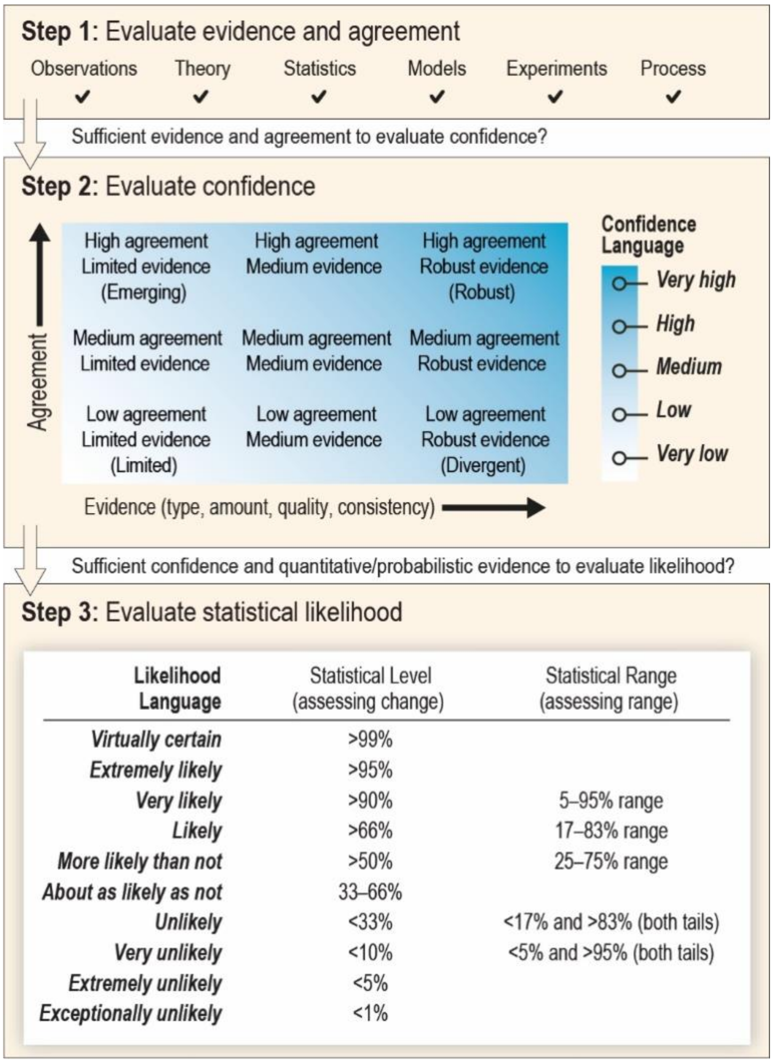

Figure 8: (fig TS.1) Schematic of the IPCC usage of calibrated language

Glossary

Aerosol A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 µm that reside in the atmosphere for at least several hours. The term aerosol includes both the particles and the suspending gas. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: through both interactions that scatter and/or absorb radiation and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow- or ice-covered surfaces thereby altering their albedo and contributing to climate feedback.

Albedo is a measure of how much sunlight that hits a surface or object is reflected without being absorbed. Something that appears white usually reflects most of the light that hits it and has a high albedo. Darker surfaces absorb more and have a low albedo which leads to warming of the surface. Clouds, snow and ice usually have a high albedo; soil surfaces cover the albedo range from high to low; vegetation in the dry season and/or arid zones can have high albedo, whereas photosynthetically active vegetation and the ocean have low albedo.

Atlantic Meridional Overturning Circulation (AMOC) The main current system in the South and North Atlantic Oceans. AMOC transports warm upper-ocean water northwards, and cold, deep water southwards, as part of the global ocean circulation system. Changes in the strength of AMOC can affect other components of the climate system.

Carbon sequestration The process of storing carbon in a carbon sink.

Carbon Sink A reservoir (natural or human, in soil, ocean, and plants) where CO2 is stored.

Climate extreme (extreme weather or climate event) An event that is rare at a particular place and time of year.

Cryosphere The components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground.

Eutrophication The process of excessive plant and algal growth in a water body due to the increased availability of one or more limiting growth factors needed for photosynthesis. Without human interference this is a very slow natural process in which nutrients accumulate in water. Anthropogenic eutrophication is often a much more rapid process in which nutrients are added to water from any of a wide variety of polluting inputs including sewage treatment, industrial waste and farming practices. This process may result in oxygen depletion of the water body after the bacterial degradation of the algae.

El Niño The term El Niño describes an oceanic event where the tropical Pacific Ocean east of the dateline warms. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to seven years, is known as the El Niño-Southern Oscillation (ENSO). During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This phenomenon has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña.

Epipelagic ecosystem The pelagic zone consists of the entire water column of the open ocean. It is subdivided into the epipelagic zone (<200m, the uppermost part of the ocean that receives enough sunlight to allow photosynthesis), the mesopelagic zone (200-1000 m depth) and the bathypelagic zone (>1000m depth).

Hypoxia refers to low or depleted oxygen in a water body.

La Niña see El Niño

Maximum catch potential Potential of the fish stocks to provide long-term fish catches.

NDC (Nationally Determined Contribution) A term used under the *United Nations Framework Convention on Climate Change (UNFCCC)* whereby a country that has joined the *Paris Agreement* outlines its plans for reducing its emissions. Some countries' NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience. According to Article 4 paragraph 2 of the Paris Agreement, each Party shall prepare, communicate and maintain successive NDCs that it intends to achieve.

Ocean acidification The reduction in the pH of the ocean, accompanied by other chemical changes, over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean.

Ocean fertilization is a proposed Carbon Dioxide Removal technique that involves adding nutrients to the upper layers of the ocean to stimulate phytoplankton activity (photosynthesis) which speeds up removal of atmospheric carbon dioxide.

Ocean stratification The process of forming of layers of ocean water with different properties such as salinity, density, and temperature that act as barrier for water mixing. The strengthening of near-surface stratification generally results in warmer surface waters, decreased oxygen levels in deeper water, and intensification of ocean acidification in the upper ocean.

Peak water refers to the year when annual runoff from the initially glacier-covered area will start to decrease due to glacier shrinkage after a period of melt induced increase.

Small Island developing states (SIDS) SIDS are a distinct group of developing countries facing specific social, economic and environmental vulnerabilities.

Tide line The line on the land up to which the highest water line reaches during the spring tide.

Tipping point A level of change in system properties beyond which a system reorganises, often in a nonlinear manner, and does not return to the initial state even if the drivers of the change are abated. For the climate system, the term refers to a critical threshold when global or regional climate changes from one stable state to another stable state. Tipping points are also used when referring to impact; the term can imply that an impact tipping point is (about to be) reached in a natural or human system.

Transient Climate Response Is a measure of the change in global mean surface temperature in response to a change in the atmospheric CO2 concentration or other forcing. The change in global mean surface temperature, averaged over a 20-year period, centred at the time of atmospheric CO2 doubling, in a climate model simulation in which CO2 increases at 1%/yr from preindustrial. It is a measure of the strength of climate feedbacks and the timescale of ocean heat uptake.

Transient Climate Response to cumulative CO2 emissions (TCRE) The change in transient global average surface temperature per unit cumulative CO2 emissions, usually 1000 GtC. TCRE combines both information on the airborne fraction of cumulative CO2 emissions and on the transient climate response (TCR).

CLIMATE
ANALYTICS