CLIMATE EMERGENCY INSTITUTE

The Health and Human Rights Approach to Greenhouse Gas Pollution

Disastrous and Catastrophic Adverse Global Climate Change Impacts on the Oceans and Cryosphere (frozen regions) from the IPCC 2019 Special Report

By Peter Carter, 29 Sept 2019

World media

The Associated Press, September 25, 2019

‘We’re all in big trouble’: UN climate report says oceans rising, ice melting faster

UPI, SEPT. 25, 2019

Climate report: 1 billion will face water, food shortages by 2050

BBC 25 September 2019

Climate change: UN panel signals red alert on 'Blue Planet'

Climate change is devastating our seas and frozen regions as never before, a major new United Nations report warns.

Note: The condensed summary for policy makers (from the full IPCC scientists report) has been approved by all world governments. Bolding of text added.

Human communities in close connection with coastal environments, small islands (including Small Island Developing States, SIDS), polar areas and high mountains are particularly exposed to ocean and cryosphere change Other communities further from the coast are also exposed to changes in the ocean, such as through extreme weather events. Today, around 4 million people live permanently in the Arctic region, of whom 10% are Indigenous. The low-lying coastal zones is currently home to around 680 million people (nearly 10% of the 2010 global population), projected to reach more than one billion by 2050. SIDS are home to 65 million people. Around 670 million people (nearly 10% of the 2010 global population), including Indigenous peoples, live in high mountain regions in all continents except Antarctica. In high mountain regions, population is projected to reach between 740 and 840 million by 2050

All people on Earth depend directly or indirectly on the ocean and cryosphere. The global ocean covers 71% of the Earth surface and contains about 97% of the Earth’s water. The cryosphere refers to frozen components of the Earth system. Around 10% of Earth's land area is covered by glaciers or ice sheets. The ocean and cryosphere support unique habitats, and are interconnected with other components of the climate system through global exchange of water, energy and carbon**. The projected responses of the ocean and cryosphere to past and current human-induced greenhouse gas emissions and ongoing global warming include climate feedbacks, changes over decades to millennia that cannot be avoided, thresholds of abrupt change, and** irreversibility

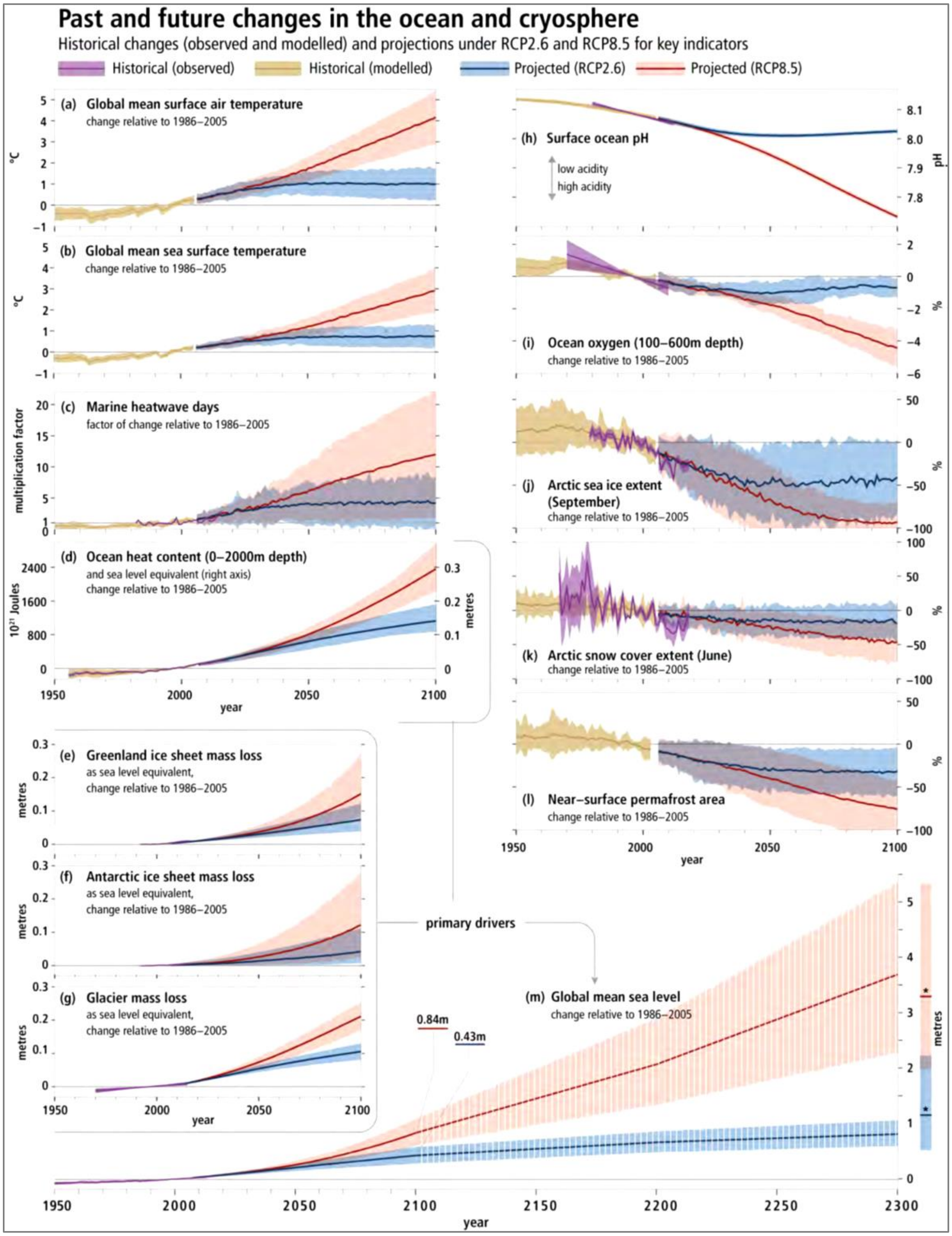


Figure SPM.1: Observed and modelled historical changes in the ocean and cryosphere since 1950, and projected future changes under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios.

Global surface warming from pre-industrial

Table SPM.1: Projected global mean surface temperature change relative to 1850–1900 for two time periods under four RCPs[16].

	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
RCP8.5	2.0	1.5 to 2.4	4.3	3.2 to 5.4

Note CO2 and methane emissions and atmospheric concentrations are currently tracking close to the worst case scenario (RCP8.5). The best case scenario (RCP2/6)

Feedbacks from the loss of summer sea ice and spring snow cover on land have contributed to amplified warming in the **Arctic where surface air temperature likely increased by more than double the global average** over the last two decades.

Changes in Arctic sea ice have the potential to influence mid-latitude weather.

A1.3 **Permafrost temperatures have increased to record high levels** (1980s-present) including the recent increase by 0.29°C from 2007 to 2016 averaged across polar and high mountain regions globally. **Arctic and boreal permafrost contain 1460–1600 Gt organic carbon, almost twice the carbon in the atmosphere**. There is medium evidence with low agreement whether northern permafrost regions are currently releasing additional net methane and CO2 due to thaw.

B1.4 Widespread permafrost thaw is projected for this century and beyond. By 2100, projected near-surface (within 3–4 m) permafrost area shows a decrease of 24 % for RCP2.6 and 69% for RCP8.5**. The RCP8.5 scenario** (current worst case) **leads to the cumulative release of tens to hundreds of billions of tons (GtC) of permafrost carbon as CO2 and methane to the atmosphere by 2100 with the potential to exacerbate climate change**. Lower emissions scenarios dampen the response of carbon emissions from the permafrost region. Methane contributes a small fraction of the total additional carbon release but is significant because of its higher warming potential.

A2.1. The ocean warming trend documented in the IPCC Fifth Assessment Report (AR5) has continued. Since 1993 the **rate of ocean warming and thus heat uptake has more than doubled** from 3.22 Zetajoules/year (0– 700 m depth) and 0.97 ZJ /year (700–2000 meters) between 1969 and 1993, to 6.28 ZJ/yr(0–700 m) and 3.86 ZJ/yr (700–2000m) between 1993 and 2017, **and is attributed to anthropogenic forcing** The Southern Ocean accounted for 35–43% of the total heat gain in the upper 2000 m global ocean between 1970 and 2017. Its share increased to 45–62% between 2005 and 2017. The deep ocean below 2000m has warmed since 1992, especially in the Southern Ocean.

A2.3 Globally, **marine heat related events have increased**; marine heatwaves, defined when the daily sea surface temperature exceeds the 99th percentile over the period 1982 to 2016, have doubled in frequency and have become longer-lasting, more intense and more extensive. It is very likely that between 84–90% of marine heatwaves that occurred between 2006 and 2015 are attributable to the anthropogenic temperature increase.

A2.4 Density stratification has increased in the upper 200 m of the ocean since 1970. Observed surface ocean warming and high latitude addition of freshwater are making the surface ocean less dense relative to deeper parts of the ocean and **inhibiting mixing between surface and deeper waters**. The mean stratification of the upper 200 m has increased by 2.3% from the 1971–1990 average to the 1998–2017 average.

A2.6 Datasets spanning 1970–2010 show that **the open ocean has lost oxygen** by a very likely range of 0.5–3.3% over the upper 1000 m, alongside a likely expansion of the volume of oxygen minimum zones by 3–8%. Oxygen loss is primarily due to increasing ocean stratification, changing ventilation and biogeochemistry

A2.5 The ocean has taken up between 20–30% of total anthropogenic CO2 emissions since the 1980s causing further **ocean acidification**. Open ocean surface pH has declined by a very likely range of 0.017–0.027 pH units per decade since the late 1980s, with the decline in surface ocean pH very likely to have already emerged from background natural variability for more than 95% of the ocean surface area.

A3. **Global mean sea level (GMSL) is rising, with acceleration in recent decades** due to increasing rates of ice loss from the Greenland and Antarctic ice sheets, as well as continued glacier mass loss and ocean thermal expansion. 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

A3.2 **Sea-level rise has accelerated due to the combined increased ice loss from the Greenland and Antarctic ice sheets** . Mass loss from the Antarctic ice sheet over the period 2007– 2016 tripled relative to 1997–2006. For Greenland, mass loss doubled over the same period

A3.3 **Acceleration of ice flow and retreat in Antarctica**, which has the potential to lead to sea-level rise of several metres within a few centuries, is observed in the Amundsen Sea Embayment of **West Antarctica** and in Wilkes Land, East Antarctica. **These changes may be the onset of an irreversible ice sheet instability**

A3.6 **Anthropogenic climate change has increased observed precipitation, winds, and extreme sea level events associated with some tropical cyclones, which has increased intensity of multiple extreme events and associated cascading impacts**. There is emerging evidence for an **increase in annual global proportion of Category 4 or 5 tropical cyclones in recent decades** (SPM-11)

A4.2 **Increased wildfire and abrupt permafrost thaw**, as well as changes in Arctic and mountain hydrology have altered frequency and intensity of ecosystem disturbances. (SPM-12)

A5.4 **Ocean warming in the 20th century and beyond has contributed to an overall decrease in maximum catch potential** , compounding the impacts from overfishing for some fish stocks (SPM-13)

A6. Coastal ecosystems are affected by ocean warming, including intensified marine heatwaves, acidification, loss of oxygen, salinity intrusion and sea level rise, in combination with adverse effects from human activities on ocean and land. Impacts are already observed on habitat area and biodiversity, as well as ecosystem functioning and services (SPM-13)

A6.1 Vegetated coastal ecosystems protect the coastline from storms and erosion and help buffer the impacts of sea level rise**. 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. Vegetated coastal ecosystems are important carbon stores; their loss is responsible for the current release of 0.04–1.46 GtC yr–1** (SPM-13)

A6.4 Warm-water coral reefs and rocky shores dominated by immobile, calcifying (e.g., shell and skeleton producing) organisms such as corals, barnacles and mussels, are currently impacted by extreme temperatures and ocean acidification. **Marine heatwaves have already resulted in large-scale coral bleaching events at increasing frequency causing worldwide reef degradation** since 1997,

Observed Impacts on People and Ecosystem Services

A7**. Since the mid-20th century, the shrinking cryosphere in the Arctic and high-mountain areas has led to predominantly negative impacts on food security, water resources, water quality, livelihoods, health and well-being**, infrastructure, transportation, tourism and recreation, as well as culture of human societies, particularly for Indigenous peoples.

A7.1 **Food and water security have been negatively impacted by changes in snow cover, lake and river ice, and permafrost in many Arctic regions. These changes have disrupted access to, and food availability within, herding, hunting, fishing, and gathering areas, harming the livelihoods and cultural identity of Arctic residents including Indigenous populations. Glacier retreat and snow cover changes have contributed to localized declines in agricultural yields in some high mountain regions,** including Hindu Kush Himalaya and the tropical Andes (SPM-13)

A7.**2 In the Arctic, 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** (high confidence). In some high-mountain areas, water quality has been affected by contaminants, particularly mercury, released from melting glaciers and thawing permafrost

SPM.B PROJECTED CHANGES AND RISKS

B1. 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) due to surface air temperature increases, with unavoidable consequences for river runoff and local hazards**. The Greenland and Antarctic Ice Sheets are projected to lose mass at an increasing rate throughout the 21st century and beyond**

B1.2 **The Greenland Ice Sheet is currently contributing more to sea-level rise than the Antarctic Ice Sheet, but Antarctica could become a larger contributor by the end of the 21st century as a consequence of rapid retreat**. Beyond 2100, increasing divergence between Greenland and Antarctica's relative contributions to GMSL rise under RCP8.5 has important consequences for the pace of relative sea-level rise in the Northern Hemisphere.

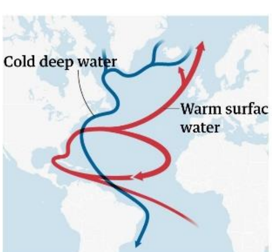
B1.4 **Widespread permafrost thaw is projected for this century and beyond. The RCP8.5 scenario leads to the cumulative release of tens to hundreds of billions of tons (GtC) of permafrost carbon as CO2 and methane to the atmosphere by 2100 with the potential to exacerbate climate change**. Methane contributes a small fraction of the total additional carbon release but is significant because of its higher warming potential. Increased plant growth is projected to replenish soil carbon in part, but will not match carbon releases over the long term

B1.5 In many **high mountain areas**, glacier retreat and permafrost thaw are projected to further decrease the stability of slopes, and the number and area of glacier lakes will continue to increase. **Floods due to glacier lake outburst or rain-on-snow, landslides and snow avalanches, are projected to occur also in new locations or different seasons**

B1.6 **River runoff in snow-dominated or glacier-fed high mountain basins is projected to change regardless of emissions scenario**, with increases in average winter runoff and earlier spring peaks. In all emissions scenarios, average annual and summer runoff from glaciers are projected to peak at or before the end of the 21st century, e.g., around mid-century in High Mountain Asia, followed by a decline in glacier runoff. In regions with little glacier cover (e.g., tropical Andes, European Alps) most glaciers have already passed this peak. Projected declines in glacier runoff by 2100 (RCP8.5) can reduce basin runoff by 10% or more in at least one month of the melt season in several large river basins, especially in High Mountain Asia during the dry season

B1.7 **Arctic sea ice loss is projected to continue through mid-century, with differences thereafter depending on the magnitude of global warming**: for stabilised global warming of 1.5°C the annual probability of a sea ice free September by the end of century is approximately 1%, which rises to 10–35% for stabilised global warming of 2°C

B2. OCEAN Over the 21st century, the ocean is projected to transition to unprecedented conditions with increased temperatures , greater upper ocean stratification, further acidification, oxygen decline, and altered net primary production. Marine heatwaves and extreme El Niño and La Niña events are projected to become more frequent. The Atlantic Meridional Overturning Circulation (AMOC) is projected to weaken



AMOC image added

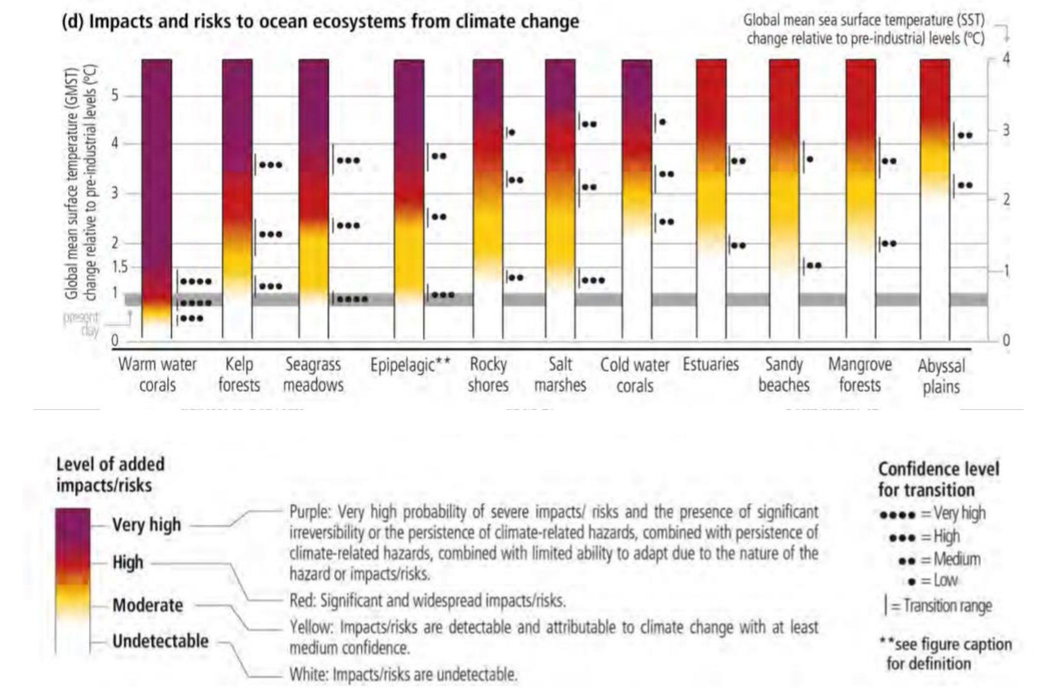


Figure SPM.3: Projected changes, impacts and risks for ocean regions and ecosystems

B2.2 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.

B2.3 **Continued carbon uptake by the ocean by 2100 is virtually certain to exacerbate ocean acidification.**

B2.4 **Climate conditions, unprecedented since the preindustrial period, are developing in the ocean**, elevating risks for open ocean ecosystems. Surface acidification and warming have already emerged in the historical period. Oxygen loss between 100 and 600 m depth is projected to emerge over 59–80% of the ocean area by 2031– 2050 under RCP8.5. The projected time of emergence for five primary drivers of marine ecosystem change (surface warming and acidification, oxygen loss, nitrate content and net primary production change) are all prior to 2100 for over 60% of the ocean area under RCP8.5 and over 30% under RCP2.6

B2.5 **Marine heatwaves are projected to further increase in frequency, duration, spatial extent and intensity** (maximum temperature). Climate models project increases in the frequency of marine heatwaves by 2081–2100, relative to 1850–1900, by approximately 50 times under RCP8.5 and 20 times under RCP2.6. The largest increases in frequency are projected for the Arctic and the tropical oceans. **The intensity of marine heatwaves is projected to increase about 10-fold under RCP8.5 by 2081–2100, relative to 1850–1900**

B2.6 **Extreme El Niño and La Niña events are projected to likely increase in frequency in the 21st century and to likely intensify existing hazards, with drier or wetter responses in several regions across the globe**. **Extreme El Niño events are projected to occur about as twice as often under both RCP2.6 and RCP8.5 in the 21st century when compared to the 20th century.**

B2.7 **The AMOC (deep ocean conveyer current) is projected to weaken in the 21st century under all RCPs,** although a collapse is very unlikely. Based on CMIP5 model projections, by 2300, an AMOC collapse is as likely as not for high emissions scenarios. Any substantial weakening of the AMOC is projected to cause a decrease in marine productivity in the North Atlantic, more storms in Northern Europe, less Sahelian summer rainfall and South Asian summer rainfall, and an increase in regional sea level along the northeast coast of North America. Such changes would be in addition to the global warming signal.

B3.1 **The global mean sea level (GMSL) rise** .. For RCP8.5, the GMSL rise is 0.71 m for 2081–2100 and 0.84 m in 2100. 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. The uncertainty at the end of the century is mainly determined by the ice sheets, especially in Antarctica

B3.4 **Global mean sea level rise will cause the frequency of extreme sea level events at most locations to increase. 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 (all scenarios). The year when the historical centennial event becomes an annual event in the mid-latitudes occurs soonest in RCP8.5, next in RCP4.5 and latest in RCP2.6. The increasing frequency of high water levels can have severe impacts in many locations depending on the level of exposure

B3.5 **Significant wave heights** (the average height from trough to crest of the highest one-third of waves) are projected to increase across the Southern Ocean and tropical eastern Pacific and Baltic Sea…under RCP8.5

B3.6 **The average intensity of tropical cyclones, the proportion of Category 4 and 5 tropical cyclones and the associated average precipitation rates are projected to increase for a 2°C global temperature** rise above any baseline period. Rising mean sea levels will contribute to higher extreme sea levels associated with tropical cyclones. Coastal hazards will be exacerbated by an increase in the average intensity, magnitude of storm surge and precipitation rates of tropical cyclones. There are greater increases projected under RCP8.5 than under RCP2.6 from around mid-century to 2100

Projected Risks for Ecosystems

B.4 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, and eventual loss of globally unique biodiversity. Wildfire is projected to increase significantly for the rest of this century across most tundra and boreal regions, and also in some mountain regions

B4.3 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. Even as the overall regional water cycle is projected to intensify, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in snow and permafrost may lead to soil drying with consequences for ecosystem productivity and disturbances. **Wildfire is projected to increase for the rest of this century across most tundra and boreal regions**, and also in some mountain regions

B5.1 **Ocean warming and changes in net primary production alter biomass, production and community structure of marine Projected ecosystems.** The global-scale biomass of marine animals across the foodweb is projected to decrease by 15.0% and 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. These changes are projected to be very likely three to four times larger under RCP8.5 than RCP2.6

B5.2 Under enhanced stratification reduced nutrient supply is projected to cause tropical ocean net primary production to decline by 7–16% for RCP8.5 by 2081–2100. In tropical regions, marine animal biomass and production are projected to decrease more than the global average under all emissions scenarios in the 21st century . … Globally, the sinking flux of organic matter from the upper ocean is projected to decrease, linked largely due to changes in net primary production. As a result, 95% or more of the deep sea (3000–6000 **m depth) seafloor area and cold-water coral ecosystems are projected to experience declines in benthic (very deep sea) biomass under RCP8.5**

B5.4 Ocean warming, oxygen loss, acidification and a decrease in flux of organic carbon from the surface to the deep ocean are projected to harm habitat-forming **cold-water corals**, which support high biodiversity, partly through decreased calcification, increased dissolution of skeletons, and bioerosion. Vulnerability and risks are highest where and when temperature and oxygen conditions both reach values outside species' tolerance ranges

B6.1 **All coastal ecosystems assessed are projected to face increasing risk level, from moderate to high risk under RCP2.6 to high to very high risk under RCP8.5 by 2100.** Intertidal rocky shore ecosystems are projected to be at very high risk by 2100 under RCP8.5 due to exposure to warming, especially during marine heatwaves, as well as to acidification, sea level rise, loss of calcifying species and biodiversity. Ocean acidification challenges these ecosystems and further limits their habitat suitability by inhibiting recovery through reduced calcification and enhanced bioerosion. **The decline of kelp forests is projected to continue in temperate regions due to warming**, particularly under the projected intensification of marine heatwaves, with high risk of local extinctions under RCP8.5

B6.2 **Seagrass meadows and saltmarshes and associated carbon stores are at moderate risk at 1.5°C global warming and increase with further warming. Globally, 20–90% of current coastal wetlands are projected to be lost by 2100**, depending on projected sea level rise, regional differences and wetland types

B6.3 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. These impacts are projected to be more pronounced in more vulnerable eutrophic and shallow estuaries with low tidal range in temperate and high latitude regions

B6.4 **Almost all warm-water coral reefs** are projected to suffer significant losses of area and local extinctions, even if global warming is limited to 1.5°C

Projected Risks for People and Ecosystem Services

B7. Future cryosphere changes on land are projected to affect water resources and their uses, such as hydropower and **irrigated agriculture in and downstream of high-mountain areas**, as well as livelihoods in the Arctic

B8. Future shifts in **fish distribution and decreases in their abundance** and fisheries catch potential due to climate change are projected to affect income, livelihoods, and food security of marine resource-dependent communities. Long-term loss and degradation of marine ecosystems compromises the ocean's role in cultural, recreational, and intrinsic values important for human identity and well-being

B8.2 The decline in warm water coral reefs is projected to greatly compromise the services they provide to society, such as food provision , coastal protection and tourism . Increases in the risks for seafood security associated with decreases in seafood availability are projected to elevate the risk to nutritional health in some communities highly dependent on seafood, such as those in the Arctic, West Africa, and Small Island Developing States. Such impacts compound any risks from other shifts in diets and food systems caused by social and economic changes and climate change over land

B8.3 **Global warming compromises seafood safety** through human exposure to elevated bioaccumulation of persistent organic pollutants and mercury in marine plants and animals , increasing prevalence of waterborne Vibrio pathogens, and heightened likelihood of harmful algal blooms. These risks are projected to be particularly large for human communities with high consumption of seafood, including coastal Indigenous communities

B8.4 Climate change impacts on marine ecosystems and their services put key cultural dimensions of lives and livelihoods at risk, including through shifts in the distribution or abundance of harvested species and diminished access to fishing or hunting areas. **This includes potentially rapid and irreversible loss of culture and local knowledge and Indigenous knowledge, and negative impacts on traditional diets and food security**, aesthetic aspects, and marine recreational activities

B9. 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 Arctic human communities without rapid land uplift, and in urban atoll islands, risks are projected to be moderate to high even under a low emissions scenario, including reaching adaptation limits. **Under a high emissions scenario (RCP8.5), delta regions and resource rich coastal cities are projected to experience moderate to high risk levels after 2050**

B9.**1 In the absence of more ambitious adaptation efforts compared to today, and under current trends of increasing exposure and vulnerability of <u>coastal communities</u>, risks, such as erosion and 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 2–3 orders of magnitude by 2100 compared to today**

B9.2 High to very high risks are approached for **vulnerable communities** in coral reef environments, urban atoll islands and low-lying Arctic locations from sea level rise well before the end of this century in case of high emissions scenarios Some island nations are likely to become uninhabitable due to climate related ocean and cryosphere change

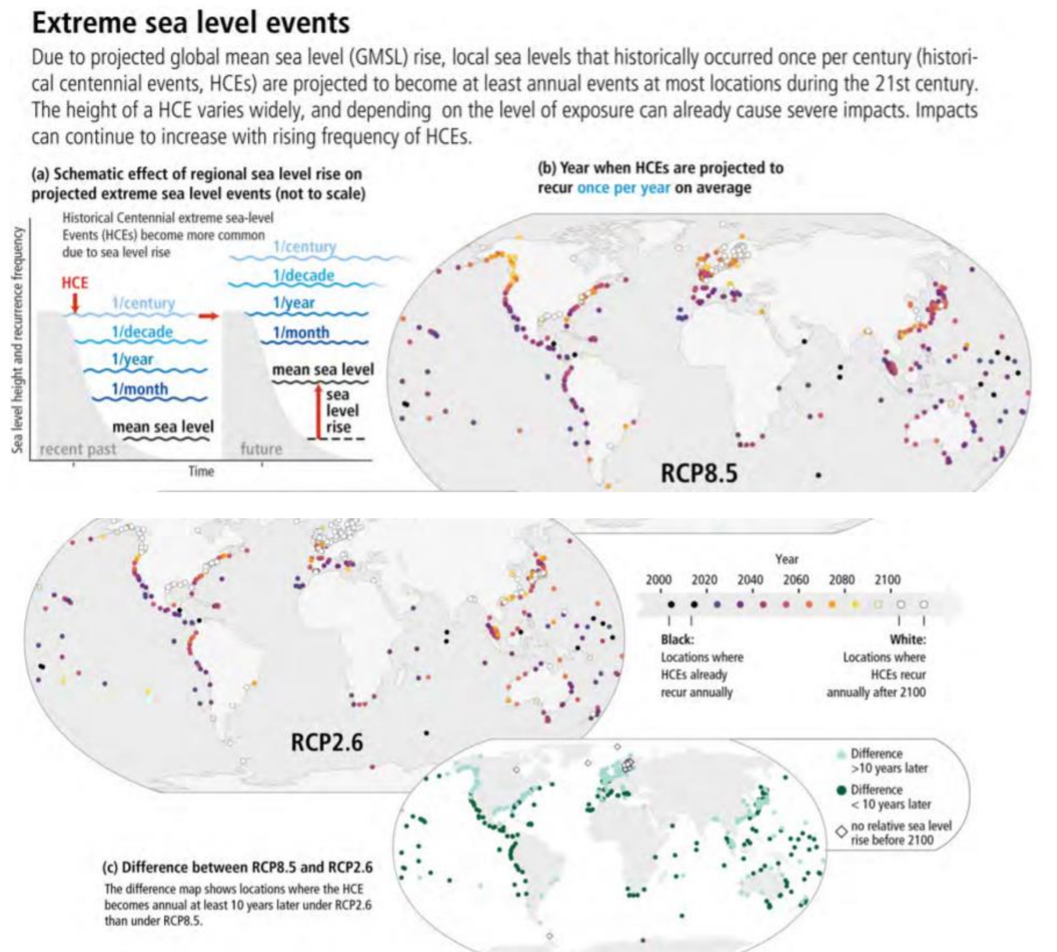


Figure SPM.4: The effect of regional sea-level rise on extreme sea level events at coastal locations

Science Chapter 1

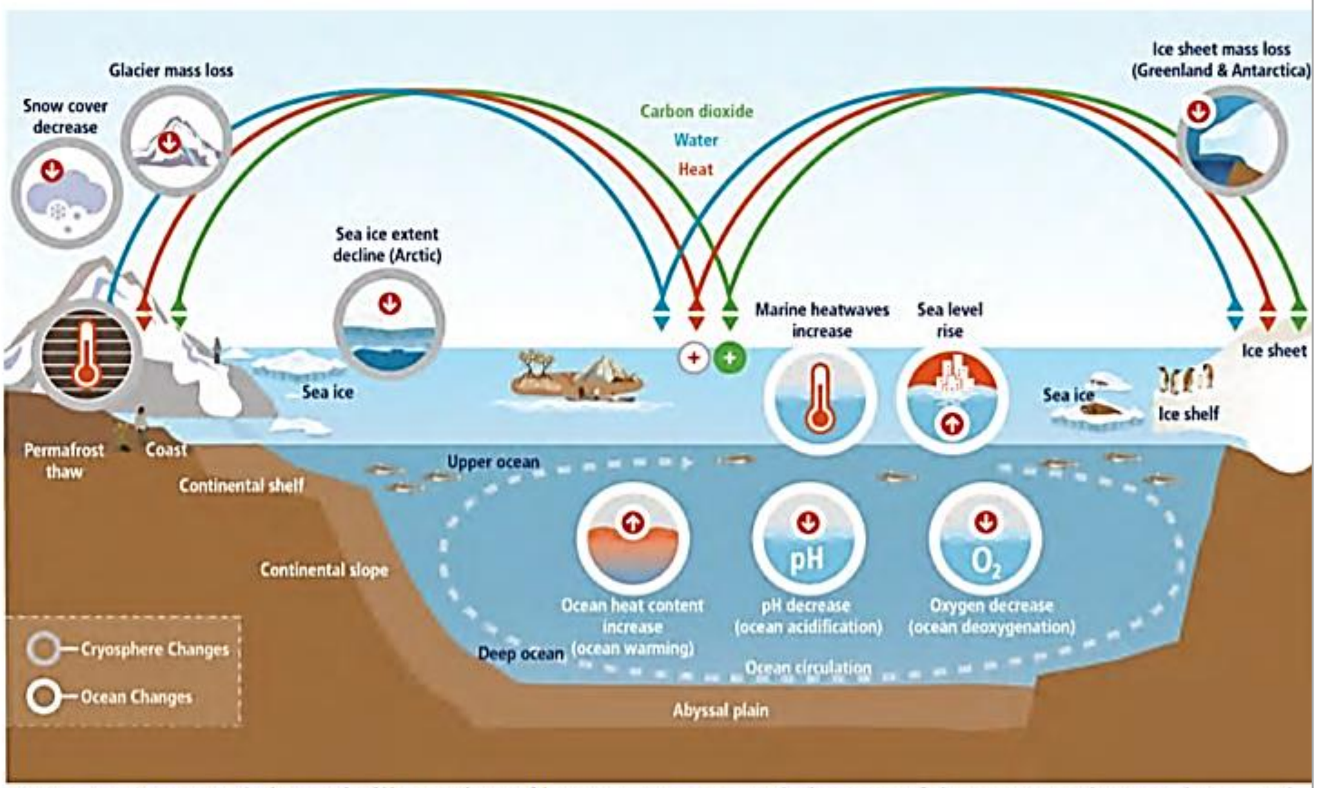
Characteristics of ocean and cryosphere change include thresholds of abrupt change, long-term changes that cannot be avoided, and irreversibility. Ocean warming, acidification and deoxygenation, ice sheet and glacier mass loss, and permafrost degradation are expected to be irreversible on timescales relevant to human societies and ecosystems. Long response times of decades to millennia mean that the ocean and cryosphere are committed to long-term change even after atmospheric greenhouse gas concentrations and radiative forcing stabilise. Ice melt or the thawing of permafrost involve thresholds (state changes) that allow for abrupt, nonlinear responses to ongoing climate warming (1-4)

The largest ice bodies on Earth are the **Greenland and Antarctic ice sheets**. Marine-based sections of ice sheets (e.g., West Antarctic Ice Sheet) sit upon bedrock that largely lies below sea level and are in contact with ocean heat, making them **vulnerable to rapid and irreversible ice loss**. (1-8)

Enhanced warming in the Arctic and in high mountains is causing **rapid surface melt of glaciers and the Greenland ice sheet.**

Thawing of permafrost …has the potential **to release vast quantities of methane and carbon dioxide into the atmosphere that will further exacerbate climate change (**1-49)

observed. Permafrost thaw can cause hazards, including ground subsidence or landslides, and influence global climate through emissions of greenhouse gases from microbial breakdown of previously frozen organic carbon.



Box 1.1, Figure 1: Schematic illustration of key components and changes of the ocean and cryosphere, and their linkages in the Earth system through the movement of heat, water, and carbon (Section 1.2). Climate

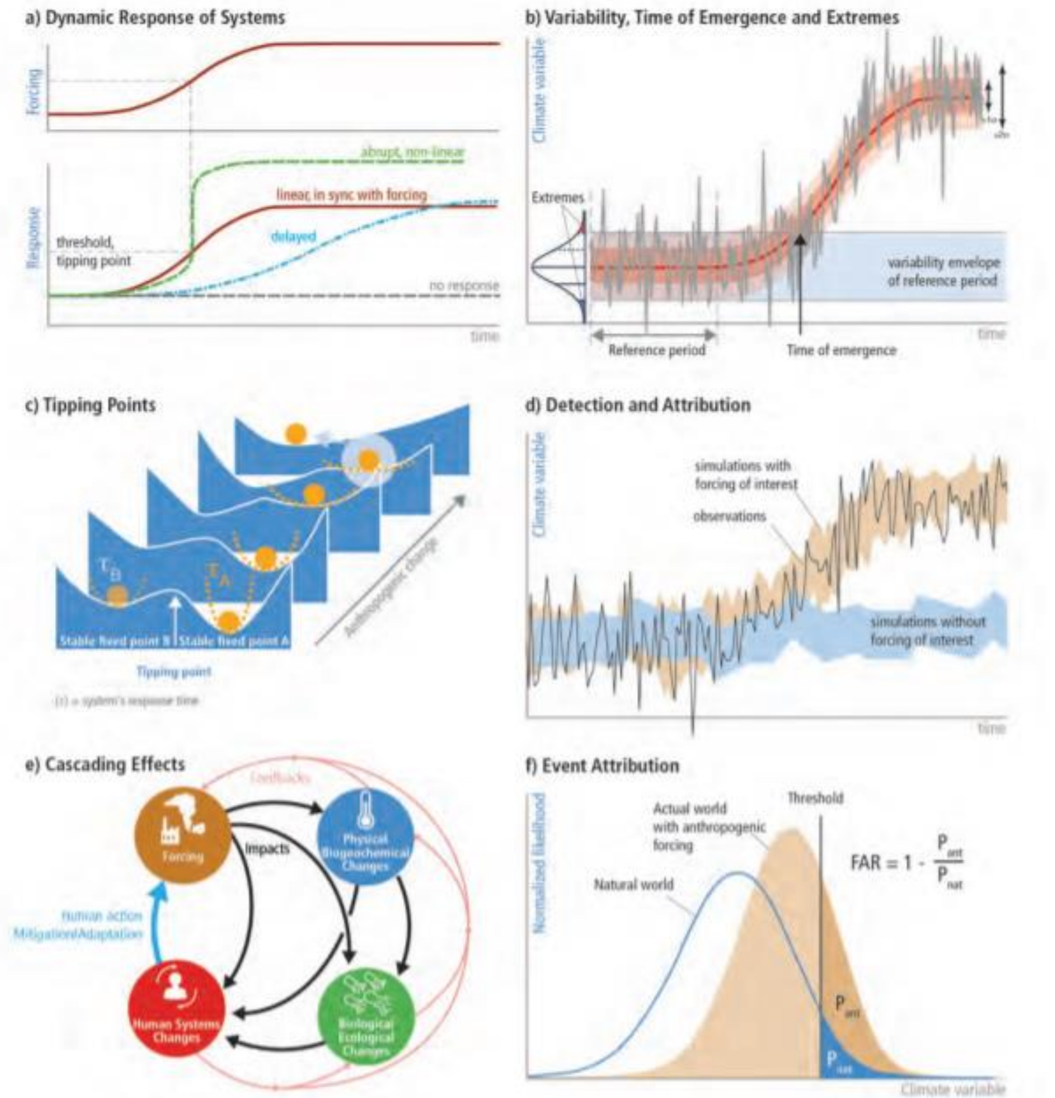


Figure 1.1: Schematic of key concepts associated with changes in the ocean and cryosphere. (a) Differing responses of systems to gradual forcing (e.g., linear, delayed, abrupt, non-linear). (b) Evolution of a dynamical system in time,

There is no global-scale analysis of the **climate feedback from permafrost in mountains**. Given that projections indicate increasing thaw and degradation of permafrost in mountains during the 21st century a corresponding increase in greenhouse gas emissions can be anticipated but is not quantified (2-25)

Chapter 3. Polar Regions

3.4.3 Consequences and Impacts 3.4.3.1 Global Climate Feedback

3.4.3.1.1 Carbon cycle Climate warming is expected to change the storage of carbon in vegetation and soils in northern regions, and net carbon transferred to the atmosphere as CO2 and methane acts as a feedback to accelerate global climate change. There is high confidence that the northern region acted as a net carbon sink as carbon accumulated in terrestrial ecosystems over the Holocene.

Arctic net carbon source

There is increasing … evidence, that changing climate in the modern period has shifted these ecosystems into net carbon sources.

CO2 release rates during the non-summer season that are now thought to be higher than previously estimated

Recent aircraft measurements of atmospheric CO_2 concentrations over Alaska showed that tundra regions of Alaska were a consistent net CO_2 source to the atmosphere, whereas boreal forest regions were either neutral or net CO_2 sinks for the period 2012 to 2014. That study region as a whole was estimated to be a net carbon source of 25 Tg CO_2-Carbon per year averaged over the land area of both biomes for the entire study period.
These future carbon emission levels would be a significant fraction of those projected from fossil fuels with implications for allowable carbon budgets that are consistent with limiting global warming,

…integrated estimates of methane emissions from observations of expanding permafrost thaw lakes that suggest a release of an additional 1.6–5 Tg CH_4/yr over the last 60 years

Some new quantifications include: cold-season methane emissions that can be >50% of the annual budget of terrestrial ecosystems (Zona 2016)

… estimates of shallow Arctic Ocean shelf methane emissions where the range of estimates based on methane concentrations in air and water has widened with more observations and now ranges from 3 Tg CH_4 /yr to 17 Tg CH_4 /yr

Global models that do include methane show that emissions may already (from 2000–2012) be increasing at a rate of 1.2 Tg CH_4 /yr in the northern region as a direct response to temperature. A model intercomparison study forecast northern methane emissions to increase from 18 Tg CH_4 yr^{-1} to 42 Tg CH_4 yr^{-1} under RCP8.5 by 2100 largely as a result of an increase in wetland extent.

…most models described above do not include many of the abrupt thaw processes that can result in lake expansion, wetland formation, and massive erosion and exposure to decomposition of previously frozen carbon-rich permafrost, leading to medium confidence in future model projections of methane. Recent studies that addressed some of these landscape controls over future emissions projected increases in methane above the current levels on the order 10-60 Tg CH_4 /yr under RCP8.5 by 2100. These additional methane fluxes are projected to cause 40-70% of total permafrost-affected radiative forcing in this century even though methane emissions are much less than CO_2 by mass

Chapter 6 Extremes, Abrupt Changes

Satellite observations reveal that marine heatwaves have *very likely* doubled in frequency between 1982 and 2016, and that they have also become longer-lasting, more intense and extensive.

Marine heatwaves will further increase in frequency, duration, spatial extent and intensity under future global warming pushing some marine organisms, fisheries and ecosystems beyond the limits of their resilience, with cascading impacts on economies and societies. Globally, the frequency of marine heatwaves is *very likely* to increase by a factor of 46- 55 by 2081-2100 under the RCP8.5 scenario and by a factor of 16-24 under the RCP2.6 scenario, relative to the 1850-1900 reference period.

Extreme El Niño and La Niña events are *likely* to occur more frequently with global warming and are *likely* to intensify existing impacts, with drier or wetter responses in several regions across the globe, even at relatively low levels of future global warming

The AMOC will *very likely* weaken over the 21st century, although a collapse is *very unlikely*. Nevertheless, a substantial weakening of the AMOC remains a physically plausible scenario. Such a weakening would strongly impact natural and human systems,leading to a decrease in marine productivity in the North Atlantic, more winter storms in Europe, a reduction in Sahelian and South Asian summer rainfall, a decrease in the number of tropical cyclones in the Atlantic, and an increase in regional sea-level around the Atlantic especially along the northeast coast of North America. Such impacts would be superimposed on the global warming signal