

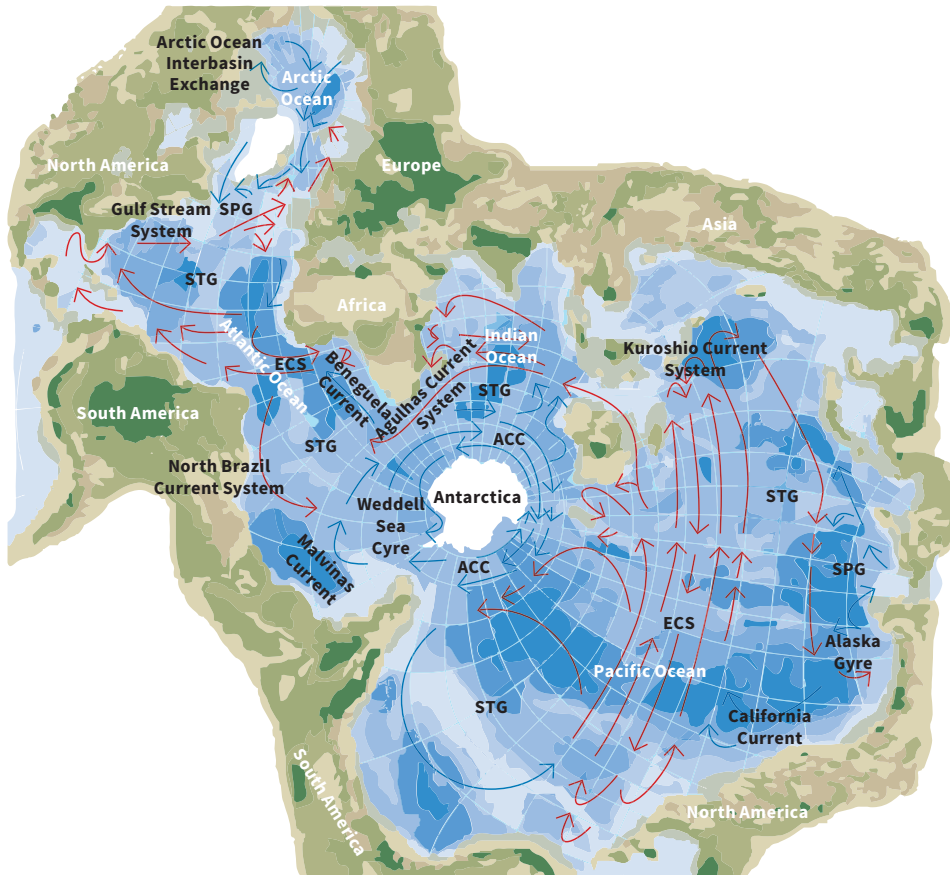
Climate Change and Its Impact on the Ocean

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1. Introduction

Over the last century, the world's human population has grown rapidly, and along with affluent lifestyles, the demand for energy has been growing. Since most of this energy is obtained from various kinds of fossil fuels, the atmospheric concentration of CO₂ has been rapidly increasing also. On land, the growing population has led to the significant loss of the natural landscape in favor of settlements and land culture. This development has resulted in many dimensions of pressure on our environment (e.g., Rockström et al. 2009). Climate change, loss of biodiversity and ocean acidification, as well as land-based pollution, all affect the ocean. The rapid depletion of natural resources and environmental pollution have led the global community to sound the alarm bells and articulate a number of global agreements to protect the planet and the life-supporting ecosystem services it provided to humanity. The Paris Climate Accord, the Sendai Framework for Disaster Risk Reduction and the all-encompassing 2030 Agenda for Sustainable Development with its Sustainable Development Goals (SDGs) all set out ambitious goals for the people and planet. The recognition that the ocean space also plays an important role for humanity in general, and its particular central role for small island developing states, has led to the inclusion of an explicit SDG for the ocean (Visbeck et al. 2014). However, the ocean dimension of the 2030 Agenda goes beyond SDG 14, and there are significant linkages across the SDGs. Some of the goals reinforce each other, while others are in conflict (Nilsson et al. 2016). Schmidt et al. (2017) provide a deeper analysis and, amongst others, highlight the connection between SDG 14 and SDG 13 as a tight nexus between ocean and climate.

Geographically, a typical world map in the often-used Mercator projection seems to suggest that there could be five separated oceans. However, they are in fact well-connected ocean basins and part of a single global ocean system (Figure 1). Ocean circulation connects all ocean basins and regions, and therefore, the ocean is host to the largest connected ecosystem of our planet and covers more than two-thirds of the Earth's surface. This large surface area combined with an enormous volume of water and mass makes the ocean a very important part of the global climate system (e.g., Schmitt 2018).



STG – Subtropical Gyre
 SPG – Subpolar Gyre
 ECS – Equatorial Current System
 ACC – Antarctic Circumpolar Current

Figure 1. Horizontal ocean currents: the ocean is traversed by a large-scale overturning circulation that sets the rate at which the deep ocean interacts with the atmosphere and is, therefore, crucial for the climate system Source: Figure by Jamie Oliver, British Antarctic Survey, 2020; used with permission.

The rising emissions of carbon dioxide (CO₂), methane and other greenhouse gases have led to planetary warming. These greenhouse gases are preventing some of the heat radiated from the Earth’s surface from escaping into space, heating the atmosphere and increasing the back radiation onto the Earth’s surface. Recent

estimates of this change in planetary energy changes have revealed that more than 93% of warming is found in the upper and deep ocean. The large volume and high heat capacity of water make the ocean the largest sink of this extra warming. In addition to buffering the heat, the ocean also directly stores almost 30% of the human emitted carbon dioxide. Taken together, these two effects have significantly slowed down human-induced climate change in the atmosphere and on land. At the same time, this warming changes the physics, biochemistry and marine ecosystems with an already noticeable impact on the marine ecosystem services.

This fundamental role of the ocean in climate variability and change has prompted member states to ask for a topical report of the Intergovernmental Panel on Climate Change called the “Special Report on the Ocean and Cryosphere in a Changing Climate” (IPCC 2019). We will make extensive use of this detailed report to highlight some of the specifics throughout this chapter.

More generically, the ocean moderates the seasonal cycle of our climate and is responsible for what we call a maritime climate with warmer winters and cooler summers. It enables the presence of monsoon systems and moderates global rainfall and regional weather variability. It plays a key role in coupled ocean–atmosphere phenomena, such as El-Niño, and enables their predictability. On longer timescales, the ocean is a critical pacemaker from decade long megadroughts, century long cold spells through the cycles of ice ages and beyond.

The ocean also interacts with other parts of the climate system—land, atmosphere, sea ice and the marine ecosystem. Its global circulation system connects ocean basins (Figure 1) and the upper ocean with the deeper waters (Figure 2). Ocean currents transport heat from warm to cold regions, and thus influence the release of heat and moisture to the atmosphere. They are connected with the atmosphere and modulate the wind system that in turn drives ocean currents. We speak of a coupled ocean–atmosphere climate system. In addition, higher levels of atmospheric CO₂ directly lead to increasing levels of dissolved CO₂ in the upper ocean, leading to a change in the ocean chemistry that lowers the pH, a process known as ocean acidification. This ocean acidification describes a movement of pH from a slightly basic pH of the sea water (pH about 8 and >7) towards pH-neutral conditions rather than turning acidic (pH < 7).

The effects of a changing ocean have a high impact on our lives. Humans depend on the ocean directly by living at the sea and indirectly through profiting from the ocean ecosystem services (e.g., Visbeck et al. 2014). Any change in the ocean will also affect those services, sometimes directly and sometimes more indirectly, through complex interactions with the climate system. For many marine ecosystems, the

combined stress from climate change, overuse, habitat destruction and pollution lead to dramatic shifts in ways that are often not understood. From a precautionary principles perspective, climate change needs to be minimized by decisive mitigation action in order to secure ocean ecosystem services for future generations. From the perspective that the human effects on the ocean and use of the ocean services need to become more sustainable, clear guiding principles can be articulated to inform sustainable development for humanity.

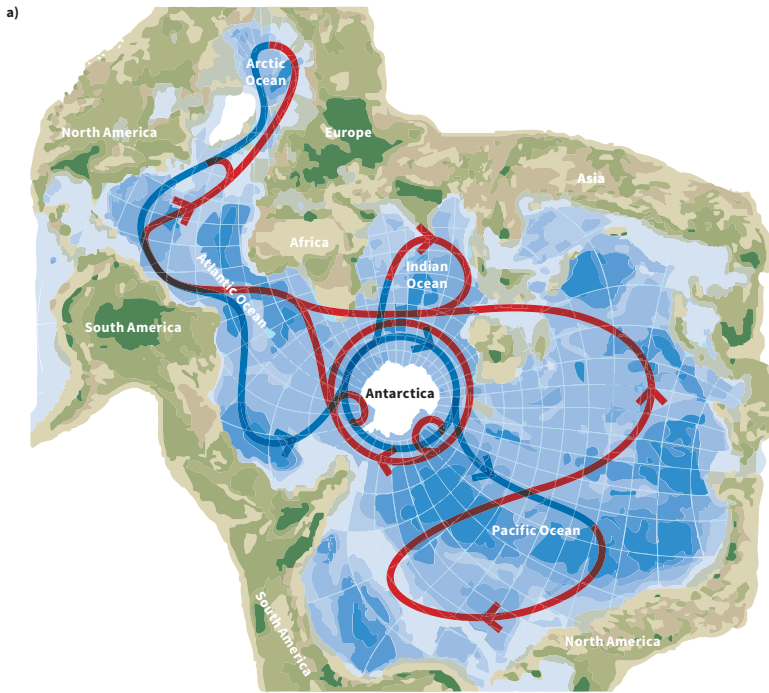


Figure 2. *Cont.*

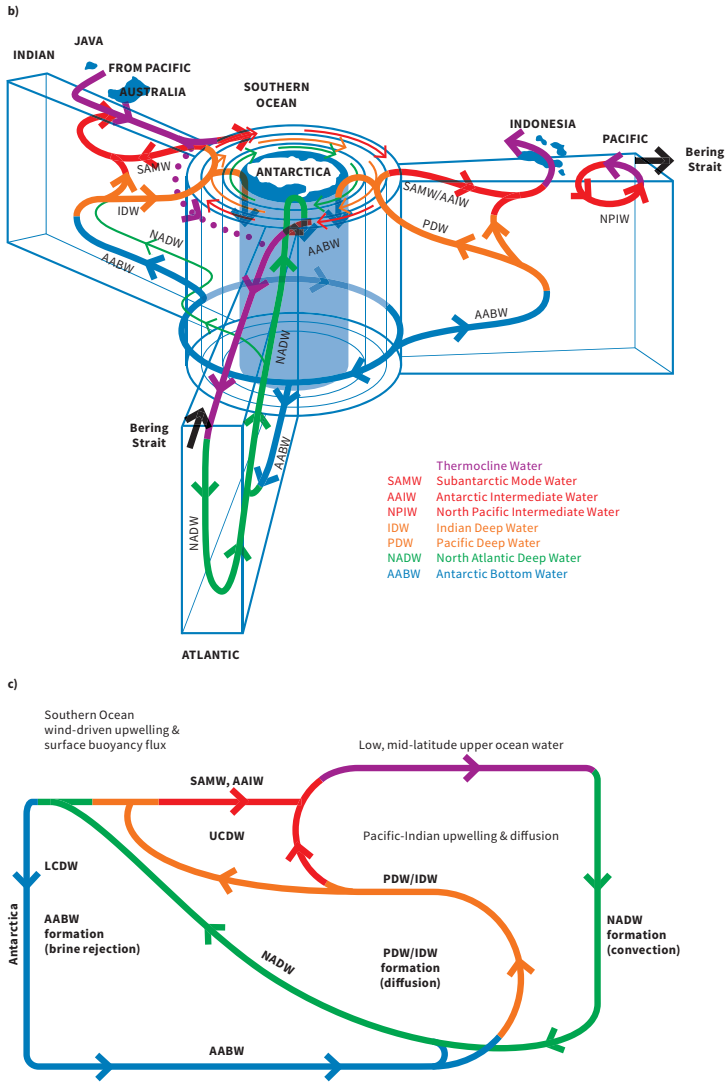


Figure 2. (a) Meridional ocean circulation: the ocean is traversed by a large-scale overturning circulation. This circulation sets the rate at which the deep ocean interacts with the atmosphere and is, therefore, essential for the climate system. The red arrows

depict a simplified pathway of the warmer water close to the surface, and the blue arrows show the spreading of cold water at depths. (b) Sketch of zonally averaged vertical circulation for three ocean basins shows the interconnection between the different water masses of the global ocean. (c) Replotting of the Atlantic Basin. Surface waters: purple; intermediate waters: red; NADW: green; Indian Ocean Deep Water (IDW): orange; Pacific Deep Water (PDW): orange; and Antarctic Bottom Water (AABW): blue Source: (a) adapted from (. Meredith 2019); figure by Jamie Oliver, British Antarctic Survey, 2020; used with permission; (b,c) figure by (Talley 2013); used with permission.

Knowledge about anthropogenic-induced climate change has been assessed by the Intergovernmental Panel on Climate Change since 1990 in a series of extensive reports. The latest IPCC Synthesis Report was published in 2014. The overall observations reported in the report confirm that the atmosphere and the ocean have warmed, the amounts of snow and ice have diminished and sea level has risen (IPCC 2014). The recent Special Report of the IPCC with a focus on the ocean and cryosphere (Special Report on the Ocean and Cryosphere in a Changing Climate, IPCC 2019) also emphasizes that climate change has led, for instance, to increasing ocean heat content, sea level rise, ocean heatwaves, coral bleaching and melting of ocean-terminating glaciers and ice sheets around Greenland and Antarctica. More indirect but measurable impacts are growing oxygen minimum zones, and there is an expectation that the global ocean overturning circulation will slow down in the future. In the following, we will repeat and highlight some of the key findings from that report that are particularly relevant in the context of sustainability.

2. The Ocean as a Heat and CO₂ Buffer

Since the pre-industrial era, human activities such as burning fossil fuels, e.g., coal and oil; deforestation; and cement production have led to an increase in atmospheric concentrations of carbon dioxide (CO₂), methane and nitrous oxide. The IPCC Synthesis report states that their effects, “together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century” (IPCC 2014). The IPCC 2018 states that approximately 1.0 °C of global warming above pre-industrial levels, with a likely range of 0.8 to 1.2 °C, has been caused by human activities and estimates that global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate (IPCC 2018).

The ocean's role in global warming is associated with its heat capacity, heat transport in the ocean and the global water cycle. The ocean has absorbed more than 90% of the increased heat (e.g., IPCC 2019). Consequently, the atmospheric warming would be much more dramatic today without the ocean's uptake of heat. About two thirds of the excess heat have been absorbed within the upper 700 m of the ocean. However, the warming has also reached the deep ocean through deep-water formation regions and by changing the ocean circulation (IPCC 2019).

In the past 100 years, the ocean has absorbed a third of man-made carbon dioxide. Without the ocean as a sink, the ever-increasing CO₂ emissions would already have caused much more pronounced global warming (e.g., IPCC 2014).

In addition to the heat buffer effect, the ocean has absorbed one third of global CO₂ emissions (IPCC 2014). When the concentration of CO₂ in the atmosphere rises, the atmosphere ocean pCO₂ gradient increases, leading to increased ocean CO₂ uptake. However, this exchange process is also moderated by the absolute ocean temperature. The colder the seawater is, the more CO₂ can be dissolved in the ocean. This means, in reverse, that a warming ocean will decrease the CO₂ uptake potential of the ocean. Moreover, a warmer surface ocean will increase the ocean's stratification and will make it harder to tap into the deeper ocean layers that provide enormous CO₂ uptake potential. A significant part of the drawdown of surface CO₂-rich waters is facilitated by the overturning ocean circulation, which itself is expected to decrease. In summary, there is an expectation that the ocean might not be able to continue to uptake its current share of the anthropogenic CO₂ emissions, which would increase the temperature effect per emitted ton of CO₂ more strongly (IPCC 2019).

3. Ocean Currents Regulate Global Climate

The Arctic, Atlantic, Indian, Pacific and Southern Oceans are all interconnected and part of a single Global Ocean. The circulation of the ocean together with exchanges between the ocean and the atmosphere, and to a lesser degree, with the coastal systems, determine the distribution of heat, freshwater, nutrients, oxygen, carbon dioxide and dissolved chemical components around the planet. The large-scale circulation of the ocean comprises an interaction of the dominantly wind-driven upper-ocean circulation of the various gyres (Figure 1). The vertical exchange between the surface and deeper layers is more complex. A prominent example is the global meridional overturning circulation (MOC) connecting the sinking regions of the higher latitudes with the upwelling regimes around the globe. This interaction leads to a complex three-dimensional circulation throughout the global ocean.

For example, in the Atlantic sector, the MOC brings warm tropical water northward in both hemispheres, mitigating the temperature difference between the equator and pole in the North Atlantic while amplifying the pole-to-equator temperature difference in the South Atlantic. This transport of heat in the upper limb of the Atlantic MOC contributes to the Gulf Stream (indicated in Figure 1) and heating of Western Europe, in particular, the Nordic Countries and Seas (Figure 2).

Global warming can affect this circulation in two ways. First, the melting of glacial ice produces low salinity waters that, together with warmer temperatures, increase the ocean's stratification and reduce the formation of deep-water. Second, a warmer upper ocean globally makes it more difficult to mix and upwell the cold waters from below towards the surface. Thus, experts are expecting a slow-down of the MOC in the coming decades. However, the full impact of these changes in the physical ocean is not fully understood, and future ocean observation and better understanding are needed globally.

A changing climate will also result in an atmospheric wind system. This in turn will directly influence the upper ocean circulation. However, the large interannual variability of the wind systems to date is significantly larger than climate change-induced signals. There is some evidence for a poleward shift of all major boundary currents over the last century and some suggestions of an intensification of the trade winds. All of this will affect the connectivity of the open ocean with the coasts of its ecosystems with significant regional differences (IPCC 2014 synthesis report).

4. Climate Change Induces Challenges for the Future Ocean

Unabated carbon emissions from human activities causing ocean warming, ocean acidification and oxygen loss, with some evidence of changes in nutrient cycling and primary production, will lead to more climate change. Some of the key parameters with their observed trend are listed in Figure 3. Two scenarios, a high emission and low emission one, are compared in the time series in Figure 4. The different projections for the climate future are described by Representative Conservation Pathways (RCPs), all of which are considered possible depending on the volume of greenhouse gases emitted in the years to come. Only the lowest projection represents mitigation pathways compatible with the 1.5 °C warming limit of the Paris Agreement. In particular, the high emission scenarios will cause several challenges for the future of the ocean.

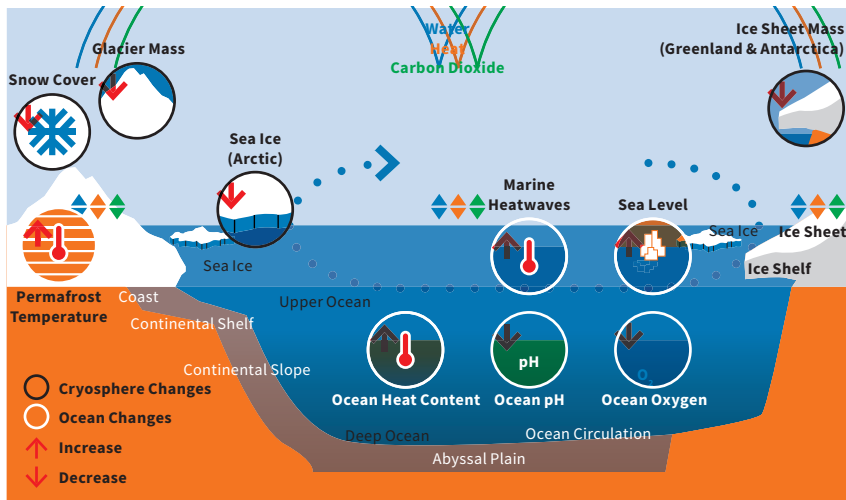


Figure 3. “Schematic illustration of key components and changes of the ocean and cryosphere, and their linkages in the Earth system through the global exchange of heat, water, and carbon. Climate change-related effects (increase/decrease indicated by arrows in pictograms) in the ocean include sea level rise, increasing ocean heat content and marine heatwaves, increasing ocean oxygen loss and ocean acidification. For illustration purposes, a few examples of where humans directly interact with ocean and cryosphere are shown” Source: Reprinted from (IPCC 2019, p. 43); used with permission. Figure TS.2 from IPCC 2019 Technical Summary.

- Ocean warming

The ocean has warmed progressively in recent decades. This trend is readily detectable in oceanic observations. The processes of global warming are scientifically well understood, and projections through climate models consistently show the global warming trend (IPCC 2019). The IPCC states: “These trends in the global average ocean temperature will continue for centuries after the anthropogenic forcing is stabilized” (IPCC 2019). The IPCC concludes that “this temperature increase corresponds to an uptake of over 90% of the excess heat accumulated in the Earth system over this period by the ocean and also causes it to expand and has contributed about 43% of the observed global mean sea level rise” (IPCC 2019). The IPCC summarizes that

The ocean has warmed unabated since 2005, continuing the clear multidecadal ocean warming trends. The warming trend is further confirmed by the improved ocean temperature measurements over the last decade. (. . .) By 2100 the ocean is very likely to warm by 2 to 4 times as much for low emissions and 5 to 7 times as much for the high emissions scenario compared with the observed changes since 1970. (. . .) The overall warming of the ocean will continue this century even after radiative forcing and stabilized mean surface temperatures. (IPCC 2019)

- Sea level rise

Global mean sea level is rising, with acceleration in recent decades (IPCC 2019). The IPCC report states that the sum of glacier and ice sheet contributions is now the dominant source of sea level rise followed by ocean warming (IPCC 2019). Future sea level rise caused by thermal expansion, melting of glaciers and ice sheets and land water storage changes is strongly dependent on which emission scenario is followed by society (IPCC 2019). Under all scenarios of the IPCC's projections—including those compatible with achieving the long-term temperature goal set out in the Paris Agreement—sea level rise will be faster at the end of the century (IPCC 2019). Projections of the IPCC conclude that the global mean sea level will rise between 0.29 and 0.59 m for low emissions and 0.61–1.10 m for high emissions by 2100 (IPCC 2019). However, sea level does not rise globally uniformly and varies regionally as “thermal expansion, ocean dynamics and land ice loss contributions will generate regional departures of about $\pm 30\%$ around the mean” (IPCC 2019). The differences from the global mean can be even greater in areas of rapid vertical land movements, including those caused by local anthropogenic factors, such as groundwater extraction (IPCC 2019). Therefore, the IPCC concludes that regional sea level rise is, in particular, a high risk to low-lying islands, coasts, cities and settlements, and needs response options and pathways to resilience and sustainable development along the coast (IPCC 2019).

- Ocean acidification

In the past 50 years, the ocean has taken up 20–30% of total carbon dioxide released into the atmosphere by human activities (IPCC 2019). However, as consequence, the average pH at the ocean surface has lowered from 8.2 to 8.1, which translates into a 30% increase in acidity (IPCC 2018).

Past and future changes in the ocean and cryosphere

Historical changes (observed and modelled) and projections under RCP2.6 and RCP8.5 for key indicators

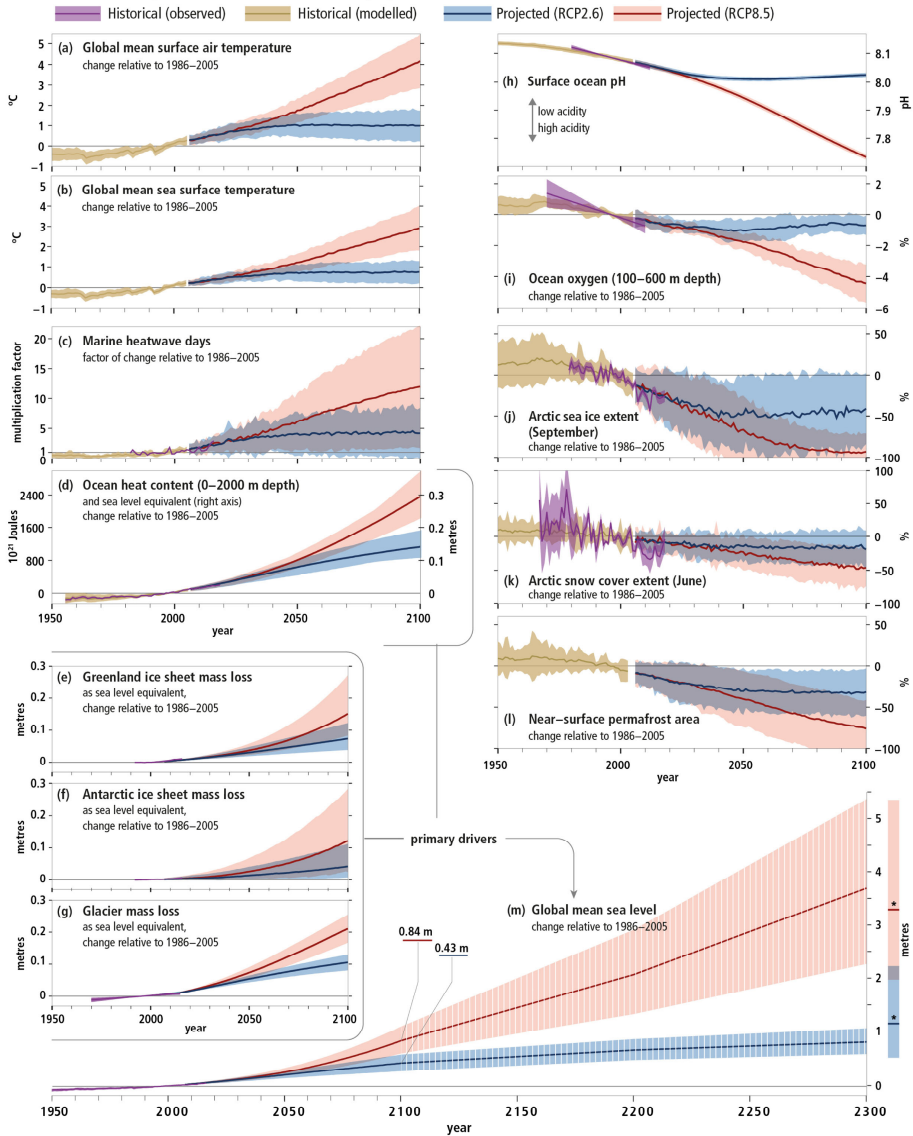


Figure 4. “Observed and modeled historical changes in the ocean and cryosphere since 1950, and projected future changes under low (Representative Concentration Pathways (RCP) 2.6; requires that carbon dioxide emissions start to decline by 2020

and go to zero by 2100) and high (RCP8.5) greenhouse gas emissions scenarios (emissions continue to rise throughout the 21st century). 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 ($\epsilon \approx 0.125$ 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; and (g) Glacier mass loss. Further cryosphere-related changes with very likely ranges for (j) Arctic sea ice extent change for September; (k) Arctic snow cover change for June (land areas north of 60° N); and (l) Change in near-surface (within 3–4 m) permafrost area in the Northern Hemisphere.” Source: Reprinted from (IPCC 2019, pp. 17, 44); used with permission. Figure SPM.1 from IPCC 2019 Summary for Policymakers in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Higher acidity affects the balance of minerals in the water, which, for example, can make it more difficult for marine animals building their protective skeletons or shells. Some studies show the impact of ocean acidification on food chains and biodiversity, “but more efforts are required to strengthen our knowledge about the impact of acidification on the wider food web”, states the IPCC (2019).

The ocean is continuing to acidify in response to ongoing ocean carbon uptake. The open ocean surface water pH is observed to be declining (virtually certain) by a very likely range of 0.017–0.027 pH units per decade since the late 1980s across individual time series observations longer than 15 years. The anthropogenic pH signal is very likely to have emerged for three-quarters of the near-surface open ocean prior to 1950 and it is very likely that over 95% of the near surface open ocean has already been affected. These changes in pH have reduced the stability of mineral forms of calcium carbonate due to a lowering of carbonate ion concentrations, most notably in the upwelling and high-latitude regions of the ocean. (IPCC 2019, p. 59)

- Ocean deoxygenation

Dissolved oceanic oxygen supports the largest ecosystems on the planet. Global warming impacts ocean oxygen in two ways: firstly, warmer water has a reduced capacity to hold oxygen and, secondly, the reduction in ocean mixing and circulation limits the uptake of oxygen from the atmosphere, because when water is not mixed, the top layer will be saturated with oxygen, while the bottom becomes anoxic. The oxygen in the ocean also depends on oxygen producing organisms living in the ocean. These organisms also depend on the water temperature and light availability and are influenced by climate change. Deoxygenation disrupts marine ecosystems causing loss of habitats and biodiversity, which can have knock-on effects, such as harming natural fish stocks and aquaculture.

There is a growing consensus that the open ocean is losing oxygen overall with a very likely loss of 0.5–3.3% over the period 1970 to 2010 from the ocean surface to 1000 m. Globally, the oxygen loss due to warming is reinforced by other processes associated with ocean physics and biogeochemistry, which cause the majority of the observed oxygen decline. The oxygen minimum zones (OMZs) are expanding by a very likely range of 3–8%, most notably in the tropical oceans, but there is substantial decadal variability that affects the attribution of the overall oxygen declines to human activity in tropical regions. Ocean model simulations predict a very likely decline in the dissolved oxygen content of the ocean by 3.2–3.7% (high emission scenario) by 2081–2100, relative to 2006–2015, or by 1.6–2.0% for the low emission scenario (IPCC 2019). The volume of the oceans OMZ is projected to grow by a very likely range of $7.0 \pm 5.6\%$ by 2100 during the high emission scenario, relative to 1850–1900 caused by a combination of a warming-induced decline in oxygen solubility and reduced ventilation of the deep ocean (IPCC 2019).

Deoxygenation accompanies ocean warming and ocean acidification as one of the three major oceanic consequences of rising atmospheric CO₂ levels (Levin and Breitburg 2015).

The decline in the oceanic oxygen content can affect ocean nutrient cycles and the marine habitat, with potentially detrimental consequences for fisheries, ecosystems and coastal economies. Oxygen loss is closely related to ocean warming and acidification caused by CO₂ increase driven by CO₂ emissions as well as biogeochemical consequences related to anthropogenic fertilization of the ocean. A combined effort investigating the different stressors will be most beneficial to understand future ocean changes (Schmidtko et al. 2017).

- Marine heatwaves

Marine heatwaves are periods of extremely high ocean temperatures. Scientists found that marine heatwaves have doubled in frequency and have become longer-lasting and more intense. The IPCC reports that marine heatwaves “have negatively impacted marine organisms and ecosystems in all ocean basins over the last two decades, including critical foundation species such as corals, sea grasses and kelps” (IPCC 2019). However, marine heatwaves are projected to further increase in frequency, duration, spatial extent and intensity (maximum temperature) (Frölicher et al. 2018). The IPCC reports that “climate models project increases in the frequency of marine heatwaves by 2081–2100, relative to 1850–1900, by approximately 50 times under a high emission scenario and 20 times under the low emission scenario” (IPCC 2019). 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 a high emission scenario by 2081–2100, relative to 1850–1900 (IPCC 2019).

In the absence of more ambitious adaptation efforts compared to today, and under current trends of increasing exposure and vulnerability of coastal communities, 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 (very high confidence). Under the same assumptions, annual coastal flood damages are projected to increase by 2–3 orders of magnitude by 2100 compared to today (high confidence). (IPCC 2019)

- Extreme events

Projections in the IPCC show that climate change influences extreme events. Climate change is even projected to potentially cause abrupt changes in the ocean and the cryosphere (IPCC 2019).

In the ocean, a possible abrupt change is associated with an interruption of the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is an important component of global ocean circulation. A slowdown of the AMOC could have consequences around the world: rainfall in the Sahel region could reduce, hampering crop production; the summer monsoon in Asia could weaken; increase in regional sea level around the Atlantic, especially along the northeast coast of North America; and there might be more winter storms in Europe (IPCC 2019).

- Impacts on marine ecosystems

The ocean is home to at least 230,000 known species in a variety of habitats that stretch from the flat coastline to the deep sea. Despite the ocean's important role in the climate system, its biodiversity serves, among other things, as an important food source. Changing physics and biochemistry of the ocean change the marine ecosystems and its services to humans. Marine biodiversity includes organisms that live in suspension in the water column with limited mobility (plankton), animals that live in the water column that can actively swim (nekton) and organisms that live within or on the sea floor (benthos). Moreover, most living phyla have marine representatives, with sizes that range from the smallest (archaea and viruses) to the largest living beings (the blue whale) (e.g., European Marine Board EMB). They play different roles throughout their life, inhabiting different environments and providing different functions. Particularly, wild fish capture is an important ecosystem service, and its abundance depends, among other factors, on the climatic related ocean conditions.

The IPCC states that ocean warming has contributed to observed changes in the biogeography of organisms ranging from phytoplankton to marine mammals, consequently changing community composition, and in some cases, altering interactions between organisms (IPCC 2019; summary provided in Figure 5). The IPCC projections show that along with ocean warming and changes in net primary productivity during the 21st century, global marine animal biomass and the maximum potential catches of fish stocks will be reduced, although with regional differences in the direction and magnitude of changes (IPCC 2019).

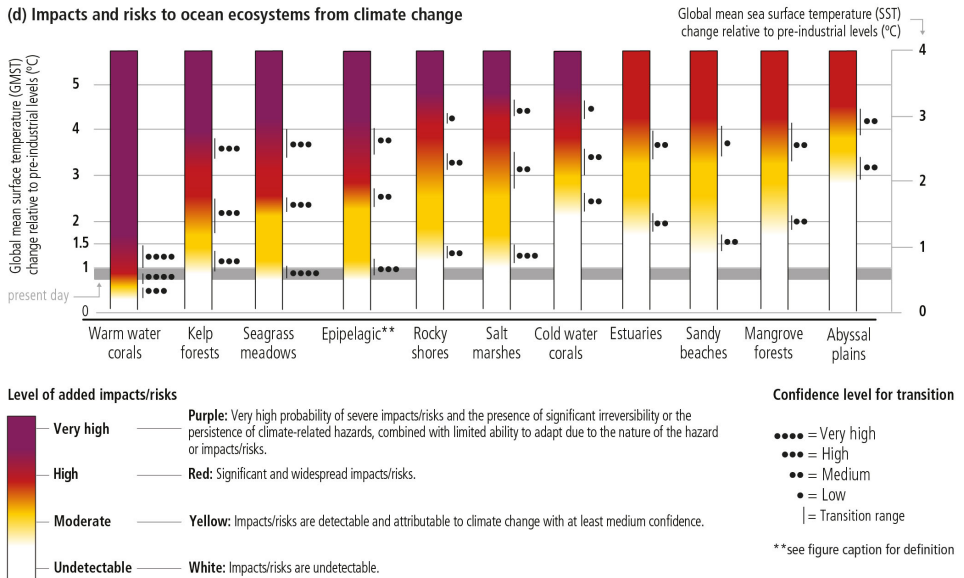


Figure 5. “Projected changes, impacts and for coastal and open ocean ecosystems. Specifically, assessment of risks for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. Impacts and risks are shown in relation to changes in Global Mean Surface Temperature (GMST) relative to pre-industrial level. Since assessments of risks and impacts are based on global mean Sea Surface Temperature (SST), the corresponding SST levels are shown.” Source: Reprinted from (IPCC 2019, p. 33); used with permission. Figure SPM.3 (d) from IPCC 2019 Summary for Policymakers in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

The projections from the IPCC show that these “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 compromise the ocean’s role in cultural, recreational, and intrinsic values important for human identity and well-being” (IPCC 2019).

The projected redistribution of resources and abundance increases the risk of conflicts among fisheries, authorities or communities. 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, and for economic sectors such as fisheries, aquaculture, and tourism. (IPCC 2019, p. 26)

Higher acidity affects the balance of minerals in the water, which, for example, can make it more difficult for certain marine animals to build their protective skeletons or shells, as they must have access to available calcium in the seawater. This affects, for example, reef-building hard corals, as well as oysters, clams and snails that are composed of calcium carbonate (IPCC 2019). For coral polyps, for example, a 52–73% decline in larval settlement on reefs under lower pH levels has been shown (e.g., van Doorn et al. 2015). When the coral polyps have grown, scientists can also measure the calcification rates of hard corals. Studies show that ocean acidification has had a negative impact on the rate at which corals calcify, making them more brittle and less resilient to other factors influencing their survival in the future (e.g., van Doorn et al. 2015).

Coral reefs form habitats in the ocean, being home to the richest and most diverse biodiversity of our ocean. The survival of thousands of other marine species depends on coral reefs—many of which we rely on for food. In addition, they act as buffers against sea-level rise and increased storm intensity and thus play a critical role in mitigating and adapting to climate change (IPCC 2019).

- Impacts on coastal communities

Coastal areas are particularly vulnerable to the effects of climate change, such as sea level rise, storm intensity and flooding, increased temperatures, ocean acidification and low oxygen zones, all resulting in changing marine ecosystems. At the same time, coastal areas are highly populated, and today, about two-thirds of the world's population live within 60 km of the coast (United Nations Atlas of Oceans n.d.), and societies depend on global transport via shipping routes and harbors (e.g., IPCC 2019). More than 600 million people (around 10 per cent of the world's population) live in coastal areas that are less than 10 m above sea level (IPCC 2019). The IPCC summarizes that “coastal areas are zones of concentrated biodiversity and natural productivity and will be particularly affected by multiple stressors because this is where most human activities take place and where pressure accumulates” (IPCC 2019).

The IPCC report states that increased mean and extreme sea level, ocean warming and ocean acidification will be the major threats for communities in low-lying coastal areas, delta regions and resource rich coastal until 2050 under current adaptation

(IPCC 2019). At global scale, coastal protection could reduce flood risk by 2–3 orders of magnitude during the 21st century, but depends on large investments, and some island communities have already lost their homes due to sea level rise (IPCC 2019). Such investments can be cost efficient for densely populated urban areas, but they might be difficult to afford for rural and poorer areas (IPCC 2019).

5. Conclusions

Climate change is among the main drivers of change also for the ocean system. At the same time, the ocean is part of the climate system and provides “memory” and regional redistribution of climate signals. In the 2030 Agenda for sustainable development, both climate and ocean have specific goals (SDG 13 and 14, respectively). While both the ocean and climate issues transgress many of the goals (e.g., Nilsson et al. 2016), the rapidly advancing scientific understanding of both the ocean and climate system has allowed for the in-depth assessment of what is known (e.g., IPCC 2019, extensively referred to in this paper).

On the other hand, the 2030 Agenda for Sustainable Development and the Paris Climate Agreement are focused on action. While the scientific evidence and problem diagnostic down to the regional level is well advanced, the impacts on the local level and the assessment of development options and solutions to adapt and mitigate climate and ocean change are less well researched. A recent report from the High Level Panel for Sustainable Ocean Economy discusses “The Ocean as a Solution for Climate Change: 5 Opportunities for Action” (Hoegh-Guldberg et al. 2019) and suggests that up to 25% of the needed CO₂ emission reductions can be obtained by ocean-related actions, which include innovation and efficiency gains in the maritime industry but also nature-based solutions to increase ocean uptake of CO₂ and ocean-based energy production.

Connecting Ocean Science with the quest for action and solutions is the focus of the upcoming UN Decade of Ocean Sciences for Sustainable Development (e.g., Ryabinin et al. 2019). In order to fully achieve the Ocean Decade Objectives as well as the ocean dimension of the 2030 Agenda, growth and transformation in how we conduct ocean science towards more integration across disciplines and knowledge systems are essential (Pendleton et al. 2020). This will require a sustained ocean observation system; all ocean data shared freely; new and more effective ways of analyzing observational data fused with ocean and climate model; and enhancing timely assessment, predictions and scenario development of future ocean conditions (Visbeck 2018). At the same time, we need to grow ocean science capacity and capabilities worldwide and establish the sharing of resources and information.

A particular focus is the countries of the global south and small island states who are fully aware of the challenges. Ocean science must come together to be in a position to support decision makers by providing knowledge and frameworks to weigh the ecological, environmental and human impacts of different sustainable development pathways. New and innovative ways of collaborating amongst all ocean stakeholders will need to be identified. Disciplines and perspectives not always represented in ocean science will need to be involved in order to share their knowledge and attain a more holistic understanding.

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