Climate Science

Zero Carbon Analytics

Briefing · September 2019

IPCC report on the ocean and cryosphere[1]

The oceans and frozen cryosphere are vital to human wellbeing. All people depend, indirectly or directly, on the many services they provide. The cryosphere – the frozen parts of the planet – holds around 69 per cent of global freshwater. The Hindu Kush Himalaya alone provides freshwater for nearly 2 billion people. Coasts provide a home to around 1.9 billion people and over half of the world's megacities. The planet relies on the cryosphere and the oceans to regulate the climate, but both are extremely vulnerable to climate change.

Accelerating change in the ocean and cryosphere is one of the most visible and dramatic symptoms of the climate crisis. Both will continue to change even if the climate stabilizes, and some of the damage caused by climate change is irreversible on timescales relevant to human societies[2]. But by cutting emissions, risks can be reduced or avoided, and adaptation made easier and more effective.

1. Changes to the Earth's frozen poles

Antarctica, a continent surrounded by the ocean, and the Arctic, an ocean surrounded by land, make up the polar regions of the world. Both are particularly vulnerable to climate change[3]. These massive white spaces perform a vital service in regulating the planet's temperature by reflecting the Sun's heat back into space. As a result, any loss of these frozen regions accelerates climate change.

The Arctic is also home to over four million people and a range of complex ecosystems. These are directly at risk from climate change, which is threatening food and water security, infrastructure[4], key transportation routes, and increasing the risk of death, injury, disease and mental health impacts for people in the region.

Snow, ice sheets and polar glaciers

The future Arctic will be warmer and wetter. Temperature rise in the Arctic has been more than double the global average over the last two decades, and Arctic snow cover is declining dramatically[5]. Western Antarctica and the Antarctic Peninsula are warming, while east Antarctica is slightly cooling, although confidence in Antarctic changes is low due to limited data.

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[1] The Special Report on the Ocean and Cryosphere in a Changing Climate is the latest special report from the Intergovernmental Panel on Climate Change (IPCC). It will be published in September 2019. It explores past, ongoing and future changes to the ocean and cryosphere, based on a comprehensive assessment of the latest scientific literature, and drawing on indigenous and local knowledge. It highlights how climate change is impacting mountains, polar regions, coasts, low-lying islands and the open ocean.

[2] https://www.nature.com/articles/nature15706; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015RG000493; https://journals.ametsoc.org/doi/full/10.1175/1520-0442%281999%29012%3C2169%3ATDROTG%3E2.0.CO%3B2; https://www.nature.com/articles/nclimate2964; https://science.sciencemag.org/content/356/6338/580.summary

[3] This is predominantly due to "polar amplification", resulting from cascading "feedbacks" primarily caused by the loss of albedo.

[4] https://www.nature.com/articles/s41467-018-07557-4; https://link.springer.com/chapter/10.1007/978-3-319-05266-3_5

[5] https://iopscience.iop.org/article/10.1088/1748-9326/6/4/045204/meta; https://www.earth-syst-sci-data.net/7/137/2015/essd-7-137-2015.html; https://www.ametsoc.net/sotc2017/StateoftheClimate2017_lowres.pdf (p 169).

The Antarctic and Greenland ice sheets are both rapidly losing ice as the regions warm, providing the main cause of global sea level rise, and ice loss is speeding up. Greenland lost about 247 gigatonnes of ice each year over the period 2012 to 2016. The loss from the Greenland ice sheet alone could fill over 270,000 Olympic swimming pools a day[6], and results in about 0.7mm sea level rise every year. Polar glaciers are also shrinking, and will continue to lose substantial amounts of ice over this century[7], adding to global sea level rise and challenging fresh water management.

These changes are irreversible on timescales of centuries and beyond. The future of the huge Antarctic ice sheet is also increasingly precarious. A collapse[8] of the west Antarctic ice sheet could increase the amount and speed of sea level rise. While it is difficult to assess exactly how much this cryosphere change can be attributed to natural versus human activity, it's clear that decline is being driven by both ocean and atmospheric temperature increases.

Sea ice

Sea ice is an important feature of the polar environment. In the Arctic, sea ice extent and thickness[9] has been rapidly decreasing and will continue to decline during the next century. The change is largest in the summer - September Arctic sea ice has declined about 12.8 per cent per decade between 1979 and 2017[10]. With two degrees of warming the chances of having an ice-free September[11] by the end of the century increase drastically, while limiting warming to 1.5 degrees will likely preserve some sea ice[12].
Antarctic sea ice declined in 2016 and 2017, a change from the gradual increase seen between 1979 and 2017. The loss is regionally uneven, and closely related to wind trends. Exactly why is still under investigation, meaning there is low confidence in future predictions of Antarctic sea ice cover.

Permafrost

Permafrost, frozen soil that stores huge reservoirs of carbon, will continue melting under all emissions scenarios[13] but less so if emissions are cut. Permafrost throughout the northern hemisphere is already experiencing record temperatures; the European Alps, the Tibetan Plateau and Scandinavia all show consistent warming.

Thawing soil will release carbon dioxide and methane, causing further climate change[14]. Methane is a powerful greenhouse gas and is about 28 times more powerful than carbon dioxide at warming the Earth. A likely minimum of 30 per cent and a maximum of almost

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[6] From the period 2006-2015. See https://sealevel.nasa.gov/news/114/10-things-all-about-ice, using stat of 400,000*278/365
[7] https://www.cambridge.org/core/journals/journal-of-glaciology/article/glaciermip-a-model-intercomparison-of-globalscale-glacier-massbalance-models-and-projections/30495AC402766F4A1D84007DA7A9F54B; https://link.springer.com/article/10.1007/s00382-013-1719-7; https://www.frontiersin.org/articles/10.3389/feart.2015.00054/full
[8] https://www.nature.com/articles/s41561-018-0082-z; https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL081229
[9] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009JC005312; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/grl.50193
[10] Relative to the 1981-2010 mean. Smallest loss is in winter months, though still significant. With a recorded decline of -41 000 km^2 per year.
[11] https://science.sciencemag.org/content/354/6313/747.abstract; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2011JD016709; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL070067
[12] https://www.nature.com/articles/s41558-018-0127-8; https://science.sciencemag.org/content/354/6313/747.abstract; https://www.nature.com/articles/s41558-018-0124-y
[13] https://onlinelibrary.wiley.com/doi/abs/10.1002/ppp.720; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JD024108; https://journals.ametsoc.org/doi/full/10.1175/JCLI-D-12-00341.1; https://www.nature.com/articles/nclimate3262
[14] Warming leads to carbon release, which in turn amplifies warming and causes more carbon release creating a “feedback”.

all near surface permafrost could be lost by 2100 if emissions are not cut, potentially causing tens or hundreds of billions of tonnes of carbon to be released – there is almost twice as much carbon stored in the Arctic and Boreal regions as in the entire atmosphere. The risk of abrupt thaw from sudden land collapses makes predictions harder. Such events could double the release of harmful greenhouse gases, with around 20 per cent of the northern hemisphere frozen zones at risk.

Degradation of permafrost creates a risk to infrastructure. 70% of Arctic infrastructure and 45% of Russian oil and gas fields are located in areas expected to thaw by 2050. In Alaska alone, climate-related infrastructure losses could total US$5.5bn[15] by the end of the century, although adaptation and mitigation could reduce this by about US$1.3bn.

2. Changes to the ocean

The ocean is absorbing excess heat and carbon dioxide from the overloaded atmosphere. It is becoming warmer, more acidic, less salty, and losing oxygen content. These changes are fundamentally altering ecosystems and the global climate.

Around 93% of the extra heat the planet has accumulated in recent decades from climate change has gone into the oceans. This is warming the ocean, and because it is slow to heat up, warming will continue even if greenhouse gas emissions are cut. The ocean will likely absorb two to three times more additional heat by the end of the 21st century than it has since 1900, even with big emissions cuts. If emissions are not cut the amount of heat absorbed could double[16].

The salinity (or saltiness) of the ocean is also changing. High latitude oceans are becoming fresher as melting sea ice and ice sheets add fresh water to the ocean. But closed-off, high-evaporation basins like the Mediterranean are expected to become saltier. The ocean is divided into layers based on differences in temperature, salinity or both and changes are leading to the upper ocean becoming more 'stratified'. This constricts mixing and ocean circulation which plays a vital role in redistributing heat, carbon, oxygen and nutrients around the planet.

One important example is the heat transported by the Atlantic Meridional Overturning Circulation (AMOC), which helps keep the Northern Europe climate relatively mild. The AMOC is expected to gradually weaken under all future climate scenarios, with greater weakening if emissions are not cut. There is a very unlikely possibility that further warming could cause a collapse of the AMOC, fundamentally and dramatically changing the climate system with a cascade of potential abrupt impacts including decreasing tropical cyclones, decreased monsoons, changing rainfall patterns, increased sea level rise, and increased European winter storms.

Ocean acidification and deoxygenation

The ocean exchanges carbon with the atmosphere and acts as a net 'sink' of carbon dioxide. Most of the absorbed carbon dioxide is transported to the deep ocean and stored. So far, the ocean has absorbed between 20-30% of the carbon dioxide emitted by human

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[15] However estimates do not take into account the loss to private infrastructure, and is thus just a percentage of total costs.
[16] https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007GL031712; https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00752.1; https://www.jstage.jst.go.jp/article/sola/13/0/13_2017-030/_article/-char/ja/; https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap30_FINAL.pdf

activity since the 1980s. This is hugely important – it means that about a quarter of the extra greenhouse gases we have put into the atmosphere have been captured instead of warming the planet. It is virtually certain that the ocean will continue to absorb carbon dioxide from the atmosphere, but as the planet warms there could be a reduction in how much it captures, with potentially profound implications for the global carbon budget.

This extra carbon dioxide is fundamentally altering ocean chemistry, causing ocean acidification, with severe impacts on marine ecosystems and human livelihoods. Future acidification depends on how much we emit in the future. Global oxygen levels in the ocean have also fallen by more than two per cent since the 1960s[17], affecting nutrient cycles and marine life, and damaging fisheries and coastal economies. The largest decreases are in the North Pacific, Southern Ocean and South Atlantic[18]. Without emissions cuts, oxygen levels are expected to continue declining, with a three to four per cent loss of oxygen in 2100 compared to 2005.

Polar oceans

The fragile polar oceans are changing fast. The Arctic Ocean is freshening, stratifying and warming, with continued warming predicted under all emissions scenarios. Melting snow and ice are changing ocean circulation and nutrient patterns, disrupting ecosystems[19] and shifting habitats[20].

The Southern Ocean, which has a particularly important role in regulating the Earth's climate and ocean ecosystems, has accounted for up to 70% of the total heat increase in the global upper ocean in the last 15 years. An additional 1-3 degrees of warming of the surface ocean is expected by the end of the century under a business-as-usual emissions scenario. The Southern Ocean is also the most important region for the uptake of carbon dioxide, but the future of the southern ocean sink is uncertain. It will likely continue to digest carbon dioxide and may even increase its capacity to do so over this century. If emissions continue, the increase in carbon dioxide uptake could stop, suggesting the ocean can reach a point where its capacity to act as a sink of emissions becomes depleted.

Ocean polynyas are areas of open ocean surrounded by ice, and could be threatened by decreasing sea ice. Polynyas are biological hot-spots, supporting Arctic and Antarctic food webs by providing access to food for marine animals such as seals, whales, penguins and fish. These sites have provided hunting grounds for Arctic people for thousands of years. The loss of traditional hunting could decrease food security, force diet transitions and harm traditional ways of life for Arctic people.

Extreme weather events

Marine heatwaves see abnormal ocean temperatures which can stretch thousands of kilometers, and into the deep ocean. They have become twice as frequent since the 1980s,

[17] These declines will expand Oxygen Minimum Zones (OMZs), which develop in the ocean as a result of changes to circulation
[18] Estimating the oxygen reduction in the Tropics is more challenging due to the limited evidence.
[19] https://www.nature.com/articles/ncomms14499?origin=ppub; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JC011687; https://ueaeprints.uea.ac.uk/59780/
[20] https://www.sciencedirect.com/science/article/pii/S0967064510001888; https://www.sciencedirect.com/science/article/pii/S0960982213006763; https://onlinelibrary.wiley.com/doi/full/10.1002/ece3.1869; https://www.ccamlr.org/es/system/files/science_journal_papers/Trathan%20et%20al_0.pdf

and are now occurring in all oceans[21]. They have devastating, cascading impacts on marine ecosystems and people.

In the Tasman Sea a 2015/16 heatwave lasted for 251 days, causing disease outbreaks and death in shellfish that are farmed for food, and the invasion of new species. In the Gulf of Alaska, record temperatures in 2016 delayed or prevented marine harvests and favoured certain types of harmful algae, leading to shellfish poisoning and the closure of oyster farms. A 2017 heatwave off the coast of Peru was associated with a strong increase in rainfall, triggering landslides and floods which killed several hundred people and caused severe infrastructure damage[22].

Today, around 90% of marine heatwaves can be directly linked to climate change. Heatwaves will increase in duration, extent, intensity and frequency[23] under all future climate scenarios, causing irreversible damage to marine ecosystems. Heatwaves affecting Australia's Great Barrier Reef are expected to become at least twice as frequent under two degrees of warming.

The number of storm events triggering coastal flooding are expected to increase. Storms that are currently rare will occur frequently by 2050, increasing flood risk to coastal communities. Rising sea levels and temperatures may also make tropical cyclones more intense, dumping more rainfall and causing higher storm surge levels[24], which are already responsible for most of the damage and loss of life associated with cyclones.

Extreme El Niño[25] and La Niña events will likely occur more often even if emissions are limited, but the effects will be worse with more warming. A doubling in the frequency of extreme El Niños is expected if emissions are not cut. Extreme versions of these natural climate cycles could cause widespread disruption. For example, the extreme 2015/2016 El Niño is thought to have affected tropical cyclones, marine ecosystems[26] and caused coral bleaching, forest fires, property damage, as well as human and animal disease, including outbreak of the devastating Zika virus.

3. Sea level rise and coastal damage

Climate change is the main cause of sea level rise, which is one of its most damaging and visible impacts. Melting ice sheets and glaciers add water to the sea, while warming of ocean water causes it to expand. Together, these processes are raising sea levels and worsening extreme sea level events.

Sea levels will continue to rise for many centuries, whatever we now do. If emissions are not cut sea levels could rise by 74cm (a range of 52 to 98cm) by the end of the 21st century.

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[21] https://www.frontiersin.org/articles/10.3389/fmars.2017.00136/full; https://link.springer.com/article/10.1007/s10584-016-1650-0

[22] United Nations, 2017: *North coast of Perú Flash Appeal*. Office for the Coordination of Humanitarian Affairs, Geneva, Switzerland., 49pp

[23] https://www.nature.com/articles/ncomms16101; https://link.springer.com/article/10.1007/s13753-017-0151-8; https://www.elementascience.org/articles/10.1525/elementa.191/; https://link.springer.com/article/10.1007/s00382-019-04661-z; https://www.nature.com/articles/s41467-018-03163-6

[24] https://journals.ametsoc.org/doi/full/10.1175/JCLI-D-17-0068.1; https://journals.ametsoc.org/doi/full/10.1175/JCLI-D-15-0129.1; https://www.pnas.org/content/114/45/11861.short; https://www.nature.com/articles/nclimate1389

[25] Extreme El Niño events can be defined as events which are characterized by a pronounced eastward extension of the west Pacific warm pool and development of atmospheric convection, and hence a rainfall increase of greater than 5 mm per day during December-February

[26] https://www.sciencedirect.com/science/article/pii/S0924796316300653; https://www.us-ocb.org/enso-impacts-on-ecosystem-indicators-in-the-california-current-system/;

Big emission cuts could limit sea level rise to 44cm (28 to 61cm) by 2100, according to previous IPCC assessments, although some newer research suggests these may be underestimates.

Future sea level rise is very dependent on what happens to the Antarctic ice sheet. Antarctic melt will likely cause tens of centimeters of sea level rise by the end of the century. Beyond 2100 estimates are deeply uncertain, but it is certain that sea level rise will be worse if warming continues. The few studies looking beyond the end of the century suggest multi-meter sea level rise if emissions are sustained.

People who live in low-lying islands and coasts make up more than ten percent of the global population and are particularly vulnerable to sea level rise and impacts. Their livelihoods are already impacted and even if warming is limited to 1.5 degrees they face further risks. Some island nations may become uninhabitable due to climate change,[27] and coastal megacities are also at risk. The future of such populations depends on limiting sea level rise and successful adaptation.

Coastal regions face hazards including permanent land loss, more frequent and intense flooding, enhanced coastal erosion, degradation of coastal ecosystems, salinization of soil and water, and a loss of natural drainage. The loss of ecosystems like corals, seagrass and mangroves which play a role in reducing wave height will magnify these challenges. Agriculture is already being damaged by salinization, for example in the Mekong and Ebro deltas and on Micronesian islands. The impacts of sea level rise will also spread far beyond the coast - annual losses from marine flooding alone are expected to account for 0.3 to 9.3 per cent of global GDP by the end of the century, depending on the amount of sea level rise.

4. Mountain regions and the cryosphere

The high-mountain regions of the world are particularly vulnerable to climate change, warming up to twice as fast[28] as the global average[29], causing permafrost, snow and ice to decline. Mountains are expected to lose substantial snow cover, even if emissions are cut[30]. These changes will have far-reaching global impacts for agriculture, energy supply and tourism[31]. They will impact livelihoods, cause migration[32] and erode landscapes which often have deep spiritual and intrinsic value[33].

[27] https://onlinelibrary.wiley.com/doi/full/10.1111/1477-8947.12082; Gerrard, Michael B., and Gregory E. Wannier, eds. Threatened island nations: legal implications of rising seas and a changing climate. Cambridge University Press, 2013.
[28] https://www.geo.umass.edu/climate/papers2/MRI_NatureCC_2015.pdf; https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.5509
[29] This amplified warming effect has been termed Elevation Dependent Warming (EDW).
[30] Here the loss is defined below the snow line. Well above the snowline there will likely be no loss. Decline will start at the margins - snowlines are expected to retreat to higher elevations as the climate warms.https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000514
[31] https://journals.openedition.org/geomorphologie/7901; https://pubag.nal.usda.gov/catalog/1291042; https://www.tandfonline.com/doi/abs/10.1080/14616688.2015.1084529
[32] https://www.tandfonline.com/doi/abs/10.1080/24694452.2016.1243039; http://lib.icimod.org/record/34509/files/fenvs-07-00091.pdfhttps://www.tandfonline.com/doi/abs/10.1080/09669582.2013.855222 ;
[33] https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007EO250001; https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017WR020840%4010.1002/%28ISSN%291944-9208.COMHES1

Around [30 per cent] of earth's glaciers are in mountainous regions[34]. Mountain glaciers are receding fast due to atmospheric warming[35], and would continue to lose mass even with no further warming, adding to global sea level rise. Without emissions cuts, central Europan glaciers may completely disappear by the end of the century.

Water security and river runoff

Mountains act as the water towers of the world, storing fresh water as ice and snow, releasing it as they thaw, and providing water for people in and beyond mountainous regions. Climate change will reduce water supplies overall and lead to changes in predictability, impacting water security, and disrupting hydropower[36]and agriculture.

Climate change driven melting will actually cause an initial surge in water runoff, temporarily increasing water supply. Increased annual runoff has already been observed in Asia, the European Alps and Alaska. But this peak water effect will be short-lived, and as glacial water storages deplete supplies will shrink, potentially until complete loss. Falling agricultural water supply has already been observed in the Central Andes, Central and Western Himalaya and in the Cascades. Peak water has already been reached, or will be reached within the next decade or two, in many parts of the world [37].

Glacial water supplies are expected to continue to decline through the 21st century in Asia, Central Europe, South America and North America. An increase and then decrease in glacial water supply is expected in the European Alps and western Himalaya. In the Andes, Quito, Lima and La Paz are especially vulnerable - 15% of La Paz's water comes from glaciers on average. Population growth and poor infrastructure will also contribute to water scarcity.

Water quality will also suffer. Amounts of toxic mercury are expected to increase[38] in glacially supplied water; mercury can also be released by permafrost thaw. Northern hemisphere permafrost may store about 793 Gg of mercury, twice what is present in all other soils, the atmosphere, and the ocean combined. Other toxic legacy contaminants risk release. Glacial runoff will also shift the supply of downstream nutrients, impacting ecosystems.

Natural hazards

Thawing permafrost[39], glacier retreat[40] and changing snow cover[41] all increase the risk of natural hazards. Melting snow and ice on mountain slopes will destabilize slopes and trigger landslides, floods and avalanches[42], with loss of human life and damage to infrastructure. Outbursts from lakes dammed by degrading glacial ice have directly caused at least 12,000 deaths over the last two centuries. Rain-on-snow events, where flooding is

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34 This definition excludes the glaciers of Antarctica and Greenland, which are dealt with in the polar section.
35 They declined at an annual rate of around 610 kg per square meter between 2006-2015, compared to 470 between 1986-2005.
36 https://link.springer.com/article/10.1007/s11269-013-0458-1; https://www.sciencedirect.com/science/article/pii/S1462901114001014
37 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013JF002931; https://www.nature.com/articles/s41558-017-0049-x
38 In Alaska mercury increases have already been observed, but depends on the way mercury is partitioned between chemical phases.
39 https://link.springer.com/chapter/10.1007/978-3-319-09300-0_81; https://pubs.geoscienceworld.org/gsa/geology/article/45/4/371/195473/climate-driven-thaw-of-permafrost-preserved
40 https://www.sciencedirect.com/science/article/pii/B9780123948496000160; https://link.springer.com/article/10.1007/s10346-010-0222-z
41 https://www.sciencedirect.com/science/article/pii/S0165232X13001535; https://www.igsoc.org/journal/59/216/t12J205.pdf
42 Climate change will cause major shifts in avalanche activity and character, but how this will manifeste is still unclear.

caused by combined rapid snow melt and heavy rain, have been increasing over recent decades in high latitude areas, but decreasing at low latitudes[43]. Such events cause significant damage and destruction.

The biggest overall risk for mountainous areas come from combined, cascading hazards. For example, slope instability along fjords could cause tsunamis[44], as recently experienced in Alaska. Changes to the mountain snow and ice could also alter volcanic activities. Estimated economic impacts of natural mountain hazards were US$45bn for the Hindu-Kush Himalaya region, US$7bn in the Alps, and $US3bn in the Andes, over the period 1985-2014.

5. Changes to ecosystems

Ocean ecosystems

Marine organisms are now being impacted by climate change in every ocean and at every ocean depth, as heat forces species to relocate polewards and into the cool, deep ocean[45]. Many marine species are already being faced with temperatures that push them beyond their optimum living conditions. Acidification of the ocean is thought to damage vital biological processes[46], and hundreds of coastal sites already have oxygen concentrations low enough to harm animal populations.

Climate driven changes in the ocean are expected to disrupt the supply and distribution of nutrients which primary producers[47] like phytoplankton rely on. Changes to the organisms that make up the base of the food web will spread upwards to impact marine mammals, birds and reptiles. The effects will be complex, and it is likely that there will be winners and losers. For example, some penguin populations have plummeted, whilst others are thriving.[48]and although in the tropics overall primary production is projected to decrease, there may be an increase at the poles.

Ocean ecosystems will continue to change as the planet warms. What effect this has on marine life will depend on how quickly individual species, communities and food webs can adapt. Species that have limited habitat availability or small populations face an increasingly precarious future. Business-as-usual emissions could lead to a 17 per cent[49] decline in marine life by the end of the 21st century.

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[43] https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.7094; https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015GL065320; https://www.hydrol-earth-syst-sci.net/18/2695/2014/ ; https://www.int-res.com/abstracts/cr/v71/n2/p111-125; https://www.sciencedirect.com/science/article/pii/S0022169412009857
[44] https://link.springer.com/chapter/10.1007/978-3-319-04996-0_104; https://link.springer.com/chapter/10.1007/978-3-319-08660-6_13
[45] https://www.frontiersin.org/articles/10.3389/fmars.2016.00062; https://academic.oup.com/icesjms/article/72/3/741/2835882; https://science.sciencemag.org/content/341/6151/1239.short; https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-2486.2010.02246.x
[46] https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/ecm.1297 ; https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0088308
[47] All marine life depends on primary producers - defined as organisms which capture the energy in sunlight by photosynthesis. The vast majority of primary production in the sea is by microscopic single-celled plants called phytoplankton.
[48] Adelie and Chinstrap penguins have decreased while Gentoo Penguin colonies have increased.
[49] Critically this number does not include biomass decrease from fishing. The number has high uncertainty 17+/- 11.1%. This means possible decrease by up to 28.1% or as low as 5.9%. The number reflects uncertainty in the model inputs.

Deep sea ecosystems

The deep sea supports marine ecosystems that are critical in regulating the climate, and while the effects of climate change will be slower to reach the deep ocean and less well understood, they will nonetheless be harmful. The deep ocean is warming and will continue to do so. Within the next fifty years most deep sea ecosystems will experience rising temperatures, declining oxygen, increased acidification and decreased food supply[50].

Food supply to the seafloor from warmer shallower waters could decline by about 40 per cent[51] by the end of this century as a result of warming, stratification and ocean acidification. Changes will however be regionally dependent, and polar oceans could experience an increase in food supply and seafloor biomass. 82 per cent of the underwater mountains, or seamounts, which provide oases of abundance and support a high diversity of marine life are projected to experience marine biodiversity loss under a business-as-usual emissions scenario.

Coastal ecosystems

Coastal seas only make up a small part of the earth's oceans but provide 30% of global marine primary production, 90% of the world's fish catch and account for about 40% of the value of the world's ecosystem services. Virtually all coastal ecosystems are under stress. Untangling the effects of climate change is harder than for the open ocean because of the often overlapping presence of human activity, but it is clear that climate change is impacting the abundance and distribution of fish stocks and causing the degradation and loss of coastal ecosystems, such as kelp forests, mangrove forests, seagrass meadows and saltmarshes.

Fishing supports the livelihoods of between 660 and 820 million people, providing more than 2.9 billion people with at least 20 per cent of their animal protein. Globally, the maximum catch potential is predicted to decline about 16 to 25 per cent by the end of the century[52], if emissions continue. Shifts in fish abundance, species distribution and catch are expected to impact the revenues of 89 per cent of the worlds fishing countries by 2050. In some places, fish are expanding their range due to warming, and such redistribution of fish stock is projected to increase. Tropical regions will experience the biggest impact, with communities already vulnerable to climate change at especial risk. For example, fishing provides up to 30 per cent of GDP for many Pacific Islands including the Marshall Islands, the Solomon Islands and Micronesia.

Coral reefs are under extreme pressure from climate change; warming and acidification harms coral growth, triggers large-scale coral bleaching events and fuels tropical storms that damage coral. Coral reefs are projected to decline by up to 90 per cent even if warming is limited to 1.5 degrees, with near complete loss of corals at two degrees of warming[53]. 500 million people currently derive food, protection and income from coral reefs[54].

More flooding is increasing the risk of phytoplankton blooms in coastal ecosystems. Alongside nutrient pollution from sewage and agriculture, these contribute to the spread of

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[50] https://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-14-00381.1; https://authors.library.caltech.edu/84616/
[51] Under a business-as-usual scenario http://nora.nerc.ac.uk/id/eprint/503466/
[52] Relative to a 2000 baseline, see page 68 of the FAO report.
[53] https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf Page 8
[54] https://www.annualreviews.org/doi/abs/10.1146/annurev-marine-010816-060551; https://www.sciencedirect.com/science/article/pii/S0169555X16309977

oxygen depleted dead-zones, which alter food web structures and release nitrous oxide, a potent greenhouse gas. Sea level rise, the subsequent erosion of sandy beaches and warming will squeeze coastal habitats and harm coastal species, for example harming turtle reproduction.

Salt marshes and mangroves are extremely productive coastal ecosystems which along with seagrasses are estimated to provide between one and ten per cent of marine primary production and provide valuable coastal protection. Nearly half the pre-industrial extent of salt marshes has been lost through human activity, and between 20 and 35 per cent of mangrove area has been lost since 1980[55]. These ecosystems are threatened by overexploitation, sea level rise, increasing temperatures and falling oxygen levels. Their degradation and loss will also lead to huge stocks of so-called 'blue carbon' being released into the atmosphere; currently between 0.15 and 1.02 billion tons of carbon dioxide are being released annually, equivalent to 3 to 19 per cent of the emissions from global deforestation.

Polar and mountain biodiversity

The polar regions provide a home to a rich diversity of fish and animals. Species adapted to life on or under sea-ice are directly threatened by habitat loss, and the poleward migration of sub-Arctic species is creating additional pressures. On Arctic land, northward expansion has been recorded in numerous species including a variety of mammals in Russia, and moose and beaver in Alaska. This polar 'squeeze' is displacing native species. Species as diverse as polar bears and the commercially fished Arctic Char are showing population declines and a contraction in their range. Overall, these shifts and pressures are expected to lead to a loss of global biodiversity[56].

In mountain regions decreasing snow and ice cover are changing biodiversity across land[57], rivers and lakes. More water has actually led plant species to increase, but this trend may reverse as warming continues. Changes in vegetation may be rapid, especially in areas where changes in snow and ice lead to fire, landslides, floods or increasing invasive species. Shrinking glaciers will eventually decrease river flow and increase water temperatures. An 11 to 38 per cent decrease in species could occur if glacier water supply is lost, with warm water species becoming more dominant.

6. Conflict, governance and adaptation

Economic activity linked with the ocean is estimated to involve at least US$24 trillion in assets, making it an important part of the global economy. Coastal communities are responding to sea level rise with a variety of measures. These include building safeguarding structures, or ecosystem-based adaptation. Retreat is the final choice of people moving away from harm. This is increasingly being considered as an option[58], although it uproots people from their homes.

Adaptation will increasingly require difficult choices, with numerous trade-offs, and depends on economic resources. Because of this, sea level rise could lead to a diverging world where richer and more densely populated areas hide behind protection, leaving

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55 http://www.fao.org/3/a1427e/a1427e00.pdf; https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0010095
56 As reported in CAFF the conservation of Arctic Flora and Fauna. 2013 and AMAP, 2018.
57 https://www.ncbi.nlm.nih.gov/pubmed/30258229; https://www.nature.com/articles/s41586-018-0005-6;
58 https://www.islandstudies.ca/sites/default/files/ISJPerumalClimateMigrationVanuatu.pdf; https://link.springer.com/chapter/10.1007/978-3-319-33880-4_15; https://onlinelibrary.wiley.com/doi/abs/10.1111/sjtg.12202

poorer and less populated communities to struggle with impacts, and eventually retreat from the coasts.

In polar regions, all economic sectors will be impacted by climate change, from growing costs for infrastructure maintenance and new Arctic shipping routes, to the potential for so-called last chance tourism. Reducing infrastructure damage will require engineering, land-use planning, and in some cases relocation. Increased use of the Arctic will create new risks, including the risk of accidents, oil spills, waste and the introduction of invasive species. Regulation will therefore be crucial. Fishing rights are especially contentious, and transboundary shifts in the distribution and abundance of fish stocks could lead to international conflicts and disputes.

Changes in water supply and food security could cause other transboundary challenges, although some cooperative efforts to address such issues have already started[59]. Large-scale early warning monitoring and forecasting systems are needed to guard against natural hazards and extreme weather. Climate change will also impact our ability to achieve the Sustainable Development Goals (SDGs).

Many of the impacts of climate change on the oceans, mountains and cryosphere can be lessened by cutting greenhouse gas emissions. We can also blunt the effects of change by restoring and protecting critical ecosystems, and investing in adaptation measures. The vulnerability of people can be reduced by managing compounding human pressures, such as habitat degradation, pollution, poverty and overfishing.

Currently, an emphasis on short-term adaptation is not building resilience to the potential broad range of future impacts. There is a need for increased levels of international cooperation, benefiting from a wide diversity of cultural, geographic and disciplinary perspectives, and integrating indigenous and local knowledge[60]. Adaptation will need to be underpinned by fundamental changes in policies, policy-making processes, institutions, human behavior and cultural values[61].

[59] Such as the Central Asia Knowledge Network.
[60] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4818986/; https://www.mdpi.com/2071-1050/9/7/1232; https://www.sciencedirect.com/science/article/pii/S1462901117306366; https://www.sciencedirect.com/science/article/pii/S0967064518300316
[61] https://academicworks.cuny.edu/hc_pubs/460/; https://kclpure.kcl.ac.uk/portal/files/48161784/open_source_verion.pdf