Office for Climate Education

THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE

SUMMARY FOR TEACHERS

BASED ON THE IPCC SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE (SROCC)

Coordinator
Lydie Lescarmontier (Office for Climate Education – OCE, France).

Authors
Eric Guilyardi (Institut Pierre Simon Laplace, France), Lydie Lescarmontier (OCE), Robin Matthews (IPCC Working Group I Technical Support Unit, France), Nathalie Morata (OCE, France), Mariana Rocha (OCE, France), Jenny Schlüpmann (Freie Universität Berlin, Germany), Mathilde Tricoire (OCE, France), David Wilgenbus (OCE, France).

Copy editors
Simon Klein (OCE, France), Maria A. Martin (Potsdam Institute for Climate Impact Research, Germany), Anwar Bhai Rumjaun (Mauritius Institute of Education, Mauritius), Gabrielle Zimmermann (*La main à la pâte*, France).

Date of publication
March 2020.

Acknowledgements
Experts who support the OCE: Juan Carlos Andrade, Laurent Bopp, Badin Borde, Eric Brun, Caroline Côté, Sanny Djohan, Randy Fananta, Serge Janicot, Jean Jouzel, Pierre Léna, Claudia Martinez, Valérie Masson-Delmotte, Cliona Murphy, Natalie Nicetto, Anna Pirani, Jean-Baptiste Sallée, Pramod Kumar Sharma, Aline Tribollet, Martin Vancoppenolle.

The following organisations for their scientific, operational and financial support: Technical Support Unit of IPCC Working Group I, Institut Pierre Simon Laplace (IPSL), Institut de Recherche pour le Développement, Fondation *La main à la pâte*, Fondation Luciole, Météo-France, Association Météo et Climat, Fondation Prince Albert II de Monaco, Siemens Stiftung, Sorbonne Université, UNESCO, ADEME, CASDEN.

Photos
Jake Hawkes (cover), Quang Nguyen Vinh (page 7), Riccardo Maccarini (page 9), Chrissy from Chicago (page 11), Наталья Коллегова (page 14), Benjamin Jones (page 24), Stekirr (page 25), Bishnu Sarangi (page 28), Canislupus (page 29), Daniil Vnoutchkov (page 31), AkshayaPatra Foundation (page 34).

Art work
Mareva Sacoun (mareva.sacoun@gmail.com).

SUMMARY FOR TEACHERS

The ocean and cryosphere in a changing climate

Based on the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).

The ocean and cryosphere sustain us.
The ocean and cryosphere are under pressure.
Changes to the ocean and cryosphere affect all of our lives.
The time for action is now.

Summary

Introduction

THE INDUSTRIAL REVOLUTION

The Industrial Revolution resulted in the most profound changes in the history of humanity and its influence continues to be part of our lives today. Beginning in Great Britain in the 18th century, the Industrial Revolution was a period in which advances in science and technology led to rapid developments in industry, transportation and agriculture across Europe and the United States.

The world's population also grew rapidly, due to progress in hygiene and medicine. The Industrial Revolution led to several shifts: people moved from the country to cities, and from working in the fields to working in factories, while animal power was replaced by engines powered by fossil fuels. Together, these factors led to a rapid increase in fossil fuel consumption, and consequently, to substantial greenhouse gases emissions.

HOW ARE WE CHANGING THE EARTH'S CLIMATE?

Greenhouse gases (mainly water vapour, carbon dioxide, methane, nitrous oxide and ozone) released by human activities have a direct impact on the global temperature rise through a process called the "**greenhouse effect**".

To date, human-generated emissions of greenhouse gases since the beginning of the Industrial Revolution (i.e. since "pre-industrial" times) have led to global warming of approximately 1.0°C [1]. If this continues at current rates, we are likely to reach warming of 1.5°C between 2030 and 2052 – an additional increase of 0.5°C from today's level (see note 1).

The greenhouse effect starts with solar radiation (the sun's energy) travelling through space until it reaches the Earth's surface. Part of the energy is sent back to space, and the rest travels through the atmosphere until it reaches the Earth's surface and warms it. When warmed, the Earth's surface emits infrared radiation (IR – heat) into the atmosphere. Some of this heat is trapped on its escape to space by greenhouse gases in the atmosphere and sent back towards the Earth's surface. Greenhouse gases thus act like a "blanket", trapping heat. As a consequence, the temperature of the lower atmosphere is warmer than it otherwise would be.

In fact, without greenhouse gases, the average temperature at the Earth's surface would be around -18°C rather than the actual average of +15°C.

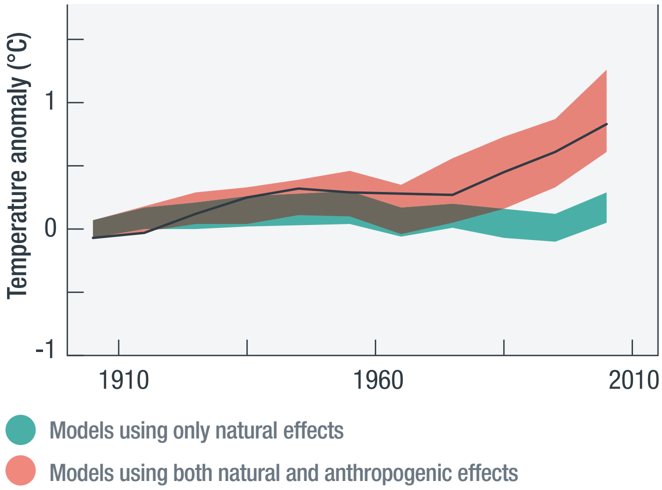


FIGURE 1 **Comparison of observed warming (black line) with two types of model simulations. In one simulation, only natural influences on Earth's climate are accounted for (green line). In the other, both natural and human effects are included (red line). The observed warming is only reproduced in the second case, once human effects (i.e. greenhouse gases emissions) are added in.**

Adapted from IPCC's Assessment Report 5. Fig. SPM.06.
https://archive.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG1&f=SPM

CLASS ACTIVITY # QUESTIONS

- Find a diagram on the internet, which shows that the global surface temperature on Earth has increased by approximately 1.0°C since the Industrial Revolution. Check that the diagram stems from a reliable source (such as IPCC, NASA, etc).
- Looking at Figure 1, explain how global warming is caused by humans.
- Name other greenhouse gases besides CO_2.
- Read up on and explain how the main greenhouse gases are produced.

1 IPCC Special Report "Global Warming of 1.5°C", http://www.ipcc.ch/sr15/chapter/spm/, paragraph A.1

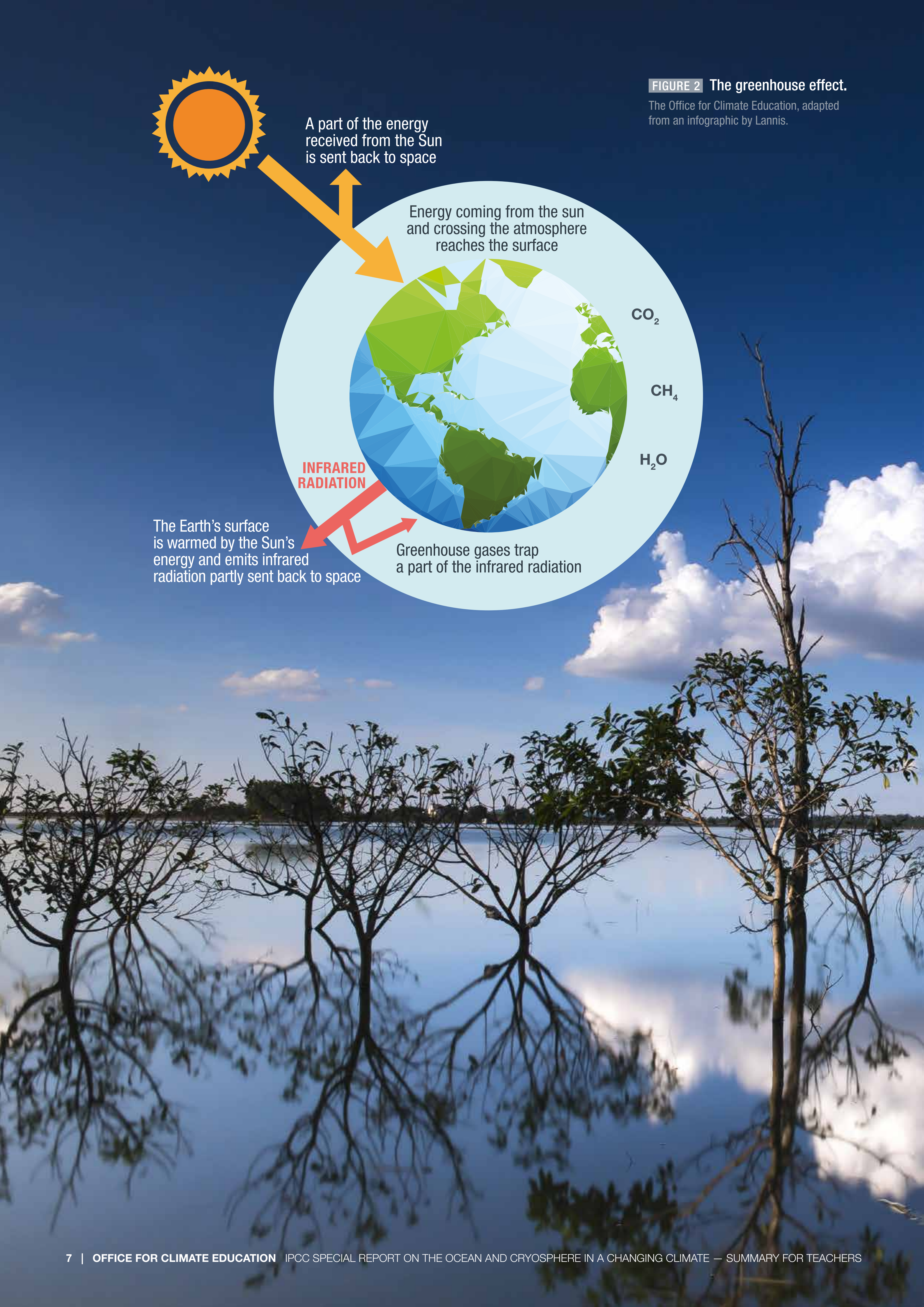


FIGURE 2 **The greenhouse effect.**
The Office for Climate Education, adapted from an infographic by Lannis.

1. What is the IPCC and why prepare a summary for teachers?

In 1988, The Intergovernmental Panel on Climate Change (IPCC) was created by the United Nations, in order **to provide assessments of climate change science.** It assesses the current state of knowledge on climate change, including possible impacts and options on how to adapt to these changes, and ways of reducing greenhouse gas emissions. These assessments present projections of future climate change based on different global emissions scenarios (continued growth, rapid reduction, etc.) and the corresponding risks for humans and the planet.

The reports are policy relevant which means they lay out response options and their implications, **but they are not policy prescriptive:** they do not tell policymakers which actions to take. IPCC assessments are written by hundreds of scientists from around the world and formally adopted by the governments of its 195 member countries. **The IPCC works by assessing existing published literature,** rather than conducting its own scientific research.

The IPCC periodically releases detailed reports, either on specific topics ("Special Reports") or more general. **Each IPCC report is accompanied by a Summary for Policymakers (SPM),** more compact, easier to read and understand.

In its current Sixth Assessment cycle, the IPCC has already published three Special Reports:

— *Global warming of 1.5°C* – October 2018
— *Climate Change and Land* – August 2019
— *The Ocean and Cryosphere in a Changing Climate* – September 2019.

While these reports are designed for policymakers, they are not adapted to the teacher's needs, even though the importance of education systems for preparing the youth to the ecological transition is recognized in the Art.12 of Paris Agreement (COP21, 2015). To fill that gap and starting in 2018, the Office for Climate Education prepares dedicated **Summaries for teachers** of the IPCC Reports. The present document presents a Summary of the Special Report *Ocean and Cryosphere in a Changing Climate*, alongside a selection of related activities and exercises that can be implemented in the classroom[2].

2 Another Summary for Teachers, for the IPCC Special Report on Global Warming of 1.5°C, is available on the OCE website (www.oce.global) in English, French, Spanish and German.

HOW THE IPCC WORKS

The Summary for Policymakers is approved, which means that every single line has been validated by all of the member states – including the United States and Saudi Arabia. Negotiations take place as to how the content is to be presented in the summary, but under no circumstances can it go against what is said in the long report. This approval gives the summary significant political weight.

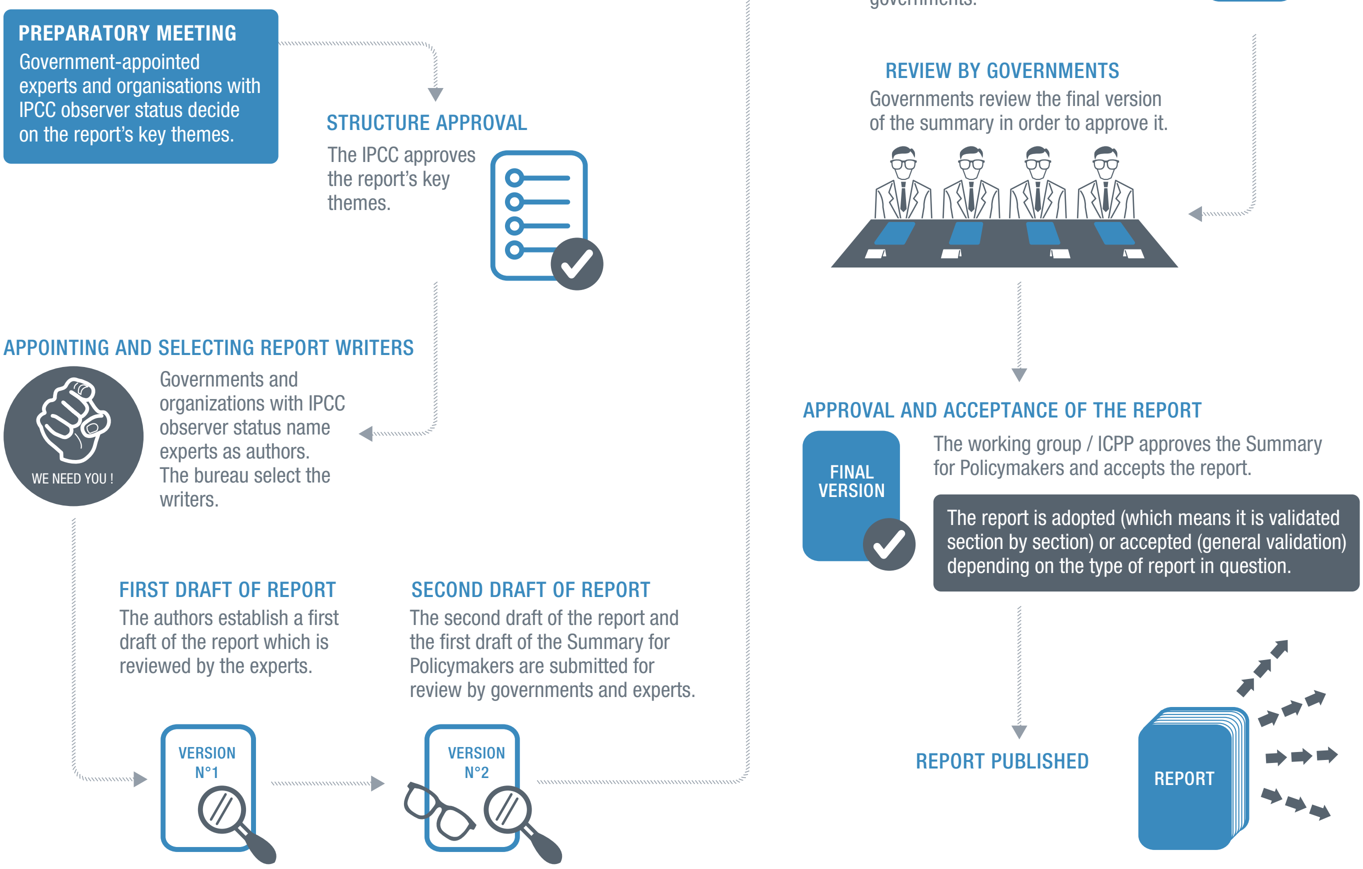


FIGURE 3 The functioning of the IPCC.

Adapted from an infographic by Citoyens pour le climat – https://citoyenspourleclimat.org/2019/03/24/informations/

2. The ocean and cryosphere

Geography of the ocean and cryosphere

The ocean covers around 70% of the Earth's surface, and contains **about 97% of the Earth's water.** Some even suggest that our planet should be called Ocean rather than Earth. Five major oceans are part of the global ocean: the Arctic, the Southern, the Atlantic, the Pacific and the Indian oceans. Even though the surface of the ocean may seem homogenous, its temperature, salinity, colour and ecosystems vary geographically.

The *cryosphere* (the global mass of frozen water, comprised of snow and ice) also covers a large part of the Earth, with **the great ice sheets of Antarctica and Greenland alone covering around 3% of the Earth's surface. In addition, there are nearly 200,000 glaciers worldwide**, including those at high altitude in the tropics (where it is cold, despite the tropical climate). A lesser known fact is that *permafrost* (permanently frozen ground) covers around a quarter of land in the northern hemisphere. Certain components of the cryosphere vary seasonally. For instance, each winter, snow covers around a third of land in the northern hemisphere (known as "seasonal snow"), while sea ice in the Arctic and Antarctic expands each winter and shrinks each summer.

People and wildlife live in harmony with the ocean and cryosphere. Many of the world's megacities are located on the coast, and in 2010 about **28% of the global population lived less than 100 kilometres from the coastline and 100 metres above sea level. Around 10% of the world's population lives in high mountain** regions, while around 4 million people live in the Arctic. Unlike the Arctic, the Antarctic, protected by an international treaty, is only visited by scientists, explorers and tourists, and has no permanent residents[3].

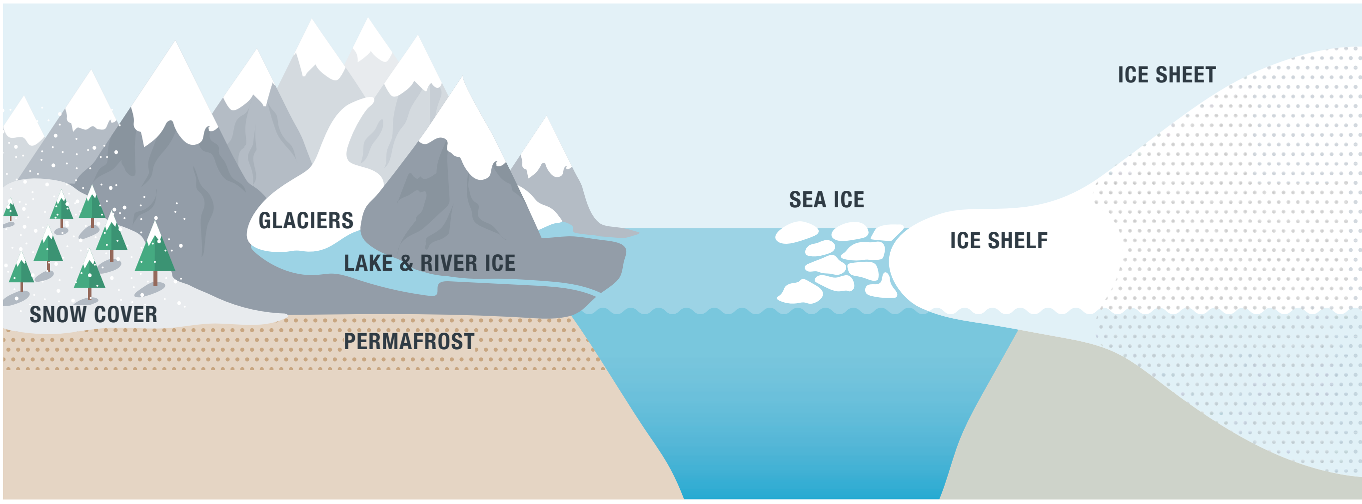


FIGURE 4 The components of the Earth's cryosphere.

Adapted from Fig 4.25 of the IPCC WG1 of the AR5 (2013) – https://www.ipcc.ch/site/assets/uploads/2018/02/Fig4-25_errata-1.jpg

3 https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf, Startup Box, p. 5

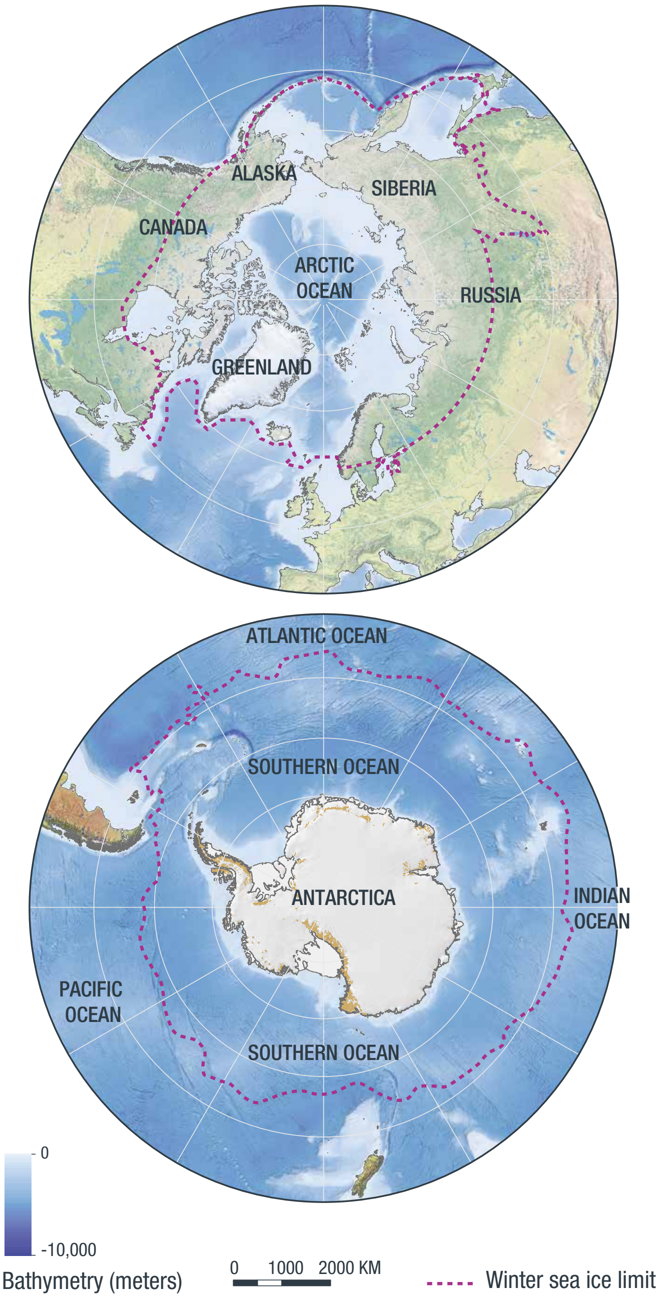
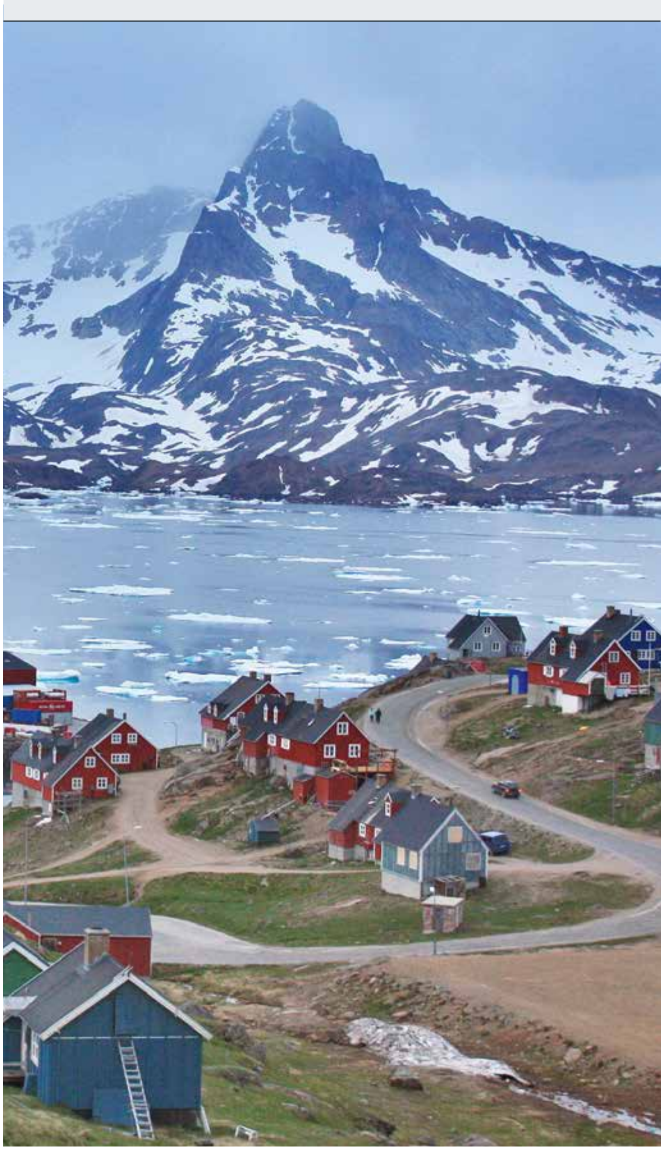


FIGURE 5 The Arctic (top) and Antarctic (bottom) polar regions. The dotted lines denote approximate boundaries for the polar regions. Note that the Arctic is comprised of an ocean surrounded by land while the Antarctic is the opposite: land surrounded by water. Antarctica is nearly entirely covered by ice (the Antarctic ice sheet,) while the Arctic's equivalent is the Greenland ice sheet.

Adapted from the SROCC, Chapter 3, IPCC 2019 – http://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/07_SROCC_Ch03_FINAL.pdf

CLASS ACTIVITY # ACTIVITY

— On a world map, locate these geographical entities: North Pole, South Pole, Atlantic Ocean, Pacific Ocean, Indian Ocean, Arctic sea ice, Antarctic sea ice, Greenland ice sheet, Antarctic ice sheet. Which entities are part of the ocean and which are part of the cryosphere?
— Read up on the areas covered by these geographical entities and compare them with the area of the Earth's land surface.
— What is the cryosphere? Read up on the etymology of the word cryosphere.
— What is permafrost? How does it form?
— Can you name the different types of continental ice?
— Read up on how sea ice is formed. Is sea ice as salty or less salty than sea water? What about the salt content (also called the salinity) of the Antarctic or Greenland ice sheets?
— Explain why our planet is sometimes called the "blue planet".



The importance of the ocean and cryosphere for people

The resources and services the ocean and cryosphere provide can be categorised into different ecosystem services: regulating, provisioning, cultural and supporting services.

REGULATING SERVICES

The ocean and cryosphere help regulate the global climate: they interact with other components of the climate system – like land and the atmosphere – through the global exchange of water, energy and carbon. An example of a regulating service is the coastal protection provided by coral reefs and mangrove forests.

PROVISIONING SERVICES

The ocean and cryosphere also provide services. In particular, they provide us with food (fish, algae and shellfish), water and energy. Fisheries are a key global food source, with fish and shellfish accounting for over 50% of the animal protein consumed in many least developed countries[4]. The ocean also provides renewable energy in the form of wave and tidal power, along with fossil energy sources like oil and gas, and minerals from the seafloor. Glaciers supply river basins with water used for drinking, irrigation and hydropower. Around 800 million people[5] are partly reliant on run-off from the Himalayan glaciers alone. Transport is another service provided. In winter, frozen rivers and lakes in the Arctic provide a significant transportation network, while the vast majority of goods are moved across the planet by oceangoing ships.

CULTURAL SERVICES

Cultural services are the third category of ecosystem services. In terms of the ocean and cryosphere, these include jobs in fishing and recreation, local traditions and cultures, and religious beliefs. In several regions, tourism depends on the ocean or cryosphere (such as ski resorts). In tropical regions, many island economies depend on snorkeling, scuba diving and beach activities.

SUPPORTING SERVICES

Finally, there are the supporting services that contribute to the provision of the three previous types of services. These include primary production, food sources such as ocean phytoplankton (microscopic single-cell algae called phytoplankton, at the base of most marine food webs, are consumed by mostly microscopic animals called zooplankton).

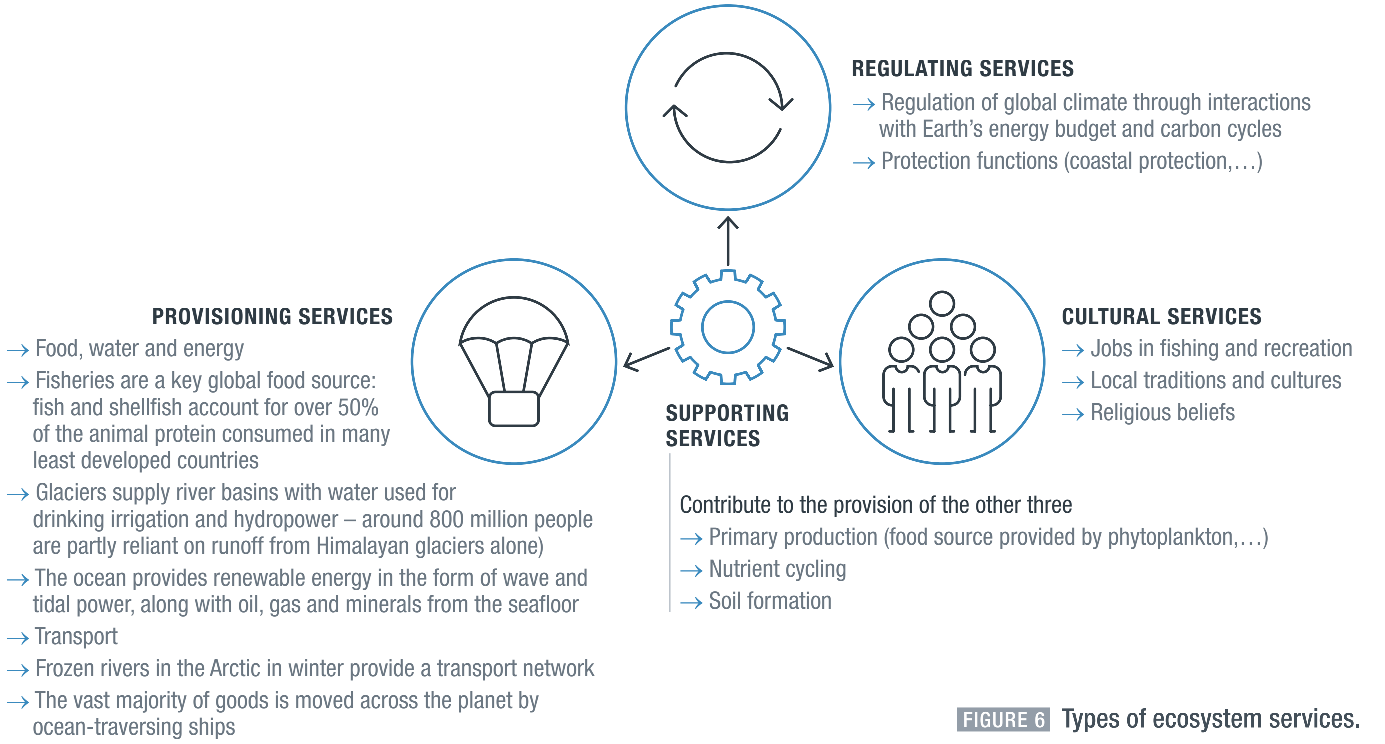


FIGURE 6 Types of ecosystem services.

4 http://www.fao.org/fishery/topic/16603/en
5 https://www.aaas.org/news/spy-satellites-reveal-himalayan-ice-loss-has-doubled-2000

Biodiversity and ecosystems

Like supporting services, biodiversity, or the diversity of organisms and their networks, also permeates ecosystem services, since it helps the ecosystem to function. **Biodiverse ecosystems are also more resilient to climate change[6].**

The ocean is highly biodiverse with hotspots found, for instance, in coral reef ecosystems. At the top of the phytoplankton and zooplankton food webs are sharks and marine mammals, such as seals and whales, some of which migrate long distances across the ocean. Species diversity maintains ecosystem functions, but each ecosystem has its own specific key organisms at play. While our knowledge of ocean biodiversity is rapidly growing with thousands of new species discovered every year[7], it is also limited, and marine biologists estimate that hundreds of thousands of species remain unknown.

6 Epple and Dunning (2014). Ecosystem resilience to climate change: What is it and how can it be addressed in the context of climate change adaptation? UNEP - WCMC.
7 World Register of Marine Species – http://www.marinespecies.org/index.php

CLASS ACTIVITY # ACTIVITIES

One of the threats to marine biodiversity is overfishing. An alternative to fishing could be fish farming, also called aquaculture. Today, just as many fish are produced in aquaculture as those caught wild in the oceans. In rich countries, people mainly eat tuna and salmon. But these two fish species are carnivorous and have a major drawback: they eat 10 times their weight as they grow (1 kg of salmon "eats" 10 kg of herring!).

- Calculate how much herring is required to farm 800,000 tonnes of salmon, equivalent to the record catch of cod in 1968?
- If an adult eats 100 g of salmon every day (on average) how many adults can be fed with 800,000 tonnes of salmon?
- How many adults could have been fed on the herring that was fed to the salmon?
- Comment on whether you think that aquaculture is a viable solution to protect marine biodiversity.

The International Union for Conservation of Nature (IUCN) monitors the number of threatened species worldwide. It regularly updates and publishes the Red List of Threatened Species.

- Look up the definition of the different Red List categories – from "Extinct" to "Least Concern".
- Go to the IUCN homepage and look at the "amazing species". Choose one that lives in or comes from the ocean. Look up additional information and make a short presentation of this species to your classmates. Emphasize how this species is important for other marine species.

FIGURE 7 Example of different marine and coastal ecosystems in the world.

3. Observed and projected impacts

Physical changes

The SROCC compiles the impacts of climate change on the ocean, on coastal, polar and mountain ecosystems, as well as on the human communities that depend on them. It deals with the vulnerability of ecosystems and humans and evaluates the adaptation capacities. Additionally, options for achieving climate-resilient development pathways are presented.

The future climate projections, as presented in the SROCC, include two different emission scenarios: **RCP2.6 and RCP8.5** – RCP stands for Representative Concentration Pathway. The RCP2.6 assumes that greenhouse gas emissions will decline in response to major steps taken by human societies to reduce emissions so that global warming is kept below 2.5°C by 2100 (for reference, we reached 1°C global warming in 2018). By contrast, the RCP8.5 assumes that greenhouse gas emissions will increase rapidly throughout the 21st century, resulting in global warming of around 4°C by 2100. Hereafter, we will refer to the RCP2.6 and RCP8.5 scenarios as "low emissions scenario" and "high emissions scenario" respectively.

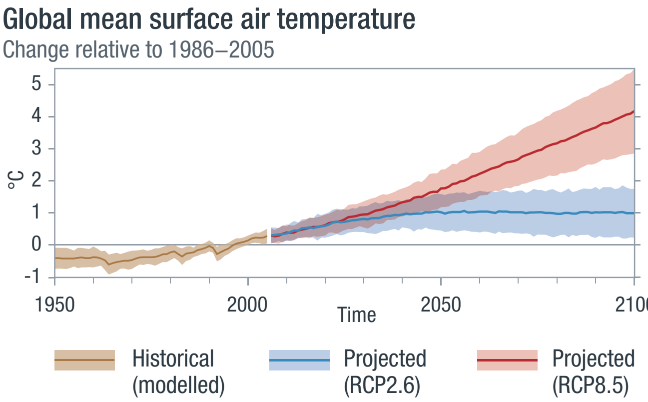


FIGURE 9 **Historical change of the global mean surface air temperature and projected change under the two emission scenarios RCP2.6 and RCP8.5.**

https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/IPCC-SROCC-TS_3.jpg

SHRINKAGE OF THE CRYOSPHERE

LAND CRYOSPHERE

Today, ice sheets and glaciers worldwide are losing mass due to the rise in global temperature. Mass loss is measured in gigatons (Gt), with 1 Gt of ice equivalent to 1 km^3 of meltwater (a cube of water measuring 1000 m on each side!).

In Antarctica, ice loss is dominated by glacier thinning and retreat caused by ice melt due to warm ocean water entering beneath the different ice shelves (especially in West Antarctica). In Greenland, where the atmospheric temperature is higher than in Antarctica, mass loss is dominated by surface ice melting, which sets in when the atmospheric temperature rises above 0°C.

From 2006 to 2015, the Greenland ice sheet lost mass at a rate of 278 Gt/yr and the Antarctic ice sheet lost mass at a rate of 155 Gt/yr. In comparison, glaciers world-wide lost mass at a rate of 220 Gt/yr. This ice, sitting on land, contributes to a sea level rise of 0.77 mm/yr for the Greenland ice sheet, 0.43 mm/yr for the Antarctic ice sheet and 0.61 mm/yr for glaciers.

A RCP2.6 scenario would mean that, between 2015 and 2100 (see Figure 10):
- glacier mass will be reduced by 18%, which will contribute to a sea level rise of 9.4 cm;
- melting of the Greenland ice sheet will contribute to sea level rise of 7 cm;
- melting of the Antarctica ice sheet will contribute to sea level rise of 4 cm.

A RCP8.5 scenario would mean that, between 2015 and 2100 (see Figure 10):
- glacier mass will be reduced by 36%, which contributes to a sea level rise of 20 cm;
- melting of the Greenland ice sheet will contribute to a sea level rise of 15 cm;
- melting of the Antarctica ice sheet will contribute to a sea level rise of 12 cm.

Mountain glaciers (in Central Europe, North Asia, Scandinavia, tropical Andes, Indonesia) are projected to lose 80% of their current ice mass by 2100 under RCP8.5, and many glaciers are projected to disappear regardless of whether a high or low emission scenario is followed. Loss of glaciers initially leads to an increase in the river runoff to which they contribute, followed by a decline in the river runoff. Overall, runoff from glaciers is expected to peak at or before 2100, although places with small glaciers have already peaked. Other consequences of warming are expected to impact high mountain regions, such as the loss of slope stability as glaciers retreat and permafrost grounds thaw, the occurrence of floods caused by breaches in glacier lakes, as well as landslides and avalanches.

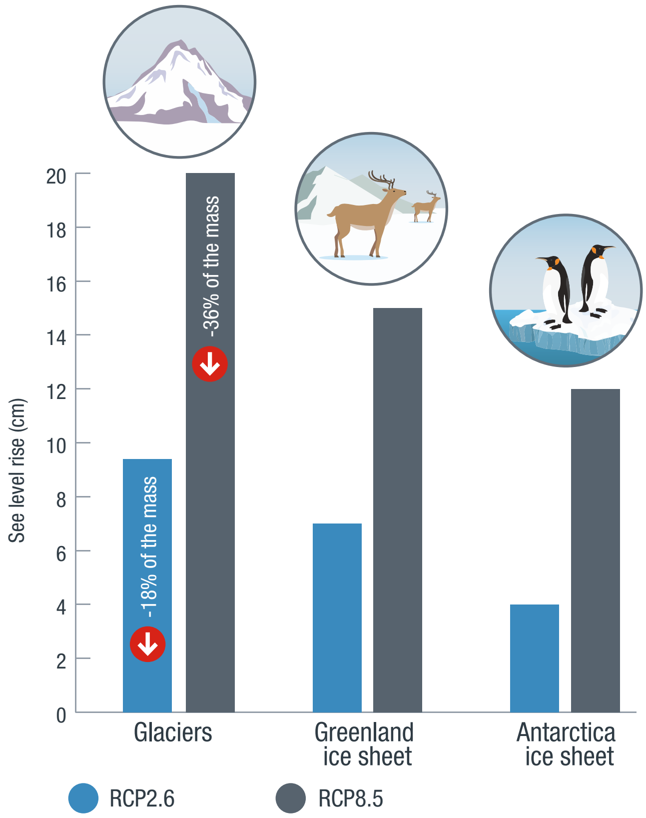


FIGURE 10 **Compared contributions of cryospheric reservoirs to sea level rise depending on the projected scenario.**

Snow cover is declining in thickness, extent and duration. In the Arctic, the area covered by snow in June has declined by about 13% per decade since 1967. The snow cover decline is dependent on the altitude: the higher the altitude, the lower the temperature, and the snow cover decline is less accentuated.
Under RCP2.6, Arctic autumn and spring snow cover would decrease by 5-10% from their 1990s level by 2040 before stabilising. Under RCP8.5, Arctic autumn and spring snow cover would decrease by 20-35% from their 1990s level by 2100. In high mountains, low altitude snow would decline by 10-40% (RCP2.6) and by 50-90% (RCP8.5) from its 1990s level by 2090.

The temperature of **permafrost** grounds (i.e. the subsurface of soil that remains frozen throughout the year) has increased to levels unprecedented in the observation records (1980s - present). Once permafrost ground warms to 0°C, it thaws. The main concern with permafrost thaw is the potential release of carbon dioxide and methane. Permafrost grounds can be found in the northern hemisphere (mainly in Siberia, Canada, Alaska and Greenland) but also in some alpine regions covering one fifth of the global land surface.

Currently, some 1460-1600 Gt of organic carbon are stored in permafrost grounds. This is about twice the amount of carbon currently present in the atmosphere as CO_2. Evidence is divergent as to whether permafrost warming is currently causing the release of additional greenhouse gases to the atmosphere or not. Permafrost thaw and glacier retreat have decreased the stability of high-mountain slopes (which is ensured by frozen ground and glacier ice). The area of near-surface permafrost (grounds that are frozen to a depth of 3-4 m) recedes in both scenarios: it is reduced by between 2% and 66% for RCP2.6 compared to 30-99% for RCP8.5. Tens to hundreds of billions of tonnes of permafrost carbon could be released due to permafrost thawing by 2100 (RCP8.5) with the potential to exacerbate climate change. Interestingly, the increased plant growth from the newly available non-frozen land – known as greening – should partially offset this release of carbon.

FIGURE 11 **Thawing permafrost grounds in Alaska.**

NASA/JPL-Caltech - https://www.jpl.nasa.gov/news/news.php?feature=4376

ARCTIC SEA ICE

The sea ice cover in the Arctic has been declining. The sea ice extent reaches its annual minimum each September at the end of the summer before expanding to its annual maximum in March. Over the past 40 years, the areal coverage at the September minimum has decreased by about 12.8% per decade, equivalent to about 40% in total surface. It is likely that these changes have not been seen for at least 1000 years. Warm winters in 2016, 2017 and 2018, during which surface temperatures in the central Arctic reached 6°C above normal, caused a record low in sea ice cover at a time of the year when it usually reaches its maximum extent. Coinciding with the steady loss in areal coverage, less sea ice remains from one melt season to the next, and therefore the average age of the ice is also on the decline. Unlike ice melting on land, loss of sea ice does not contribute to sea level rise since it is already in the water, afloat (like melting ice cubes in a glass of water).

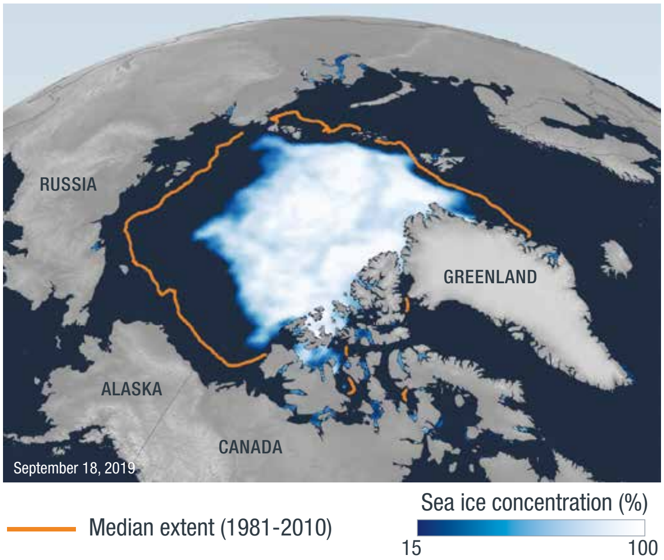


FIGURE 12 **Evolution of Arctic sea ice concentration.**

NOAA. Data NSIDC - https://www.climate.gov/sites/default/files/ClimateDashboard_ArcticSealce_minimum_2019_map_large.jpg

The loss of summer sea ice, together with the loss of spring snow cover on land, have amplified the warming in the Arctic through a number of effects, such as changes in moisture content and albedo. Air temperature in the Arctic has risen twice as fast as the global average over the last two decades, and changes in the Arctic sea ice have the potential to influence mid-latitude weather.

What about the future? In both scenarios, sea ice loss will continue until 2050. If warming is stabilised at 2°C, the Arctic would be free of sea ice in September up to every three years.

TO SUM UP

Melting glaciers and ice sheets, permafrost thaw, and a decline in snow cover and the Arctic sea ice are being observed and are projected to continue over the next two decades. The rate of mass loss from the Greenland and Antarctic ice sheets will continue to increase throughout the 21st century. Arctic sea ice extent and age are decreasing and contributing to amplified warming in the Arctic.

Even if greenhouse gas emissions are rapidly reduced, the cryosphere will continue to change until 2050, altering river runoff and increasing mountain hazards like avalanches and landslides.

CLASS ACTIVITY # ACTIVITY

There is ice floating in the sea (sea ice) and ice sitting on land (glaciers and ice sheets). With climate change, both types of ice are melting.

— Explain where the meltwater goes.

Answer: Meltwater from sea ice and ice sheets goes directly into the ocean; meltwater from glaciers may first flow to rivers, feed groundwater reservoirs and inland seas and lakes, and eventually reach the ocean as well.

— Explain why meltwater from sea ice and meltwater from ice on land do not contribute equally to sea level rise. Design an experiment to show the difference and carry out that experiment.

OCEAN HEAT AND CARBON UPTAKE

Since 1970, **the ocean has absorbed and stored about 93% of the excess heat** generated by global warming, playing a key role in regulating the climate system. Since 1993, the rate of ocean warming, and thus of heat uptake, has more than doubled. Ocean temperatures are rising fastest at the surface, where the heat uptake occurs, but deeper waters are also warming. Warming of the upper 2 km of the ocean has mainly occurred around Antarctica (in the Southern Ocean), which has absorbed 35-43% of the total heat gain in this layer over the past 50 years.

As a consequence of ocean warming, periods of extremely high ocean surface temperature, known as marine heatwaves, have doubled in frequency and have become longer lasting, more intense and more extensive over the last 40 years. Marine heatwaves are expected to occur more frequently (20 times more often under RCP2.6 and 50 times more often by the end of the 21st century under RCP8.5).

Surface ocean warming, together with freshwater input from land ice melt, are making the surface ocean less dense relative to deeper waters. This increase in the density difference between surface and subsurface waters inhibits mixing between the different ocean layers and has consequences on the ocean oxygen and nutrient content. The phenomenon by which ocean layers do not mix is called density stratification. By 2090, for both the RCP2.6 and RCP8.5 scenarios, oxygen and nutrients are projected to decline, with a smaller decline expected for RCP2.6.

The ocean is an important carbon sink: it has absorbed between 20 and 30% of the CO_2 released into the atmosphere by human activities since 1980.

When CO_2 dissolves in the ocean's surface water, carbonic acid is produced, which increases seawater acidity (i.e. it lowers seawater pH). This process is known as ocean acidification. Since the late 1980s, open ocean surface pH has declined by around 0.02 units per decade. It may not seem like much, but small changes can have very large impacts on the ecosystems, as we will see in the following section. The degree of ocean acidification is directly related to the amount of CO_2 released into the atmosphere. Under RCP8.5, continued uptake of CO_2 from the atmosphere by the ocean would result in ocean pH declining by a further 0.3 pH units by the end of the century.

Where is global warming going?

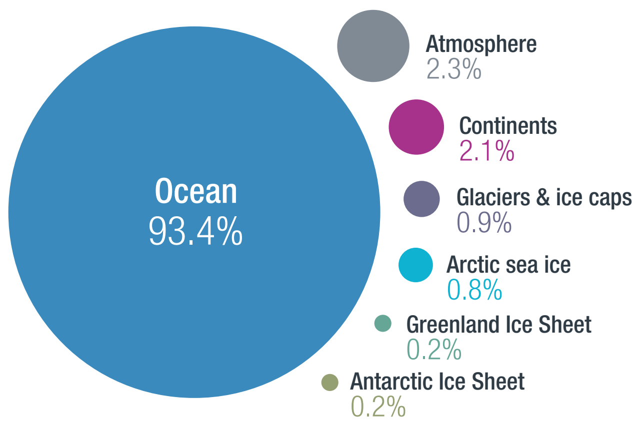


FIGURE 13 Global storage of heat excess from global warming.
https://skepticalscience.com/Infographic-on-where-global-warming-is-going.html

TO SUM UP

The ocean is warming at all depths and has absorbed over 90% of the excess heat generated by global warming. Ocean surface and the Southern Ocean have taken up most of the heat. Marine heatwaves are more frequent and more intense. The density stratification in the upper 200 metres of the ocean is increasing, causing a decrease in oxygen and nutrient content.

The ocean surface layers absorb more CO_2, leading to increased ocean acidification.

CLASS ACTIVITY # ACTIVITY

Understanding the effect of ocean acidification on corals

— Think of an experiment to demonstrate the effect of CO_2 absorption on seawater pH. In the experiment, you will have to add CO_2 to seawater. How can you do that? How can you then measure the impact on the pH?
Answer: You could, for example, blow into the water with a straw.

— Look up and explain what consequences ocean acidification has on corals and shellfish.

OCEAN CYCLES AND CIRCULATION: EL NIÑO AND THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

El Niño is an anomalous warming event that occurs in the central and eastern tropical Pacific. It has major global environmental and human impacts, including the reduction of fish catch along the coasts of Peru and Chile, and severe droughts in Indonesia, the Philippines and Australia. Throughout the 21st century, extreme El Niño events could occur more often, as a consequence of ocean warming.

Global ocean circulation is also expected to be affected by climate change. The Atlantic Meridional Overturning Circulation (AMOC – meridional meaning in the North-South direction) is the Atlantic branch of the global system of marine currents which transport heat, carbon, oxygen and nutrients throughout the world's oceans. This Atlantic branch, in particular, is projected to weaken over the 21st century, although a collapse is very unlikely. The rate and magnitude of the changes will be smaller in scenarios with low greenhouse gas emissions, but in all cases, the weakening of the AMOC would lead to decreased biological productivity in the North Atlantic, more winter storms in Northern Europe, less summer rainfall in the Sahel and South Asia, fewer hurricanes in the Atlantic and an increased sea level along the northeast coast of North America.

TO SUM UP

Ocean circulation and phenomena such as El Niño are expected to be affected by climate change. The Atlantic Meridional Overturning Circulation is projected to weaken over the 21st century, and extreme El Niño events could occur more often as a consequence of ocean warming.

SEA LEVEL RISE

Global mean **sea level has risen by 16 cm over the past century** and has been rising at ever increasing rates. The rate of rise for 2006-2015, of 3.6 mm/yr, was unprecedented in the last century, and 2.5 times larger than the rate for 1901-1990. While a few millimetres of rise per year may not sound like much, it adds up over time, and leads to more frequent extreme flooding events in coastal regions.

The main drivers of sea level rise are shown in Figure 14. Today, ice loss from ice sheets and glaciers is the main source of rise and has contributed 1.8 mm/yr to the rise over 2006-2015. Thermal expansion contributed to 1.4 mm/yr rise over the same period: as the ocean water warms, it expands and occupies a larger volume, additionally enhancing sea level rise.

As sea level rises, a storm surge can reach further inland. Compounding the resulting coastal flooding and erosion from tropical cyclones, the associated rainfall and winds can be enhanced by climate change.

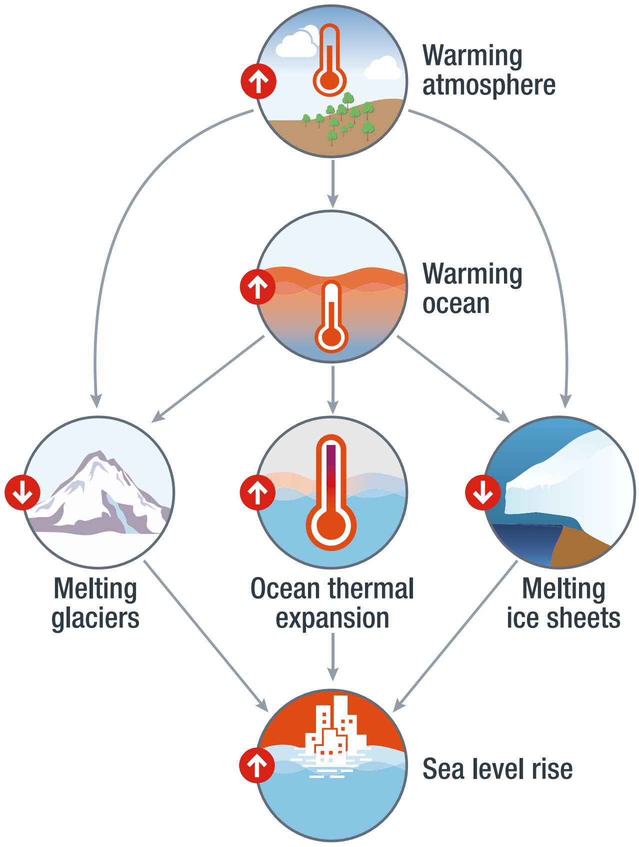


FIGURE 14 **How a warming atmosphere and a warming ocean cause sea level rise.**

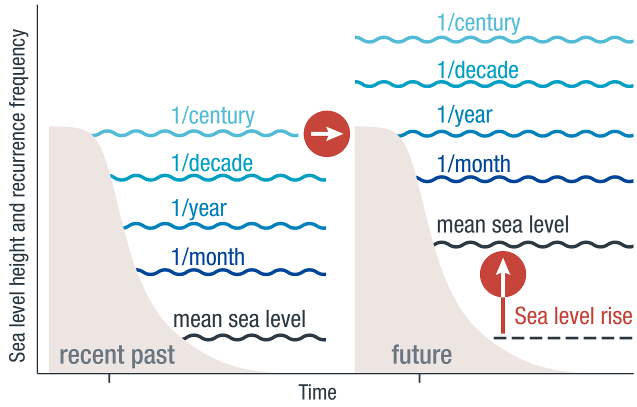


FIGURE 15 **Due to projected global mean sea level rise, local sea levels that historically occured once per century are projected to become at least annual events at most locations during the 21st century.**

http://www.ipcc.ch/srocc/chapter/summary-for-policymakers/spm-section-3/srocc_spm4_final_edit_sl/

Sea level rise is projected to continue, and at an increasing rate. Due to the slow response of the ocean associated to its thermal inertia, global sea level will continue to rise even after global temperature has stabilised.

Under RCP2.6, sea levels in 2100 could reach 29-59 cm above the 1990s level and at a rate of 2-6 mm/year. In contrast, under RCP8.5, sea level in 2100 could rise by 61-110 cm and will be rising at 1-2 cm/year. Compared to the previous IPCC sea level assessment (in the last main IPCC report AR5), this projection is 10 cm higher, due to the inclusion of a larger ice loss from the Antarctic ice sheet. Moreover, ice sheet instabilities could increase Antarctica's contribution to sea level rise to substantially higher values over the next century and thereafter. Under RCP2.6, models project a sea level rise of about 1 m, compared to up to 5 m by 2300 in RCP8.5.
As sea level rises, extreme sea level events will occur more often (see Figure 15). Events that historically occurred only once per century are projected to occur at least annually by 2100 under both scenarios.

TO SUM UP

Ice loss from glaciers and from the Greenland and Antarctic ice sheets as well as thermal expansion of seawater due to ocean warming are contributing to global sea level rise. The global mean sea level is currently rising at about 3.6 mm/year, and the rate of increase has accelerated over the last century with regional differences. Extreme sea level events that are historically rare will occur more frequently (at least once per year) in many locations by 2050.

Sea level rise is expected to continue beyond 2100 under both emissions scenarios (RCP 2.6 and RCP 8.5).

CLASS ACTIVITY # ACTIVITY

— Look at the two diagrams measuring sea level on NASA's "Sea Level Change" page: https://climate.nasa.gov/vital-signs/sea-level/. How was sea level measured until 2013? And after 2013? Explain why sea level measurements are particularly relevant to study climate change.
— Using the data provided, calculate the average sea level rise since 1880. Compare your result to the current 3.4 mm/year sea level rise and comment on your findings.
— Name two factors that contribute to sea level rise and explain why.

TROPICAL CYCLONES

The proportion of the strongest tropical cyclones, as well as their rainfall, is projected to increase as global temperatures increase. The associated storm surges will add to a raised sea level baseline, increasing the risk of greater coastal flooding events.

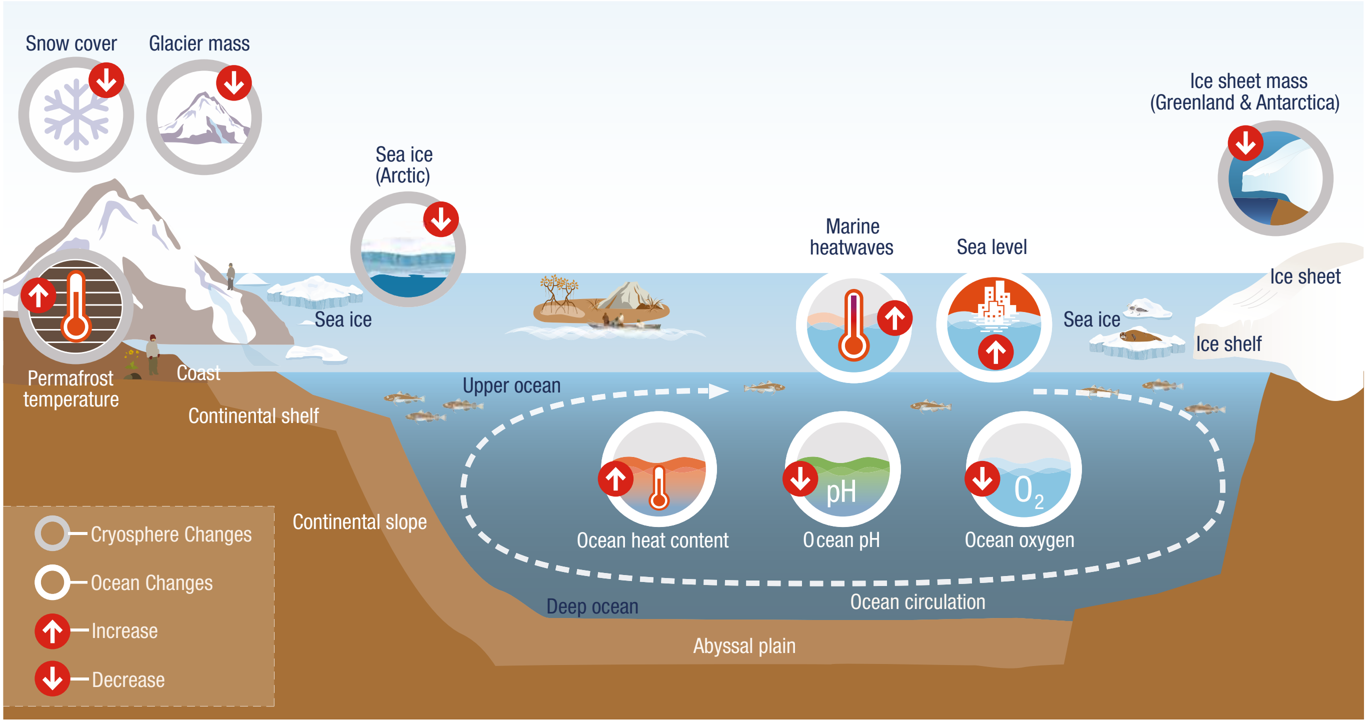


FIGURE 16 The components of the ocean and cryosphere (snow cover, permafrost, glaciers, sea ice, ice sheets and shelves) and how climate change affects them (shown in the circles). Climate change-related effects on the ocean include sea level rise, increasing ocean heat content and marine heat waves, ocean deoxygenation, and ocean acidification. Changes in the cryosphere include the decline of Arctic sea ice extent, Antarctic and Greenland ice sheet mass loss, glacier mass loss, permafrost thaw, and decreasing snow cover extent.

Adapted from the SROCC, Chapter 1, IPCC 2019 – https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/05_SROCC_Ch01_FINAL.pdf

Observed and projected impacts on ecosystems

SPECIES MIGRATION AND REDISTRIBUTION

With the atmosphere and the ocean getting warmer, **species on land and in the ocean are shifting their distribution and changing in abundance.**

Cold-adapted and snow-dependent species on land are facing habitat contraction, migrating upslope or poleward and declining in abundance, increasing their risk of extinction. On the other hand, some species are benefiting from loss of snow cover, glacier retreat and permafrost thaw, expanding into new areas and increasing their abundance. In high mountains, migration of lower elevation species upslope has increased local species richness. Meanwhile, an overall “vegetation greening” of the Arctic tundra (northernmost Arctic land) has been observed, due to an increase in plant cover. On the other hand, there is also some “vegetation browning”, i.e. a decline in vegetation, in the tundra and the boreal forest. Projections under both emissions scenarios forecast upslope migration to continue in high mountain areas, as well as a general range contraction.

In the Arctic, **unique biodiversity is projected to be lost** as species with very specific habitats are replaced by species shifting poleward. Woody shrubs and trees are projected to expand to cover 24-52% of the Arctic tundra by 2050. The boreal forest is projected to expand at its northern edge, while diminishing at its southern edge. In general, species will be forced to migrate to higher latitudes and altitudes.

Permafrost thaw and reduced snow cover will affect Arctic hydrology and contribute to an increase in wildfire, with impacts on vegetation and wildlife. About 20% of Arctic land permafrost is vulnerable to abrupt thaw resulting in ground subsidence.
Although the overall regional water cycle is projected to intensify, including precipitation, evapotranspiration

and river discharge to the Arctic ocean, decreases in snow cover and permafrost may lead to soil drying.

In the ocean, the distribution of phytoplankton, fish and marine mammals has been shifting poleward due to warming, at rates up to several tens of kilometres per decade. The shifts have been faster at the ocean surface than near the seafloor.

These changes in species' spatial distribution are accompanied by **changes in their seasonal activities**. As the warm season gets longer, in the ocean, polar and mountain regions, many species are extending their seasonal activities and changing their behaviour.

TO SUM UP

Loss of land cryosphere is altering and will continue to alter ecosystems in high mountain areas and the Arctic, resulting in migrations, shifts in species distributions and loss of biodiversity.

MARINE ECOSYSTEMS, CONSUMERS AND FISHERIES

Primary producers, such as phytoplankton, are organisms that produce organic matter from inorganic materials through photosynthesis. In turn, primary consumers, such as zooplankton, feed on primary producers. Increased stratification of the upper ocean since the 1970s has altered the supply of nutrients to surface waters, **affecting regional phytoplankton production.** However, there are poor records of these changes, so their spatial patterns are uncertain.

In the Arctic, net primary production has increased – since more water is ice-free. Furthermore, **spring phytoplankton and ice algae blooms are occurring earlier in the year.** Since zooplankton, as primary consumers, eat phytoplankton, they are directly affected by changes in phytoplankton abundance and seasonal distribution. Moreover, since plankton is at the base of many marine food webs, these changes cascade up the food web, affecting its overall structure and function, and eventually has consequences for biodiversity and fisheries.

Climate models project a decline in primary production by 4-11% by 2090 under RCP8.5, as a consequence of warming and stratification. Moreover, ocean acidification is expected to affect an important zooplankton species called pteropods. They are sometimes called "the potato chips of the ocean" due to their critical role in marine food webs, especially in the Arctic. Pteropods have shells made of calcium carbonate and are thus vulnerable to ocean acidification.
Warming and the decline in primary production are projected to cause the **global biomass of all marine animals (including fish) to decline** by 15% from their 1990s levels by 2100 (in the Arctic, this biomass will, however, increase).

Enhanced stratification has lowered the amount of oxygen in the subsurface ocean, by inhibiting the supply from the oxygen-rich sea surface that is essential to marine organisms. The global-scale loss of ocean oxygen is known as ocean deoxygenation.

In many ocean regions, warming and changes in primary production have led to a decline in the abundance of fish and shellfish species, resulting in reduced catches. The composition of catches has also altered since the 1970s, with the shallow seas of the world increasingly being populated by warm water species and fish stocks moving poleward.

TO SUM UP

The combined effects of ocean warming, stratification, heatwaves, oxygen loss and acidification are altering marine ecosystems. Changes in abundance and shifts in the distribution of marine species from plankton to fish, mammals and seabirds, have occurred due to ocean warming since the 1950s. This is altering the structure and function of marine food webs, along with fishery catches.

CLASS ACTIVITY # ACTIVITY

— Draw a simple diagram, known as a food chain, to represent the relationship in an ecosystem using the following words: primary producers, secondary producers, sun's energy, zooplankton, phytoplankton, fish, consumers.
— Using another colour, add the different impacts of climate change on the food chain you have drawn.

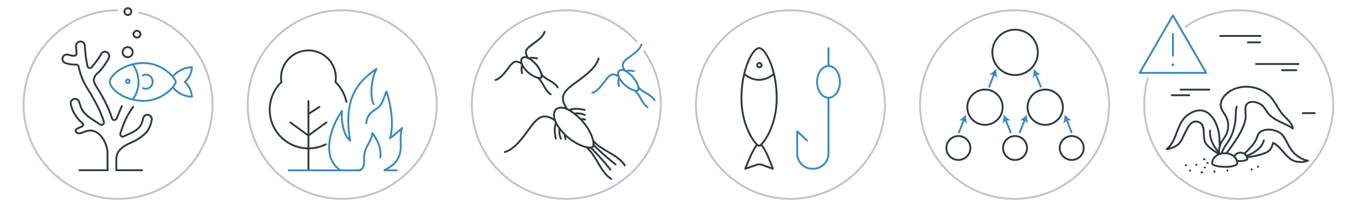


FIGURE 17 Observed and projected impacts on ecosystems.

COASTAL ECOSYSTEMS

Coastal ecosystems, such as wetlands (saltmarshes, mangrove forests, seagrass meadows), coral reefs and rocky shores **provide a large number of ecosystem services.** They protect coastlines from erosion, buffer the impacts of sea level rise, and provide food and habitat for dependent fauna and human communities. As well as ensuring invaluable cultural and spiritual functions for human populations living in those areas, they are essential for tourism.

Due to a combination of human pressures, sea level rise, ocean warming, marine heatwaves and extreme weather events, **nearly 50% of coastal wetlands have been lost over the 19th century.** Widespread die-off of mangroves has been observed since the 1960s. The loss of all these important carbon stores is resulting in the release of about 0.15-5.35 Gt of CO_2 per year. In estuaries, warming, sea level rise and tidal changes lead to the expansion of salinization (salty waters spreading into freshwater environments) and of low oxygen waters.

Global-scale coral bleaching events have been increasing in frequency, causing worldwide reef degradation since 1997. Driven by marine heatwaves, bleaching occurs when corals expel their resident algae and lose their colour (become white).

In the tropics, **almost all coral reefs are projected to suffer significant areal loss and local extinction due to warming along with ocean acidification** – even if global warming is limited to 1.5°C. Already 30% of the world's corals have been lost (due to pollution and overfishing, as well as warming). A loss of 70-90% of corals is projected for a 1.5°C warming scenario and even 99% of corals would be lost in a 2.0°C warming scenario[8]. The species composition and diversity of the remaining reef communities will differ from today's reefs.

TO SUM UP

A multitude of climate-change related effects, like ocean acidification, oxygen loss and sea ice melt, combined with local pressures from human activities, are affecting coastal ecosystems. Their biodiversity and the services they provide to humans are being altered.

The rate and magnitude of species decline are projected to be highest in the tropics. Sensitive ecosystems like coral reefs, seagrass meadows and kelp forests will be at high risk if global warming exceeds 2°C.

CLASS ACTIVITY # ACTIVITY

There are currently few invasive species in the Arctic, but more are expected to emerge with climate change and increased activity.

- Using reports from the Conservation of Arctic Flora and Fauna (CAF) https://www.caff.is/invasive-species, name some invasive species that are present in the Arctic today due to climate change and explain why their number is expected to rise.
- Discuss the effect of this increase on arctic ecosystems.
- Identify some activities and policies that have been adopted to improve management of invasions.

8 IPCC Special Report "Global Warming of 1.5°C", https://www.ipcc.ch/sr15/

Observed and projected impacts on people

ARCTIC AND HIGH-MOUNTAIN-AREA COMMUNITIES

Arctic and high mountain communities are affected by from the loss of snow cover, the loss of river and lake ice, glacier melt and permafrost thaw, in a number of ways.

Shrinkage of the land cryosphere is affecting water resources as well as food access and availability (hunting, fishing and herding) and agricultural yields. For glacier- and snow-fed river basins, loss of the cryosphere has altered the amount and seasonality of runoff. Furthermore, changes in the seasonality of water input have an impact on hydropower facilities, and this in turn affects energy supply. All these changes have consequences for communities living in and downstream of mountain areas.

The loss of the cryosphere is also affecting human health. Increased risk of food and waterborne diseases, malnutrition and injuries, and mental health challenges are some of the health impacts, with indigenous peoples being particularly affected. In some high-mountain areas, water quality has already been deteriorated by contaminants, particularly mercury, released from melting glaciers and thawing permafrost.

Loss of permafrost in the Arctic and in high mountain regions is causing land to sink and slopes to become unstable, thus damaging buildings and roads. Subsiding ground following permafrost thaw has impacts on overlying infrastructure. The majority of Arctic infrastructure is located in regions where permafrost thaw is projected to intensify by mid-century.

CLASS ACTIVITY # ACTIVITY

- Cover the bottom of an oven dish with soil. Use the soil to shape mountains, valleys and other geographical features and put the whole construction in the freezer: you will have created permafrost. Build a small town – some houses and roads – with playdough. The next day, take the oven dish out of the freezer and place your houses and roads in the landscape you have built. Leave it near a window or heater for one day.
- Describe what has happened to your town. How do you think climate change will impact communities living near the Arctic?

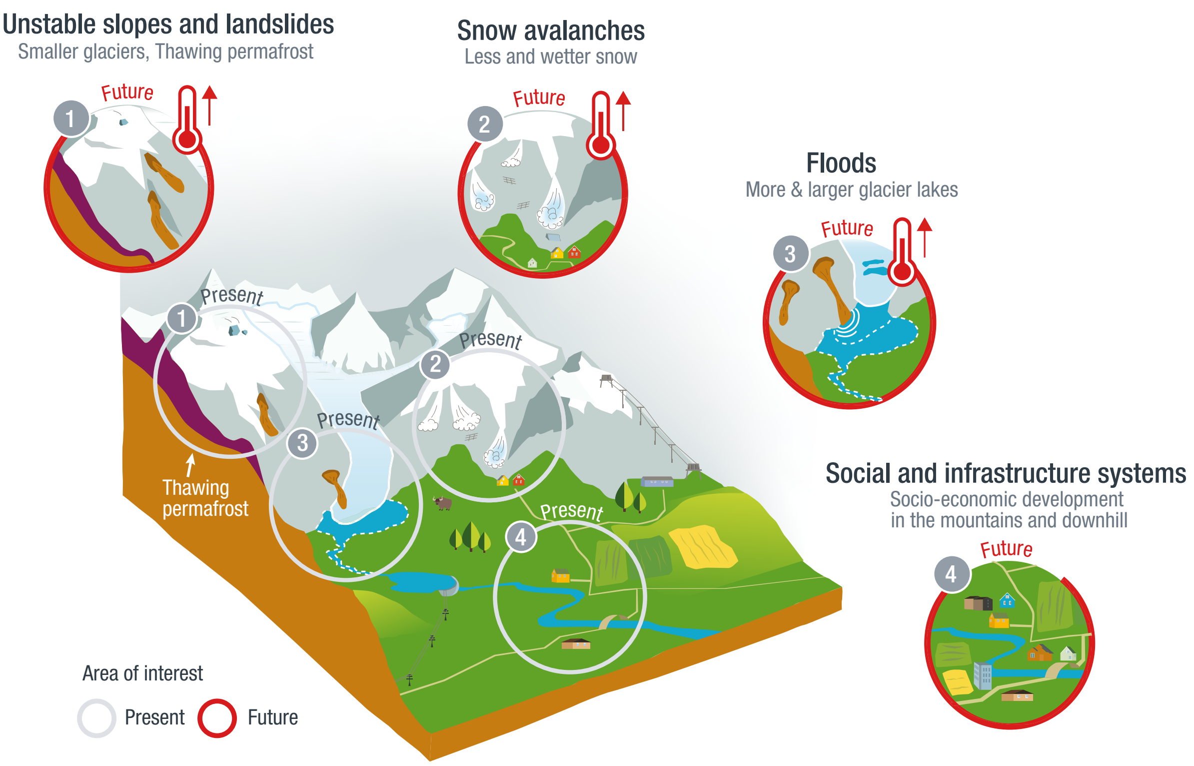


FIGURE 18 Anticipated changes in high mountain hazards under climate change, driven by changes in snow cover, glaciers and permafrost, overlay changes in the exposure and vulnerability of individuals, communities, and mountain infrastructure.

SROCC, Chapter 2, IPCC 2019 – https://www.ipcc.ch/srocc/chapter/chapter-2/2-1introduction/ipcc-srocc-ch_2_7/

The loss of the cryosphere in high mountains already impacts and will continue to impact tourism (skiing, glacier tourism, hiking and mountaineering). Snowmaking technologies in ski resorts will become increasingly ineffective as the atmosphere warms further.

The past two decades have seen an increase in **Arctic shipping** activity associated with sea ice decline. In 2011, four ships crossed the northeast passage. In 2018, 227 took the same route. The rise in shipping activities increases the risk of introducing invasive species and pollution, if actions to implement new regulations do not keep pace.

Adaptation options are available, and some have already been implemented. In the Arctic, community freezers help increase food security. Arctic communities have also adjusted the timing of their activities to respond to changes in seasonality and unsafe ice travel conditions.

In high mountains, adaptation measures include coordinated water management of various scales and industries as well as the diversification of tourism activities. In both the Arctic and high mountain areas, adaptation has been made easier thanks to the knowledge held by indigenous peoples and local populations.

TO SUM UP

Future loss of cryosphere components on land will have an impact on water resources and their uses, such as hydropower and agriculture irrigation in and downstream of high-mountain areas, as well as livelihoods in the Arctic. Increased risks from floods, avalanches, landslides and ground destabilization will affect infrastructure, tourism and safety.

CLASS ACTIVITY # ACTIVITY

— Arctic peoples have a very large number of words for snow. Can you name 5 of them? How can you explain why many countries around the world only have one word?
You can find some examples by clicking on this link: https://www.thecanadianencyclopedia.ca/en/article/inuktitut-words-for-snow-and-ice
— Do you know what a hummock is? What does it mean in Inuktitut?
Answer: A hummock means “a mountain”. A hummock is a mound of ice rising above an ice field.
— Discuss the link between the cryosphere and certain human cultures.

COASTAL ZONE

Coastal communities are exposed to multiple climate-related hazards, including tropical cyclones, storm surges and flooding, marine heatwaves, sea ice loss, and permafrost thaw. Climate hazards can interact with other "non-climate" factors, such as land subsidence, pollution, habitat degradation, reef and sand mining, and loss of indigenous and local knowledge. When several climate hazards occur simultaneously or in succession, they can lead to amplified impacts in what is known as a "compound event".

Storm surges occurring alongside a rise in mean sea level can cause loss of life, damage to infrastructure, and saline intrusion into soils and groundwater. In the Arctic, loss of sea ice is exposing coastal communities to increased shoreline erosion, affecting the infrastructure. Some coastal communities are already planning to relocate.

A wide range of options are available **to tackle each climate change hazard,** but selecting which ones are the most suitable depends on the local context. In all cases, monitoring and early-warning systems can be used to take action to reduce the risks. For sea level rise, adaptation options include coastal protection and even retreat from coasts. Barriers to implementing these options include lack of funding, knowledge and capacity.

TO SUM UP

Changes in the ocean are affecting marine ecosystems, challenging coastal communities and indigenous peoples. The impact may be seen in many areas: in food security through fisheries, in health and well-being, in local cultures and livelihoods, and on tourism and recreation. A variety of solutions is being implemented worldwide to reduce coastal hazards.

MARINE, COASTAL ECOSYSTEMS AND FISHERIES

A global reduction in **fish biomass** is projected to cause a 20% decline in (maximum sustainable) fish catches by 2100 in RCP8.5. These changes could be 3-4 times smaller in RCP2.6. Regionally, fish biomass will increase at high latitudes allowing for fishing expansion poleward, while tropical fisheries decline. These changes in fish stocks could lead to conflicts among fisheries, authorities and/or communities.

Seafood safety is also at stake, with increased accumulation of persistent organic pollutants and mercury in marine plants and animals. The risks are higher for coastal Indigenous communities that consume a lot of seafood.

Changes in marine ecosystems will lead to cultural losses, including local and indigenous knowledge. Traditional diets and food security will be negatively affected, along with recreational activities.

Each centimetre rise in local sea levels will **increase erosion, land loss, flooding, salinization, and intensify the impacts of storm surges.** Sea level will continue to rise throughout this century under both emissions scenarios. Annual coastal flooding damages are projected to increase by 2-3 orders of magnitude by 2100 compared to today, if no action is taken. Low-lying islands and coasts are most at risk, including some urban deltas, tropical island nations and coastal Arctic communities. Some island nations may become uninhabitable, although the level of sea level rise at which this will occur is extremely difficult to assess.

TO SUM UP

Shifts in fish distribution and abundance due to climate change will affect income, livelihoods and food security of fishing-dependent communities. Loss and degradation of marine ecosystems compromises the ocean's contribution to human identity and well-being. Finally, human communities in low-lying areas will be at increasing risk from sea level rise and storm surges over the coming century.

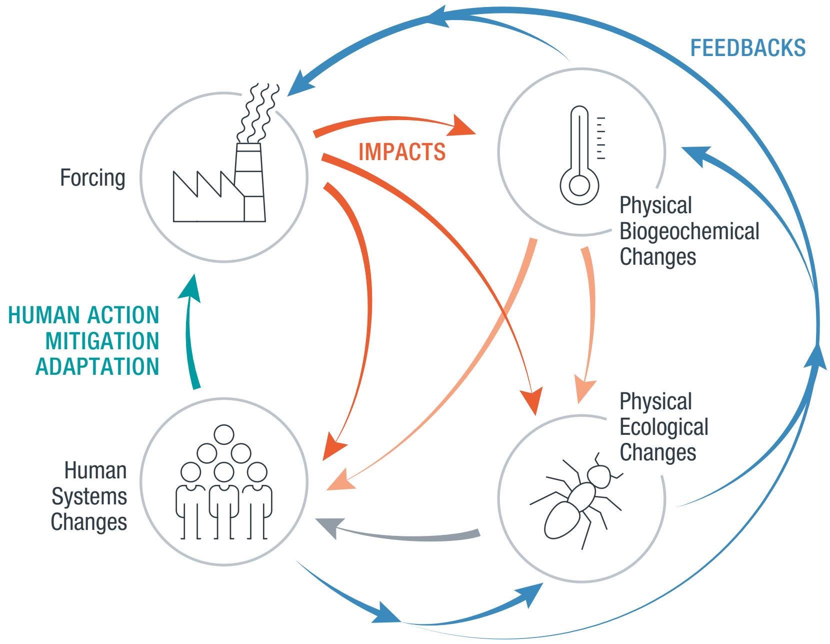


FIGURE 19 Cascading effects. We can include a concrete example:
GHG emissions rise → global warming → ocean temperature increases → abundance of primary producers decreases→ fish stocks move poleward → arctic communities catch less fish → impacts on health and livelihoods

Adapted from an infographic by IPCC, 2019 – https://www.ipcc.ch/srocc/chapter/chapter-1-framing-and-context-of-the-report/1-3time-scales-thresholds-and-detection-of-ocean-and-cryosphere-change/ipcc-srocc-ch_1_1-e1574938357439/

4. Implementing responses to ocean and cryosphere change

Challenges

There is a broad range of **challenges for adaptation** to climate change. Human interventions can be monetary, technological or institutional. The challenges to adapting ecosystems is that they require space; recovery rates following disturbances are slow, and they are put under pressure by human activities. **A key challenge is the time scale: the impacts of climate change occur over time horizons which are longer than those in which decisions are typically made in government, business and elsewhere.** Climate impacts also cross societal industries (e.g. water, food, energy) and national boundaries, requiring integrated international responses.

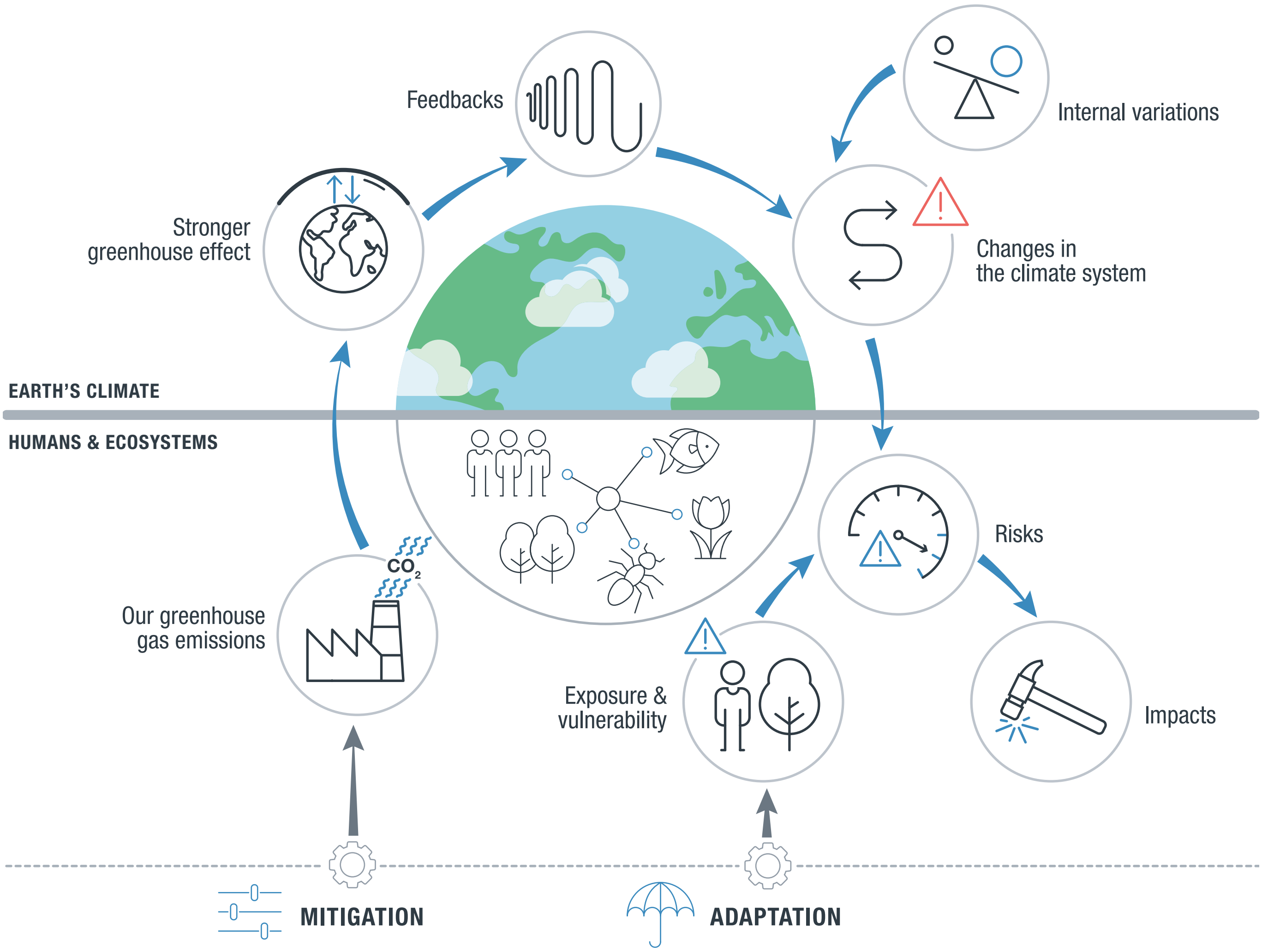


FIGURE 20 Flow diagram from human greenhouse gas emissions to the impacts of climate change and the possible solutions (mitigation and adaptation).

For both human society and ecosystems, **the faster and higher the rate of change, the less able they will be to adapt.** Ecosystems will be able to more readily adapt to slower and smaller changes. Similarly, more adaptation options will be possible for human society at lower levels of global warming.

Exposure and susceptibility to climate change, and ability to cope with the changes, are far from uniform across species, ecosystems, nations and communities. For human society, **the most exposed and vulnerable people are also often those with the lowest capacity to adapt** (they become even more exposed and more vulnerable) — for instance, poor people living in the lowest-lying areas of a coastal megacity.

Even after making major efforts to adapt, certain risks may still remain. These irreducible risks are known as **"limits to adaptation"**. An example is unavoidable flooding and inundation of low-lying coastal areas, leading to coastal retreat.

TO SUM UP

Impacts of climate-related changes on the ocean and cryosphere challenge current mechanisms and capacities for both humans and ecosystems to respond, in some cases pushing them to their limits. People who are the most exposed and vulnerable to climate change are often those with the lowest capacity to adapt.

Strengthening responses

ADAPTATION

Protection, restoration and reduction of additional stressors, such as pollution, can help ecosystems adapt. Establishing networks of protected areas can facilitate uphill migration of species and poleward movement of marine species. Species can also be assisted with their relocation. In some places, experiments with ecosystem reconstruction are carried out – "coral gardening" is one example, although these measures may fail to be effective when confronted with further warming and sea level rise. These strategies work best when local communities and their knowledge are taken into account.

Concerning fishery catches, **rebuilding overexploited stocks and management** that regularly assesses and updates measures can reduce risks. For water resources, integrated management across uses (energy, agriculture, drinking water etc.) can be effective, including the development and optimization of storage. In both cases, cooperation across boundaries (e.g., between countries) can assist management efforts.

Measures to combat sea level rise range from **building dikes and seawalls (which can be costly), to restoring coastal ecosystems (like mangroves) in order to reduce incoming wave energy,** to retreating from coastal areas. At a global scale, coastal protection can reduce flood risk by 2-3 orders of magnitude during the 21st century, but large investments are required. The higher the sea level rises, the greater the coastal protection challenge will be, mainly due to financial and social limits rather than due to technical limits.

Despite the vast uncertainties about how much the sea level will rise after 2050, **many decisions which will have an influence this far into the future are being made now.** As such, an iterative approach is necessary, in which the latest science, current adaptation plans and implemented adaptation strategies are periodically assessed and altered as needed.

A slower rate of sea level rise, or any other consequence of climate change, provides greater adaptation opportunities, hence the need to also reduce greenhouse gas emissions (discussed in the next section) in addition to adaptation.

TO SUM UP

Adaptation to sea level rise will be a worldwide problem for coastal communities. Reducing local drivers of exposure and vulnerability, implementing early-warning systems, flood-proofing buildings and ecosystem-based adaptation are effective responses in the coming decades that may, at least in the short-term, limit the need for more costly measures that cannot be afforded by resource-limited communities.

CLASS ACTIVITY # ACTIVITY

— Imagine the whole class lives in a seaside village. Each student has a different role in this community (example: the fisherman, the summer tourist, a random inhabitant, the grocery store owner, the civil engineer, the town governor, the bank owner, the surf teacher, the maritime police, the chairperson of the animal protection association, the beach bar owner, etc.).

Due to sea level rise and other factors, the local beach is getting smaller by a metre every year, and during the biggest storms the streets and buildings closest to the beach are frequently flooded.

— Let the students discuss the pros and cons of multiple possible solutions for their community from the point of view of their character, and come to the realisation that there is no simple answer.

Answer: Different characters have different priorities, and no solution is perfect and will always favour some and disadvantage others. Options could include delocalising the entire community further inland, building coastal protection structures, beach nourishment, restoring coastal local ecosystems, do nothing, etc.

Issues might be: costs, unequal profit, tourism impacts (landscape changes, beach disappearance), livelihood impacts (loss of jobs, structure damage), impacts on local biodiversity, etc.

MITIGATION

Certain types of coastal ecosystems are effective carbon sinks, so restoring them can help draw down CO_2 from the atmosphere. These carbon sinks include mangrove forests, tidal marshes and seagrass meadows, and are known as “blue carbon” ecosystems. Although their potential contribution to emissions reductions would be small in global terms — around 0.5% of current global emissions — they bring many additional local benefits, such as providing storm protection, better water quality, and benefits to biodiversity and fisheries.

Ocean renewable energy can also support climate change mitigation, and can comprise energy production with offshore winds, tides, waves, thermal and salinity gradients and algal biofuels. The emerging demand for alternative energy sources is expected to generate new economic opportunities.

TO SUM UP

Ecosystem-based adaptation and mitigation can help strengthen future response options to climate-related ocean and cryosphere changes. Ecosystem-based adaptation will be effective only under the lowest levels of warming but can provide multiple short-term benefits to ecosystems and local communities.

CLASS ACTIVITY # QUESTION

CO_2 is emitted when fossil fuels are burned.

- Think about a simple experiment to demonstrate how combustion releases CO_2.
- How can we reduce our CO_2 emissions? How can we reduce other greenhouse gas emissions like methane (CH_4) and nitrous oxide (N_2O)?

Key words: biogas production, deforestation, fertilisers, agriculture, renewable energy, energy saving.

ENABLING RESPONSES

Enabling appropriate responses will be key to tackling the impacts of climate change. This critically depends on **“rapid” and ambitious emissions reductions,** alongside major efforts in adaptation. Adaptation works best when an integrated, cooperative approach is taken. In addition, different timescales need to be accounted for both short and long-term; this is particularly true for sea level rise.

Cooperation is needed across spatial scales and sectors, and within and between countries – for instance, through treaties and conventions. Community-led responses, including experimental approaches, should also be encouraged, with the knowledge gained subsequently shared with similar communities.

In addition to good management, other essential elements for effective adaptation include:

- **education and climate literacy,** which can build public awareness, engagement and skill sets;
- **using and sharing data,** information and knowledge (including local and indigenous knowledge);
- **monitoring and forecasting;** early warning systems, such as those used today for El Niño/La Niña events, tropical cyclones and marine heatwaves, can be used to manage negative impacts;
- **addressing social vulnerabilities** and equity to build a fair and just future.

Of course, funding resources will be key to making all this happen.

TO SUM UP

Rapid transformative change is needed across nations and societies in order to tackle climate change. Key elements that can facilitate effective adaptation include cooperation, education, monitoring and forecasting, data sharing and addressing inequities.

Conclusion

The ocean and cryosphere play a major role in the Earth's climate system. The ocean absorbs and redistributes CO_2 and heat, it supplies us with food, renewable energy and raw materials, and provides us with transport facilities. The cryosphere, in the form of glacier melt water, supplies us with fresh water. Both the ocean and cryosphere are fundamentally important to our health and well-being, for recreation and our cultural values.

Climate-change-induced disturbances in the ocean and cryosphere have strong impacts on human communities – particularly on those living near the coast, on small islands, in polar areas or in high mountain regions. Today, around 4 million people live permanently in the Arctic region, of whom 10% are indigenous; 680 million people live near the coast and 670 million people live in high mountain regions. The changes will continue throughout the decades and the millennia – some occurring abruptly and (others) being irreversible.

By preserving the ocean and cryosphere and their ecosystems – through ambitious mitigation and effective adaption – we can also achieve several of the Sustainable Development Goals (SDGs) adopted by the United Nations. Conversely, if we wait before taking action, the risks of climate change impacts will increase, and so will the costs of mitigation and adaptation.

As the original Summary for Policymakers of the report concludes:

"Realising this potential depends on transformative change. This highlights the urgency of prioritising timely, ambitious, coordinated and enduring action."

CLASS ACTIVITY # ACTIVITY

— Do you know what a haiku is?

Answer: A haiku is a Japanese poem, which uses 17 syllables arranged in three lines in specific order. On the first line, you have 5 syllables, on the second line 7 and on the third one 5. Here are some examples of haiku: http://climate.miami.edu/your-haiku-to-the-environment/

— Write some haikus on the topic of climate change, the ocean and cryosphere.

Glossary

ADAPTATION The process of adjusting to current or expected climate change impacts. In human systems, the aim of adaptation is to reduce risks, increase resilience or seize on beneficial opportunities. In natural systems, human intervention may facilitate adjustments to expected climate change impacts.

ALBEDO Meaning "whiteness", albedo is the reflective power of an object or surface. For instance, ice and fresh snow have a high albedo, ranging from 40% to 80%. This means that they reflect 40% to 80% of the incoming sunlight. The ocean is darker, with an albedo of less than 10%.

ANTHROPOGENIC EMISSIONS Greenhouse gases emitted by human activities.

CARBON DIOXIDE (CO_2) A gas produced by the combustion of carbon (for example: fossil fuels). It is also produced by living organisms through respiration. CO_2 contributes to the greenhouse effect and ocean acidification.

CARBON SINK Natural reservoir that stores carbon-containing chemical compounds accumulated over time. Carbon sinks help reduce the amount of atmospheric CO_2.

CARBONIC ACID (H2CO3) This acid is formed when carbon dioxide dissolves in water, causing an increase in the acidity of the water.

CASCADING EFFECTS Inevitable and sometimes unforeseen chain of events due to an action affecting part of the climate system. Such cascading effects usually have negative impacts.

CLIMATE An average pattern of weather conditions (over a 30-year period) – defined by temperature, precipitation, humidity, wind, air pressure, etc. – and in a given area, including the distribution of their extremes.

CLIMATE CHANGE Climate change refers to changes in the global climate system that are the result of an enhanced greenhouse effect. These include changes in temperature, precipitation, extreme events, sea level rise and ocean acidification. The term is mostly used to describe the human-induced changes that have been occurring since pre-industrial times due to an increase in global average temperature. The term "global warming" is also used.

CLIMATE JUSTICE A form of environmental and social justice that acknowledges responsibilities to address climate change and recognises differences in opportunities and resources to mitigate or adapt to its impacts.

CO_2 UPTAKE All the processes that contribute to the removal of CO_2 from the atmosphere. CO_2 can be removed by biological processes such as ocean or land photosynthesis or by physical processes such as carbon absorption in seawater. It can also be artificially removed by technology.

COASTAL ECOSYSTEMS Coastal ecosystems are created where land and ocean meet. The resulting mixture of freshwater and seawater creates unique environments and ecosystems with distinct structures and diversity. They include saltmarshes, mangroves, seagrass meadows, estuaries and bays.

COASTAL EROSION A phenomenon whereby material (sand and rock) is removed from the coast, leading to loss of land. This can be exacerbated by climate change (especially by sea level rise or an increase in precipitation).

COMPLEX SYSTEM A system (such as the climate system) regulated by many factors that interact with and influence each other. For example, the atmosphere, the ocean, the cryosphere, land and the biosphere, in the case of the climate system.

CONTINENTAL ICE All ice masses on land comprising glaciers, ice sheets, ice shelves, ice caps etc. except snow, permafrost and sea ice. Continental ice is created by the accumulation and compaction of snow over a long period of time.

CRYOSPHERE The places on or beneath the Earth's surface (including the ocean) that contain snow and ice (continental ice, sea ice and permafrost).

ECOSYSTEM SERVICES An ecosystem is the totality of living beings in a given environment plus the environment itself. In an ecosystem, there is a functional interdependent relationship between the living beings and their environment. Humans can directly and indirectly benefit from ecosystems, which provide them services. For example, ecosystems produce oxygen (through photosynthesis) and food, and they provide us with raw materials. Ecosystems also preserve soil fertility (through microorganisms and fungi in the soil), fertilise plants (through pollination) and protect coasts (through intact coral reefs or mangroves).

EMISSION PATHWAYS Emission pathways refers to the modelled trajectories of global anthropogenic greenhouse gases emissions for the future following different scenarios possible (here for instance, we focus on the RCP2.6 and the RCP8.5).

EQUITY Justice, fairness: when the same opportunities are given to all – education, health, rights etc. In a climate change context, equity is about fairness in sharing the burden and opportunities of climate change impacts.

EXTREME EVENTS Unusual events that can have a high negative impact on humans and nature, for example tornadoes, storm surges, landslides, droughts and heatwaves.

GLACIER A large mass of ice on land that slowly moves downhill.

GLOBAL WARMING (see definition of climate change)

GREENHOUSE EFFECT Solar radiation crosses the atmosphere, is absorbed by the Earth's surface and warms it. The absorbed solar radiation is transformed into infrared radiation (heat). Some of this infrared radiation is trapped on its escape towards space by greenhouse gases in the atmosphere and is sent back towards the Earth's surface – heating it up even more. This is called the greenhouse effect.

GREENHOUSE GAS Greenhouse gases cause the greenhouse effect. They include water vapour, carbon dioxide, methane, nitrous oxide and ozone.

HEATWAVE A period of abnormally hot weather with high daytime temperatures and no or little cooling down at night. A heatwave can last up to several weeks.

ICE SHEET A very large and thick layer of ice on a continent.

INDUSTRIAL REVOLUTION Historical period between 1760 and the 1840s. It marks the transition from agricultural to industrial societies. The Industrial Revolution started in Europe and the United States and led to rapid development in productivity, technologies and science, and to population growth.

INFRARED RADIATION Infrared radiation is the invisible part of light we can feel as heat. It plays a key role in the greenhouse effect.

INVASIVE SPECIES Species that is not native to a specific location and have the tendency to spread to a degree that can cause damage to the environment, human economy or human health. Many factors can favour the spreading of invasive species such as the increase of the intensity of global commercial flows.

MARINE CURRENTS A flow of water through the ocean. Warm and cold currents redistribute heat around the globe.

MARINE HEATWAVE Period of time of 5 days minimum when seawater temperature exceed a seasonally based maximum temperature (with an exceeding average of minimum 2°C).

MITIGATION Human intervention to reduce global warming by reducing greenhouse gas emissions or enhancing greenhouse gas sinks.

NATURAL VARIABILITY Variations in the climate system that are not related to human activities (for example, El Niño or alternation of glacial and interglacial eras).

OCEAN ACIDIFICATION Increase in the acidity of seawater, caused by CO_2 from the atmosphere dissolving in the ocean's surface water. When CO_2 reacts with water, the water becomes more acidic.

PERMAFROST Soil, rock or sediment that is permanently frozen (for at least two consecutive years).

pH pH is a measure of acidity and alkalinity of a solution on a scale in which 7 represents neutrality. A lower value indicates a more acidic solution whereas a higher value indicates a more alkaline solution.

PRIMARY PRODUCTION Primary production is the process by which primary producers, such as phytoplankton and kelp, produce organic matter from inorganic materials through photosynthesis.

RUNOFF The draining away of water or snow from the surface of an area of land, a building or a structure.

SEA ICE Frozen seawater that floats on the ocean's surface.

SEA LEVEL RISE Rise of sea level caused by the impact of climate change, such as melting of ice sheets and thermal expansion of the oceans.

SEA SURFACE TEMPERATURE The average water temperature at a depth range from 1mm to 20 meters, according to the type of measurement.

STORM SURGE Local rising of the sea as a result of wind and atmospheric pressure changes due to a storm.

STRATIFICATION Layers of seawater masses with different properties: they vary in salinity, oxygenation, density and/or temperature. As a result, water in the ocean will not mix, leading to anoxia and lack of nutrients (the water is depleted in O_2 and/or in nutrients, which has consequences on the marine wildlife).

SUSTAINABLE DEVELOPMENT Development that meets the needs of the present generations without compromising the ability of future generations to meet their own needs.

SUSTAINABLE DEVELOPMENT GOALS (SDGs) Universal calls to action to end global poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. There are 17 different Sustainable development goals, which were adopted by all United Nations Member States in 2015: (1) no poverty, (2) zero hunger, (3) good health and well-being, (4) quality education, (5) gender quality, (6) clean water and sanitation, (7) affordable and clean energy, (8) decent work and economic growth, (9) industry, innovation and infrastructure, (10) reduced inequalities, (11) sustainable cities and communities, (12) responsible consumption and production, (13) climate action, (14) life below water, (15) life on land, (16) peace, justice and strong institutions and (17) partnerships for the goals.

THERMAL EXPANSION An increase in volume as a result of rising temperature. With regard to climate change: when the ocean gets warmer, it expands and occupies more space.

THERMAL INERTIA A property of matter characterising the speed with which it approaches the temperature of its surroundings. The slower it does this, the higher the thermal inertia.

TIPPING POINT The point at which a series of small changes or incidents becomes significant enough to cause a larger, more important change.

TRANSFORMATION Adaptation that changes the fundamental attributes of a system in response to climate and its effects.

VULNERABILITY Sensitivity of a population, a building etc. when exposed to climate change hazards.

WEATHER The state of the atmosphere at a particular time and place. To define it, many variables such as temperature, precipitation, cloudiness or wind are taken into account.

Bibliography

SCIENTIFIC DOCUMENTATION ON THE OCEAN, THE CRYOSPHERE AND THE CLIMATE

IPCC Special Report *The Ocean and Cryosphere in a Changing Climate*
www.ipcc.ch/srocc

NASA – Global Climate Change: Graphics and multimedia
https://climate.nasa.gov/resources/graphics-and-multimedia/

National Snow and Ice Data Center: Satellite images and data showing Arctic – and Antarctic – wide changes in sea ice
https://nsidc.org/data/seaice_index/

Ocean and Climate platform
www.ocean-climate.org/?page_id=4534

UNESCO – Ocean Literacy
https://oceanliteracy.unesco.org

OCE EDUCATIONAL RESOURCES

CLIM – Educational videos about the ocean and cryosphere in a changing climate
www.youtube.com/channel/UCFWnXg29G9npeWgFEaaao5w

IPCC summaries for teachers
www.oce.global/en/resources/ipcc-summaries-teachers

Professional development resources for teachers
- The greenhouse effect: www.oce.global/en/resources/professional-development/greenhouse-effect
- Ocean and climate change: www.oce.global/en/resources/professional-development/ocean-and-climate-change

The climate in our hands – Ocean and Cryosphere
www.oce.global/en/resources/class-activities/climate-our-hands-ocean-and-cryosphere

OTHER EDUCATIONAL RESOURCES

Dublin City University, Institute of Education: Trócaire and the Centre for Human Rights and Citizenship Education – "Creating Futures" resources produced in the scope of the "Education for a Just World Initiative"
www.trocaire.org/getinvolved/education/creating-futures

Eco-schools – Stories and news about sustainability projects conducted in schools
www.ecoschools.global/stories-news

La main à la pâte – The Ocean, my planet and me: A teaching unit for primary school and lower secondary school classrooms
www.fondation-lamap.org/en/20322/the-ocean-my-planet-and-me

NASA Climate Kids
https://climatekids.nasa.gov

National Oceanic and Atmospheric Administration – Teaching climate, fact sheets, lesson plans, case studies, etc.
https://oceanservice.noaa.gov/education/pd/climate/welcome.html

The Sandwatch Foundation – A network of children, youth and adults working together to enhance their beach environment and build resilience to climate change
www.sandwatchfoundation.org

TROPICSU – Resources for high-school teachers
https://tropicsu.org/un-resources/

INTERACTIVE SIMULATIONS

En-ROADS – Simulation used to understand how we can achieve our climate goals (high school)
https://www.climateinteractive.org/tools/en-roads/

University of Colorado – Simulation of the greenhouse effect (high school)
https://phet.colorado.edu/en/simulation/greenhouse

University of Manchester – Build your own Earth (high school)
http://www.buildyourownearth.com

Office for Climate Education

UNDER THE AUSPICES OF UNESCO
AND THE FOUNDATION LA MAIN À LA PÂTE

"Parties should take measures [...] to enhance climate education", states Art.12 of the Paris Agreement. *"Educating the present and future generations about climate change, and teaching them to act with a critical mind and a hopeful heart, is essential for the future of humanity. Science education must meet the challenge [...]"*, recommend the 113 science academies of the world in their recent Statement on Climate Change and Education.

Replying to these urgent calls, climate scientists and educators established an **Office for Climate Education.** Teachers are key for implementing these recommendations, especially in primary and secondary schools. Hence, the office produces for them educational resources, based on active pedagogies, such as inquiry-based science education and project-based learning. As IPCC produces "assessment reports" and "summaries for policymakers", the Office produces "resources and tools for teachers", focusing on the issues of adaptation and attenuation. It pays special attention to developing countries.

Working closely with climate scientists, involving social scientists and educators, the Office for Climate Education has an executive secretariat in Paris and a global network of local or regional partners in over 20 countries already. The teaching resources are conceived in a global frame, then are locally tested and adapted to particular situations. The numerous initiatives already taken in the same direction are documented and publicised by the Office.

The Office for Climate Education was launched in 2018 with the support of public and private funds provided by French and German partners. It amplifies its action in proportion with its resources and develops partnerships, especially with IPCC and IAP for Science– the global federation of science academies.

http://oce.global
contact@oce.global
Office for Climate Education
Institut Pierre-Simon Laplace,
Case 101
4, place Jussieu
75252 Paris Cedex 05 – France

UNDER THE AUSPICES OF

United Nations Educational, Scientific and Cultural Organization — Under the auspices of UNESCO

FONDATION La main à la pâte — POUR L'ÉDUCATION À LA SCIENCE

Commissioned in 2018 by the *La main à la pâte* foundation and the climate science community, the Office for Climate Education (OCE) promotes climate change education and associated teacher support worldwide. The OCE has been a centre under the auspices of UNESCO since 2020.

FOUNDING MEMBERS

METEO FRANCE · IRD Institut de Recherche pour le Développement FRANCE · météo et climat Société météorologique de France · SORBONNE UNIVERSITÉ

IN PARTNERSHIP WITH

ipcc INTERGOVERNMENTAL PANEL ON climate change Working Group I - The Physical Science Basis · IPSL · PIK Potsdam Institute for Climate Impact Research · iap SCIENCE HEALTH POLICY the interacademy partnership · Investir l'Avenir · Liberté • Égalité • Fraternité République Française MINISTÈRE DE L'ÉDUCATION NATIONALE ET DE LA JEUNESSE

Liberté • Égalité • Fraternité République Française MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE ET SOLIDAIRE · ADEME Agence de l'Environnement et de la Maîtrise de l'Energie · SIEMENS Stiftung · FONDATION LUCIOLE INSTITUT DE FRANCE · FONDATION PRINCE ALBERT II DE MONACO