Key Topic 1: Factors Contributing to a Changing Climate

1. Describe climate change and the process through which it occurs.
2. Outline the factors, both anthropogenic and natural, which influence climate and climate change.
3. Describe the major economic sectors that contribute to greenhouse gas (GHG) emissions.
4. Describe major energy sources and explain how each contributes to climate change.
5. Outline indicators of climate change.

Study Resources

Resource Title	Source	Located on
Basics of Climate Change	*US Environmental Protection Agency, 2019*	Pages 4-9
Causes of Climate Change	*Government of Canada, 2019*	Pages 10-12
VIDEO: Climate Change 2022: Impacts, Adaptation & Vulnerability – CLICK LINK	*Intergovernmental Panel on Climate Change (IPCC), 2020*	Page 30; 14 Minutes
Sector by sector: where do global greenhouse emissions come from?	*Our World in Data, Hannah Ritchie, 2020*	Pages 31-36
Energy and the Environment Explained	*US Energy Information Administration, 2021*	Pages 37-48

Please Note: Hyperlinks found in text are not considered required reading; however, included video links are required to watch.

Study Resources begin on the next page

Basics of Climate Change

Learn about some of the key concepts related to climate change:

- The Greenhouse Effect
- Key Greenhouse Gases
- Other Greenhouse Gases
- Aerosols
- Climate Feedback

How is the Climate Changing in the United States?

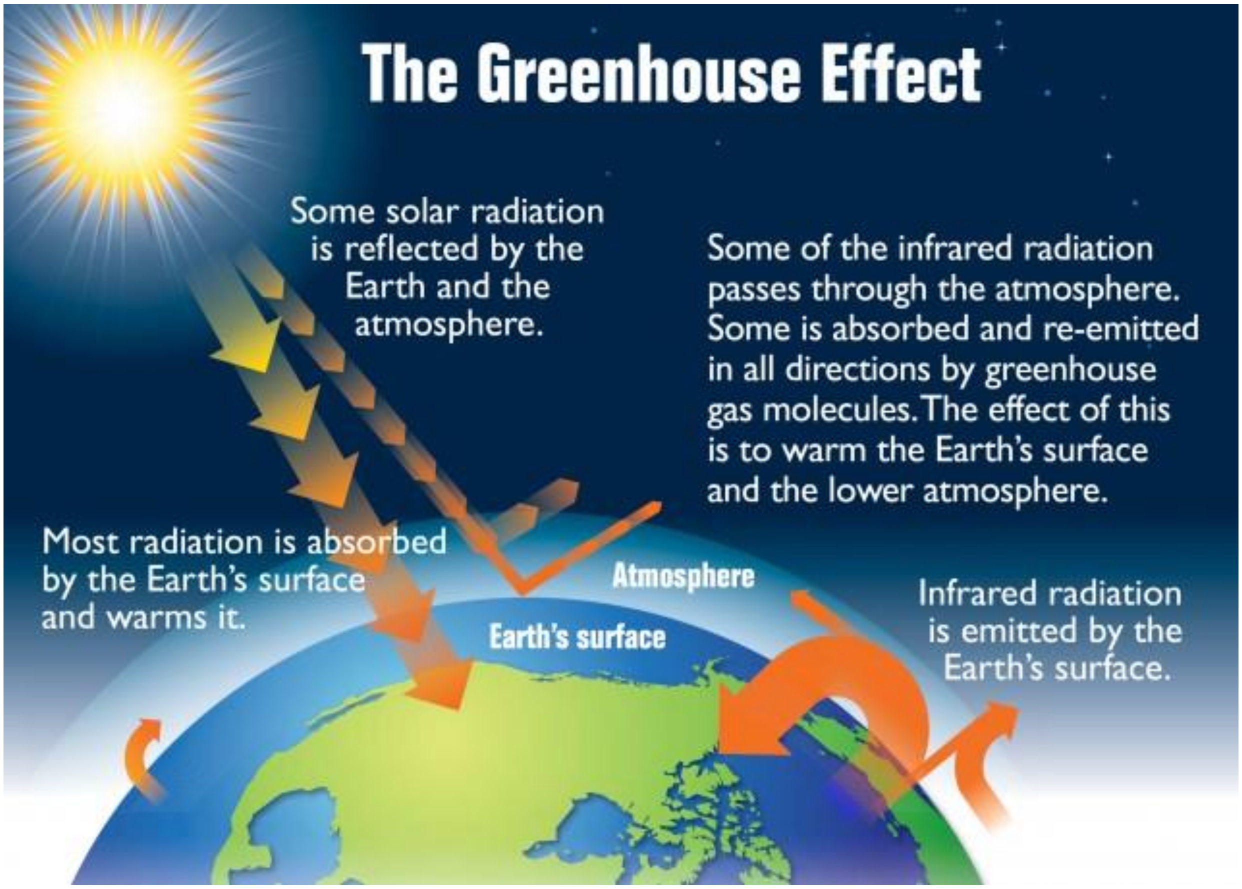
Observations across the United States and world provide multiple, independent lines of evidence that climate change is happening now. **Learn More About Climate Change Indicators** <https://epa.gov/climate-indicators> **>>**

The earth's climate is changing. Multiple lines of evidence show changes in our weather, oceans, and ecosystems, such as:

- Changing temperature and precipitation patterns <https://epa.gov/climate-indicators/weather-climate>.[1] [2]
- Increases in ocean temperatures, sea level, and acidity <https://epa.gov/climateindicators/oceans>.
- Melting of glaciers and sea ice <https://epa.gov/climate-indicators/snow-ice>.[3]
- Changes in the frequency, intensity, and duration of extreme weather events <https://epa.gov/climate-indicators/weather-climate>.
- Shifts in ecosystem characteristics <https://epa.gov/climate-indicators/ecosystems>, like the length of the growing season, timing of flower blooms, and migration of birds.

These changes are due to a buildup of greenhouse gases in our atmosphere and the warming of the planet due to the greenhouse effect.

The Greenhouse Effect



The greenhouse effect helps trap heat from the sun, which keeps the temperature on earth comfortable. But people's activities are increasing the amount of heat-trapping greenhouse gases in the atmosphere, causing the earth to warm up.

The earth's temperature depends on the balance between energy entering and leaving the planet's system. When sunlight reaches the earth's surface, it can either be reflected back into space or absorbed by the earth. Incoming energy that is absorbed by the earth warms the planet. Once absorbed, the planet releases some of the energy back into the atmosphere as heat (also called infrared radiation). Solar energy that is reflected back to space does not warm the earth.

Certain gases in the atmosphere absorb energy, slowing or preventing the loss of heat to space. Those gases are known as "greenhouse gases." They act like a blanket, making the earth warmer than it would otherwise be. This process, commonly known as the "greenhouse effect," is natural and necessary to support life. However, the recent buildup of greenhouse gases in the atmosphere from human activities has changed the earth's climate and resulted in dangerous effects to human health and welfare and to ecosystems.

Key Greenhouse Gases

Most of the warming since 1950 has been caused by human emissions of greenhouse gases.[4] Greenhouse gases come from a variety of human activities, including burning fossil fuels for heat and energy, clearing forests, fertilizing crops, storing waste in landfills, raising livestock, and producing some kinds of industrial products.

Carbon Dioxide

Carbon dioxide is the primary greenhouse gas contributing to recent climate change. Carbon dioxide enters the atmosphere through burning fossil fuels, solid waste, trees, and other biological materials, and as a result of certain chemical reactions, such as cement manufacturing. Carbon dioxide is absorbed and emitted naturally as part of the carbon cycle, through plant and animal respiration, volcanic eruptions, and ocean atmosphere exchange.

The Carbon Cycle
The carbon cycle is the process by which carbon continually moves from the atmosphere to the earth and then back to the atmosphere. On the earth, carbon is stored in rocks, sediments, the ocean, and in living organisms. Carbon is released back into the atmosphere when plants and animals die, as well as when fires burn, volcanoes erupt, and fossil fuels (such as coal, natural gas, and oil) are combusted. The carbon cycle ensures there is a balanced concentration of carbon in the different reservoirs on the planet. But a change in the amount of carbon in one reservoir affects all the others. Today, people are disturbing the carbon cycle by burning fossil fuels, which release large amounts of carbon dioxide into the atmosphere, and through land use changes that remove plants, which absorb carbon from the atmosphere.

Methane

Both natural and human activities produce methane. For example, natural wetlands, agricultural activities, and fossil fuel extraction and transport all emit methane.

Nitrous Oxide

Nitrous oxide is produced mainly through agricultural activities and natural biological processes. Fossil fuel burning and industrial processes also create nitrous oxide.

F-Gases

Chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, together called F-gases <https://epa.gov/ghgemissions/overview-greenhouse-gases#f-gases>, are often used in coolants, foaming agents, fire extinguishers, solvents, pesticides, and aerosol propellants.

Global Warming Potential

Different greenhouse gases can remain in the atmosphere for different amounts of time, ranging from a few years to thousands of years. In addition, some gases are more effective than others at making the planet warmer. Learn more about Global Warming Potential (GWP) <https://epa.gov/ghgemissions/understanding-globalwarming-potentials>, a measure of climate impacts based on how long each greenhouse gas remains in the atmosphere and how strongly it absorbs energy.

Other Greenhouse Gases

Ground-Level Ozone

Ground-level ozone <https://epa.gov/ground-level-ozone-pollution> is created by a chemical reaction between emissions of nitrogen oxides and volatile organic compounds from automobiles, power plants, and other industrial and commercial sources in the presence of sunlight. In addition to trapping heat, ground-level ozone is a pollutant that can cause respiratory health problems and damage crops and ecosystems.

Water Vapor

Water vapor is another greenhouse gas and plays a key role in climate feedbacks because of its heat-trapping ability. Warmer air holds more moisture than cooler air. Therefore, as greenhouse gas concentrations increase and global temperatures rise, the total amount of water vapor in the atmosphere also increases, further amplifying the warming effect.[5]

For more information on greenhouse gases, see Greenhouse Gas Emissions <https://epa.gov/ghgemissions>.

Aerosols

Aerosols in the atmosphere can affect climate. Aerosols are microscopic (solid or liquid) particles that are so small that instead of quickly falling to the surface like larger particles, they remain suspended in the air for days to weeks. Human activities, such as burning fossil fuels and biomass, contribute to emissions of these substances, although some aerosols also come from natural sources such as volcanoes and marine plankton.

Unlike greenhouse gases, the climate effects of aerosols vary depending on what they are made of and where they are emitted. Depending on their color and other factors, aerosols can either absorb or reflect sunlight. Aerosols that reflect sunlight, such as particles from volcanic eruptions or sulfur emissions from burning coal, have a cooling effect. Those that absorb sunlight, such as black carbon (a part of soot), have a warming effect.

Not only can black carbon directly absorb incoming and reflected sunlight, but it can also absorb infrared radiation.[6] Black carbon can also be deposited on snow and ice, darkening the surface and thereby increasing the snow's absorption of sunlight and accelerating melt.[7] While reductions in all aerosols can lead to more warming, targeted reductions in black carbon emissions can reduce global warming. Warming and cooling aerosols can also interact with clouds, changing their ability to form and dissipate, as well as their reflectivity and precipitation rates. Clouds can contribute both to cooling, by reflecting sunlight, and warming, by trapping outgoing heat.

Climate Feedbacks

Climate feedbacks are natural processes that respond to global warming by setting or further increasing change in the climate system. Feedbacks that set the change in climate are called negative feedbacks. Feedbacks that amplify changes are called positive feedbacks.

Water vapor appears to cause the most important positive feedback. As the earth warms, the rate of evaporation and the amount of water vapor in the air both increase. Because water vapor is a greenhouse gas, this leads to further warming.

The melting of Arctic **sea ice** is another example of a positive climate feedback. As temperatures rise, sea ice retreats. The loss of ice exposes the underlying sea surface, which is darker and absorbs more sunlight than ice, increasing the total amount of warming. Less snow cover during warm winters has a similar effect.

Clouds can have both warming and cooling effects on climate. They cool the planet by reflecting sunlight during the day, and they warm the planet by slowing the escape of heat to space (this is most apparent at night, as cloudy nights are usually warmer than clear nights).

Climate change can lead to changes in the coverage, altitude, and reflectivity of clouds. These changes can then either amplify (positive feedback) or dampen (negative feedback) the original change. The net effect of these changes is likely an amplifying, or positive, feedback due mainly to increasing altitude of high clouds in the tropics, which makes them better able to trap heat, and reductions in coverage of lower-level clouds in the mid-latitudes, which reduces the amount of sunlight they reflect. The magnitude of this feedback is uncertain due to the complex nature of cloud/climate interactions.[8]

Government of Canada Gouvernement du Canada

Causes of climate change

What is the most important cause of climate change?

Human activity is the main cause of climate change. People burn fossil fuels and convert land from forests to agriculture. Since the beginning of the Industrial Revolution, people have burned more and more fossil fuels and changed vast areas of land from forests to farmland.

Burning fossil fuels produces carbon dioxide, a greenhouse gas. It is called a greenhouse gas because it produces a “greenhouse effect”. The greenhouse effect makes the earth warmer, just as a greenhouse is warmer than its surroundings.

Carbon dioxide is the main cause of human-induced climate change.

It stays in the atmosphere for a very long time. Other greenhouse gases, such as nitrous oxide, stay in the atmosphere for a long time. Other substances only produce short-term effects.

Not all substances produce warming. Some, like certain aerosols, can produce cooling.

What are climate forcers?

Carbon dioxide and other substances are referred to as climate forcers because they force or push the climate towards being warmer or cooler. They do this by affecting the flow of energy coming into and leaving the earth’s climate system.

Small changes in the sun’s energy that reaches the earth can cause some climate change. But since the Industrial Revolution, adding greenhouse gases has been over 50 times more powerful than changes in the Sun's radiance. The additional greenhouse gases in earth’s atmosphere have had a strong warming effect on earth’s climate.

Future emissions of greenhouse gases, particularly carbon dioxide, will determine how much more climate warming occurs.

What can be done about climate change?

Carbon dioxide is the main cause of human-induced global warming and associated climate change. It is a very long-lived gas, which means carbon dioxide builds up in the atmosphere with ongoing human emissions and remains in the atmosphere for centuries. Global warming can only be stopped by reducing global emissions of carbon dioxide from human fossil fuel combustion and industrial processes to zero, but even with zero emissions, the global temperature will remain essentially constant at its new warmer level. Emissions of other substances that warm the climate must also be substantially reduced. This indicates how difficult the challenge is.

What is climate change?

Climate change is a long-term shift in weather conditions identified by changes in temperature, precipitation, winds, and other indicators. Climate change can involve both changes in average conditions and changes in variability, including, for example, extreme events.

The earth's climate is naturally variable on all time scales. However, its long-term state and average temperature are regulated by the balance between incoming and outgoing energy, which determines the Earth's energy balance. Any factor that causes a sustained change to the amount of incoming energy or the amount of outgoing energy can lead to climate change. Different factors operate on different time scales, and not all of those factors that have been responsible for changes in earth's climate in the distant past are relevant to contemporary climate change. Factors that cause climate change can be divided into two categories - those related to natural processes and those related to human activity. In addition to natural causes of climate change, changes internal to the climate system, such as variations.

In ocean currents or atmospheric circulation, can also influence the climate for short periods of time. This natural internal climate variability is superimposed on the long-term forced climate change.

Does climate change have natural causes?

The Earth's climate can be affected by natural factors that are external to the climate system, such as changes in volcanic activity, solar output, and the Earth's orbit around the Sun. Of these, the two factors relevant on timescales of contemporary climate change are changes in volcanic activity and changes in solar radiation. In terms of the Earth's energy balance, these factors primarily influence the amount of incoming energy. Volcanic eruptions are episodic and have relatively short-term effects on climate.

Changes in solar irradiance have contributed to climate trends over the past century but since the Industrial Revolution, the effect of additions of greenhouse gases to the atmosphere has been over 50 times that of changes in the Sun's output.

Human causes

Climate change can also be caused by human activities, such as the burning of fossil fuels and the conversion of land for forestry and agriculture. Since the beginning of the Industrial Revolution, these human influences on the climate system have increased substantially. In addition to other environmental impacts, these activities change the land surface and emit various substances to the atmosphere. These in turn can influence both the amount of incoming energy and the amount of outgoing energy and can have both warming and cooling effects on the climate. The dominant product of fossil fuel combustion is carbon dioxide, a greenhouse gas. The overall effect of human activities since the Industrial Revolution has been a warming effect, driven primarily by emissions of carbon dioxide and enhanced by emissions of other greenhouse gases.

The build-up of greenhouse gases in the atmosphere has led to an enhancement of the natural greenhouse effect. It is this human-induced enhancement of the greenhouse effect that is of concern because ongoing emissions of greenhouse gases have the potential to warm the planet to levels that have never been experienced in the history of human civilization. Such climate change could have far-reaching and/or unpredictable environmental, social, and economic consequences.

Short-lived and long-lived climate forcers

Carbon dioxide is the main cause of human-induced climate change. It has been emitted in vast quantities from the burning of fossil fuels and it is a very long-lived gas, which means it continues to affect the climate system during its long residence time in the atmosphere. However, fossil fuel combustion, industrial processes, agriculture, and forestry-related activities emit other substances that also act as climate forcers. Some, such as nitrous oxide, are long-lived greenhouse gases like carbon dioxide, and so contribute to long-term climate change. Other substances have shorter atmospheric lifetimes because they are removed fairly quickly from the atmosphere. Therefore, their effect on the climate system is similarly short-lived. Together, these short-lived climate forcers are responsible for a significant amount of current climate forcing from anthropogenic substances. Some short-lived climate forcers have a climate warming effect (‘positive climate forcers') while others have a cooling effect (‘negative climate forcers').

If atmospheric levels of short-lived climate forcers are continually replenished by ongoing emissions, these continue to exert a climate forcing. However, reducing emissions will quite quickly lead to reduced atmospheric levels of such substances. A number of short-lived climate forcers have climate warming effects and together are the most important contributors to the human enhancement of the greenhouse effect after carbon dioxide. This includes methane and tropospheric ozone – both greenhouse gases – and black carbon, a small solid particle formed from the incomplete combustion of carbon-based fuels (coal, oil and wood for example).

Other short-lived climate forcers have climate cooling effects, most notably sulphate aerosols. Fossil fuel combustion emits sulphur dioxide into the atmosphere (in addition to carbon dioxide) which then combines with water vapour to form tiny droplets (aerosols) which reflect sunlight.

Sulphate aerosols remain in the atmosphere for only a few days (washing out in what is referred to as acid rain), and so do not have the same longterm effect as greenhouse gases. The cooling from sulphate aerosols in the atmosphere has, however, offset some of the warming from other substances. That is, the warming we have experienced to date would have been even larger had it not been for elevated levels of sulphate aerosols in the atmosphere.

Global climate indicators

Global climate indicators[1] reveal the ways in which the climate is changing and provide a broad view of the climate at the global scale. They are used to monitor the key components of the climate system and describe the most relevant changes in the composition of the atmosphere, the heat that arises from the accumulation of greenhouse gases (and other factors), and the responses of the land, ocean and ice to the changing climate. These indicators include global mean surface temperature, global ocean heat content, state of ocean acidification, glacier mass balance, Arctic and Antarctic sea-ice extent, global CO_2 mole fraction and global mean sea level and are discussed in detail in the sections below. Further information on the data sets used for each indicator can be found at the end of this report.

A variety of baselines are used in this report. For global mean temperature, the baseline is 1850–1900, which is the baseline used in the IPCC Special Report on Global Warming of 1.5 °C as an approximation of pre-industrial temperatures.[2] For greenhouse gases, pre-industrial concentrations estimated from ice cores for the year 1750 are used as baselines.

For other variables and for temperature maps, the WMO climatological standard normal 1981–2010 is used, where possible, as a base period for consistent reporting of surface measurements, satellite data and reanalyses. For some indicators, it is not possible to use this base period, either because there are no measurements in the early part of the period, or because a longer base period is needed to calculate a representative average. Where the base period used is different from 1981–2010, this is noted in the text or figure captions, and more details are given in the Data set details section.

TEMPERATURE

The global mean temperature for 2020 was 1.2 ± 0.1 °C above the 1850–1900 baseline (Figure 1), which places 2020 as one of the three warmest years on record globally. The WMO assessment is based on five global temperature data sets (Figure 1). All five of these data sets currently place 2020 as one of the three warmest years on record. The spread of the five estimates of the annual global mean ranges between 1.15 °C and 1.28 °C above pre-industrial levels (see the baseline definition in the Global climate indicators section). It is worth noting that the Paris Agreement aims to hold the global average temperature to well below 2 °C above

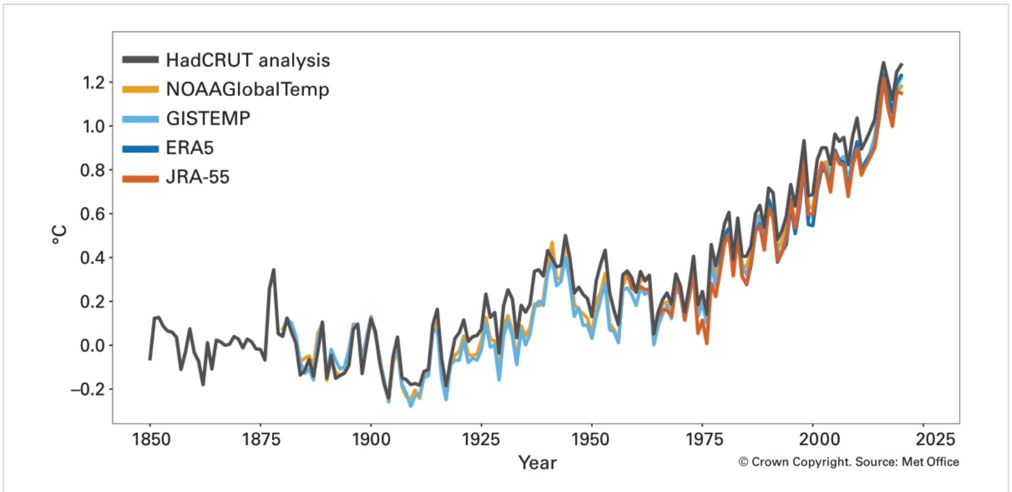


Figure 1. Global annual mean temperature difference from pre-industrial conditions (1850–1900) for five global temperature data sets. For details of the data sets and plotting, see Temperature data in the Data set details section at the end of this report.

[1] https://journals.ametsoc.org/view/journals/bams/aop/bamsD190196/bamsD190196.xml

[2] http://www.ipcc.ch/sr15/

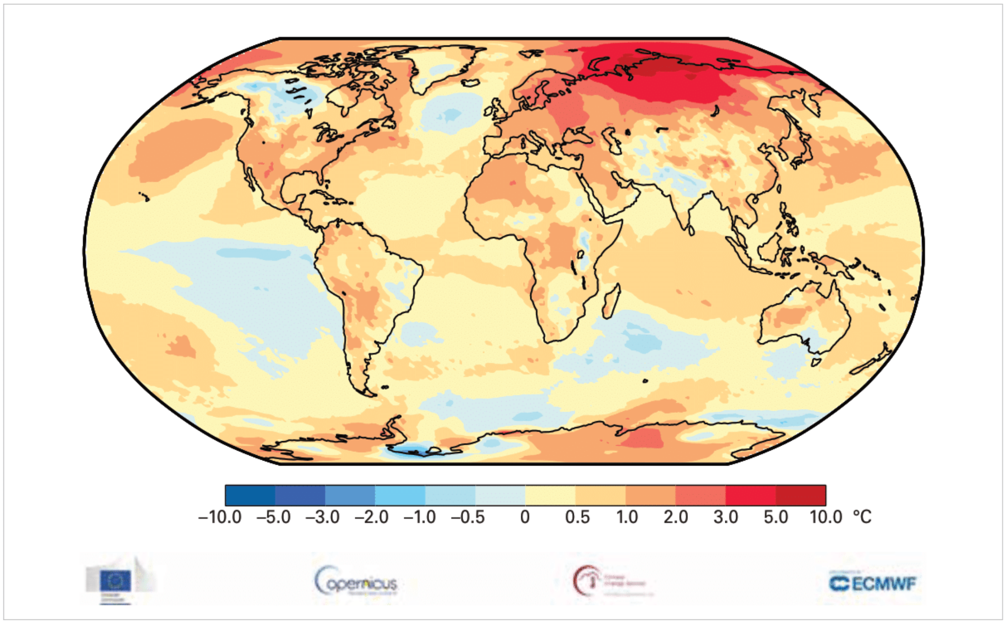


Figure 2. Temperature anomalies relative to the 1981–2010 long-term average from the ERA5 reanalysis for 2020. *Source:* Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts (ECMWF)

pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels[3]. Assessing the increase in global temperature in the context of climate change refers to the long-term global average temperature, not to the averages for individual years or months.

The warmest year on record to date, 2016, began with an exceptionally strong El Niño, a phenomenon which contributes to elevated global temperatures. Despite neutral or comparatively weak El Niño conditions early in 2020[4] and La Niña conditions developing by late September,[5] the warmth of 2020 was comparable to that of 2016.

With 2020 being one of the three warmest years on record, the past six years, 2015–2020, were the six warmest on record. The last five-year (2016–2020) and 10-year (2011–2020) averages were also the warmest on record.

Although the overall warmth of 2020 is clear, there were variations in temperature anomalies across the globe (Figure 2). While most land areas were warmer than the long-term average (1981–2010), one area in northern Eurasia stands out with temperatures of more than five degrees above average (see The Arctic in 2020). Other notable areas of warmth included limited areas of the south-western United States, the northern and western parts of South America, parts of Central America, and wider areas of Eurasia, including parts of China. For Europe, 2020 was the warmest year on record. Areas of below-average temperatures on land included western Canada, limited areas of Brazil, northern India, and south-eastern Australia.

Over the ocean, unusual warmth was observed in parts of the tropical Atlantic and Indian Oceans. The pattern of sea-surface temperature anomalies in the Pacific is characteristic of La Niña, having cooler-than-average surface waters in the eastern equatorial Pacific surrounded by a horseshoe-shaped band of warmer-than-average waters, most notably in the North-East Pacific and along the western edge of the Pacific from Japan to Papua New Guinea.

[3] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[4] https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

[5] http://www.bom.gov.au/climate/enso/wrap-up/archive/20200929.archive.shtml

GREENHOUSE GASES AND STRATOSPHERIC OZONE

GREENHOUSE GASES

Atmospheric concentrations of greenhouse gases reflect a balance between emissions from human activities and natural sources, and sinks in the biosphere and ocean. Increasing levels of greenhouse gases in the atmosphere due to human activities have been the major driver of climate change since the mid-twentieth century. Global average mole fractions of greenhouse gases are calculated from in situ observations made at multiple sites in the Global Atmosphere Watch Programme of WMO and partner networks.

In 2019, greenhouse gas concentrations reached new highs (Figure 3), with globally averaged mole fractions of carbon dioxide (CO_2) at 410.5 ± 0.2 parts per million (ppm), methane (CH_4) at 1 877 ± 2 parts per billion (ppb) and nitrous oxide (N_2O) at 332.0 ± 0.1 ppb, respectively, 148%, 260% and 123% of pre-industrial (before 1750) levels. The increase in CO_2 from 2018 to 2019 (2.6 ppm) was larger than both the increase from 2017 to 2018 (2.3 ppm) and the average yearly increase over the last decade (2.37 ppm per year). For CH_4, the increase from 2018 to 2019 was slightly lower than the increase from 2017 to 2018 but still higher than the average yearly increase over the last decade. For N_2O, the increase from 2018 to 2019 was also lower than that observed from 2017 to 2018 and close to the average growth rate over the past 10 years.

The temporary reduction in emissions in 2020 related to measures taken in response to COVID-19[6] is likely to lead to only a slight decrease in the annual growth rate of CO_2 concentration in the atmosphere, which will be practically indistinguishable from the natural interannual variability driven largely by the terrestrial biosphere. Real-time data from specific locations, including Mauna Loa (Hawaii) and Cape Grim (Tasmania) indicate that levels of CO_2, CH_4 and N_2O continued to increase in 2020.

The IPCC Special Report on Global Warming of 1.5 °C found that limiting warming to 1.5 °C

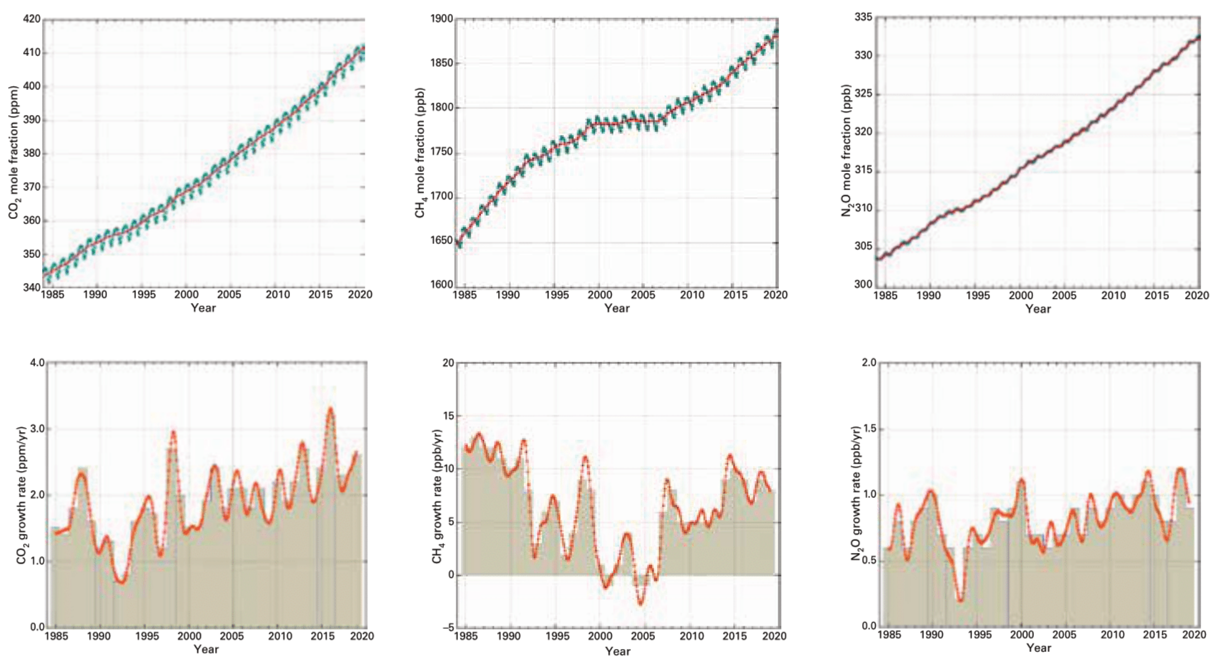


Figure 3. Top row: Globally averaged mole fraction (measure of concentration), from 1984 to 2019, of CO_2 in parts per million (left), CH_4 in parts per billion (centre) and N_2O in parts per billion (right). The red line is the monthly mean mole fraction with the seasonal variations removed; the blue dots and line show the monthly averages. Bottom row: The growth rates representing increases in successive annual means of mole fractions are shown as grey columns for CO_2 in parts per million per year (left), CH_4 in parts per billion per year (centre) and N_2O in parts per billion per year (right).
Source: WMO Global Atmosphere Watch

[6] Liu, Z. et al., 2020: Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic. *Nature Communications*, 11(1): 5172, https://doi.org/10.1038/s41467-020-18922-7.

above pre-industrial levels implies reaching net zero CO_2 emissions globally by around 2050, with concurrent deep reductions in emissions of non-CO_2 forcers.

STRATOSPHERIC OZONE AND OZONE-DEPLETING GASES

Following the success of the Montreal Protocol, the use of halons and chlorofluorocarbons has been reported as discontinued, but their levels in the atmosphere continue to be monitored. Because of their long lifetime, these compounds will remain in the atmosphere for many decades, and even if there are no new emissions, there is still more than enough chlorine and bromine present in the atmosphere to cause the complete destruction of ozone in Antarctica from August to December. As a result, the formation of the Antarctic ozone hole continues to be an annual spring event, with the year-to-year variation in its size and depth governed to a large degree by meteorological conditions.

The 2020 Antarctic ozone hole developed early and went on to be the longest-lasting and one of the deepest ozone holes since ozone layer monitoring began 40 years ago (Figure 4). The ozone hole area reached its maximum area for 2020 on 20 September at 24.8 million km^2, the same area as was reached in 2018. The area of the hole was closer to the maxima observed in 2015 (28.2 million km^2) and 2006 (29.6 million km^2) than the maximum that was reached in 2019 (16.4 million km^2) according to an analysis from the National Aeronautics and Space Administration (NASA). The unusually deep and long-lived ozone hole was driven by a strong and stable polar vortex and very low temperatures in the stratosphere.

At the other end of the Earth, unusual atmospheric conditions also led to ozone concentrations over the Arctic falling to a record low for the month of March. Unusually weak "wave" events in the upper atmosphere left the polar vortex relatively undisturbed, preventing the mixing of ozone-rich air from lower latitudes. In addition, early in the year, the stratospheric polar vortex over the Arctic was strong, and this, combined with consistently very low temperatures, allowed a large area of polar stratospheric clouds to grow. When the sun rises after the polar winter, it triggers chemical processes in the polar stratospheric clouds that lead to the depletion of ozone. Measurements from weather balloons indicated that ozone depletion surpassed the levels reported in 2011 and, together with satellite observations, documented stratospheric ozone levels of approximately 205 Dobson Units on 12 March 2020. The typical lowest ozone values previously observed over the Arctic in March are at least 240 Dobson Units.

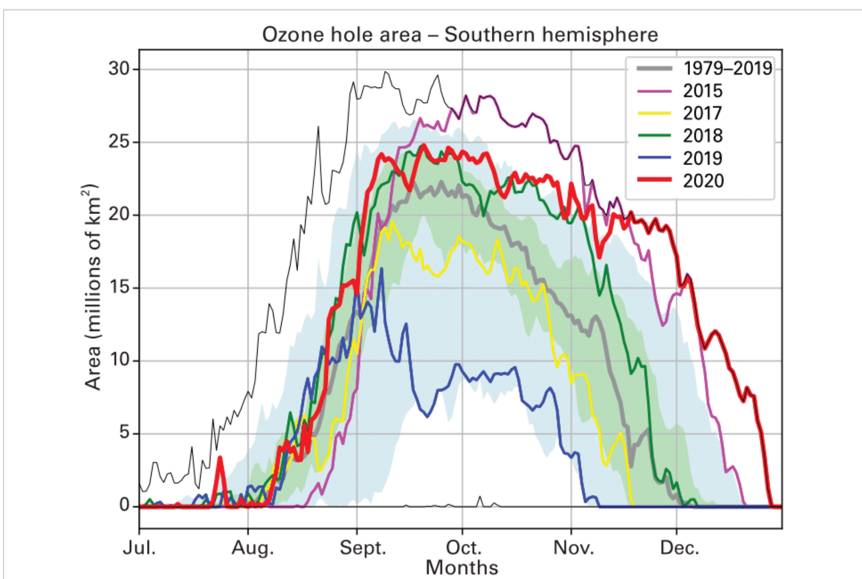


Figure 4. Area (millions of km^2) where the total ozone column is less than 220 Dobson units. 2020 is shown in red, and the most recent years are shown for comparison as indicated by the legend. The thick grey line is the 1979–2019 average. The blue shaded area represents the 30th to 70th percentiles, and the green shaded area represents the 10th and 90th percentiles for the period 1979–2019. The thin black lines show the maximum and minimum values for each day in the 1979–2019 period. The plot was made at WMO on the basis of data downloaded from NASA Ozone Watch (https://ozonewatch.gsfc.nasa.gov/). The NASA data are based on satellite observations from the OMI and TOMS instruments.

OCEAN

The majority of the excess energy that accumulates in the Earth system due to increasing concentrations of greenhouse gases is taken up by the ocean. The added energy warms the ocean, and the consequent thermal expansion of the water leads to sea-level rise, which is further increased by melting ice. The surface of the ocean warms more rapidly than the interior, and this can be seen in the rise of the global mean temperature and in the increased incidence of marine heatwaves. As the concentration of CO_2 in the atmosphere rises, so too does the concentration of CO_2 in the oceans. This affects ocean chemistry, lowering the average pH of the water, a process known as ocean acidification. All these changes have a broad range of impacts in the open ocean and coastal areas.

OCEAN HEAT CONTENT

Increasing human emissions of CO_2 and other greenhouse gases cause a positive radiative imbalance at the top of the atmosphere – the Earth Energy Imbalance (EEI) – which is driving global warming through an accumulation of energy in the form of heat in the Earth system.[7,8,9] Ocean heat content (OHC) is a measure of this heat accumulation in the Earth system as around 90% of it is stored in the ocean. A positive EEI signals that the Earth's climate system is still responding to the current forcing[10] and that more warming will occur even if the forcing does not increase further.[11]

Historical measurements of subsurface temperature back to the 1940s mostly rely on shipboard measurement systems, which constrain the availability of subsurface temperature observations at the global scale and at depth.[12] With the deployment of the Argo network of autonomous profiling floats, which first achieved near-global coverage in 2006, it is now possible to routinely measure OHC changes to a depth of 2000 m.[13,14]

Various research groups have developed estimates of global OHC. Although they all rely more or less on the same database, the estimates show differences arising from the various statistical treatments of data gaps, the choice of climatology and the approach used to account for instrumental biases.[9,15] A concerted effort has been established to provide an international assessment on the global evolution of ocean warming,[16] and an

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[7] Hansen, J. et al., 2005: Earth's Energy Imbalance: Confirmation and Implications. *Science,* 308(5727): 1431–1435, https://doi.org/10.1126/science.1110252.

[8] Intergovernmental Panel on Climate Change, 2013: *Climate change 2013: The Physical Science Basis*, https://www.ipcc.ch/report/ar5/wg1/.

[9] von Schuckmann, K. et al., 2016: An imperative to monitor Earth's energy imbalance. *Nature Climate Change,* 6(2): 138–144, https://doi.org/10.1038/nclimate2876.

[10] Hansen, J. et al., 2011: EEarth's energy imbalance and implications. *Atmospheric Chemistry and Physics*, 11(24): 13421–13449, https://doi.org/10.5194/acp-11-13421-2011.

[11] Hansen, J. et al., 2017: Young people's burden: requirement of negative CO_2 emissions. *Earth System Dynamics*, 8(3): 577–616, https://doi.org/10.5194/esd-8-577-2017.

[12] Abraham, J.P. et al., 2013: A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Reviews of Geophysics*, 51(3): 450–483, https://doi.org/10.1002/rog.20022.

[13] Riser, S.C. et al., 2016: Fifteen years of ocean observations with the global Argo array. *Nature Climate Change*, 6(2): 145–153, https://doi.org/10.1038/nclimate2872.

[14] Roemmich, D. et al., 2019: On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array. *Frontiers in Marine Science*, 6, https://doi.org/10.3389/fmars.2019.00439.

[15] Boyer, T. et al., 2016: Sensitivity of Global Upper-Ocean Heat Content Estimates to Mapping Methods, XBT Bias Corrections, and Baseline Climatologies. *Journal of Climate*, 29(13): 4817–4842, https://doi.org/10.1175/JCLI-D-15-0801.1.

[16] von Schuckmann, K. et al., 2020: Heat stored in the Earth system: where does the energy go? *Earth System Science Data*, 12(3): 2013–2041, https://doi.org/10.5194/essd-12-2013-2020.

update of the entire analysis to 2019 is shown in Figure 5 and Figure 6.

The 0–2 000 m depth layer of the global ocean continued to warm in 2019, reaching a new record high (Figure 5), and it is expected that it will continue to warm in the future.[17] A preliminary analysis based on three global data sets suggests that 2020 exceeded that record. Heat storage at intermediate depth (700–2 000 m) increased at a comparable rate to the rate of heat storage in the 0–300 m depth layer, which is in general agreement with the 15 international OHC estimates (Figure 6). All data sets agree that ocean warming rates show a particularly strong increase over the past two decades. Moreover, there is a clear indication that

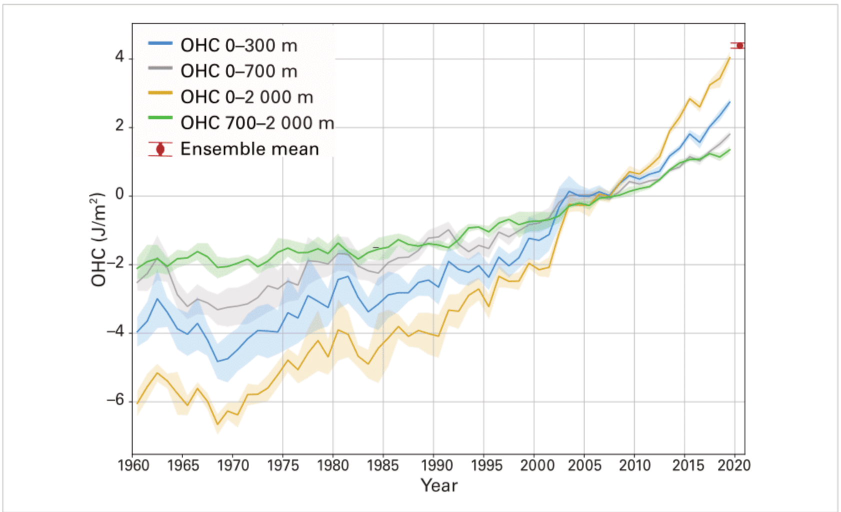

Figure 5. 1960–2019 ensemble mean time series and ensemble standard deviation (2-sigma, shaded) of global OHC anomalies relative to the 2005–2017 climatology. The ensemble mean is an outcome of a concerted international effort, and all products used are listed in Ocean heat content data and in the legend of Figure 5. Note that values are given for the ocean surface area between 60°S–60°N and limited to the 300 m bathymetry of each product. *Source:* Updated from von Schuckmann, K. et al., 2016 (see footnote 9). The ensemble mean OHC (0–2000 m) anomaly (relative to the 1993–2020 climatology) has been added as a red point, together with its ensemble spread, and is based on Copernicus Marine Environment Monitoring Service (CMEMS) (Coriolis Ocean Dataset for Reanalysis (CORA)) products (see Cheng et al., 2017 and Ishii et al., 2017 in Ocean heat content data).

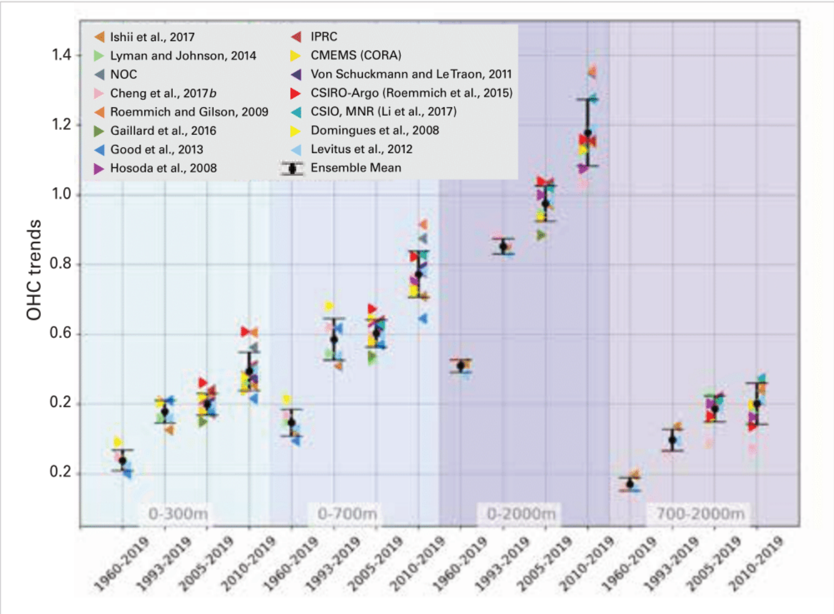

Figure 6. Linear trends of global OHC as derived from different temperature products (colours). References are listed in Ocean heat content data. The ensemble mean and standard deviation (2-sigma) is given in black. The shaded areas show trends from different depth layer integrations: 0–300 m (light turquoise), 0–700 m (light blue), 0–2 000 m (purple) and 700–2 000 m (light purple). For each integration depth layer, trends are evaluated over four periods: historical (1960–2019), altimeter era (1993–2019), golden Argo era (2005–2019), and the most recent period of 2010–2019. *Source:* Updated from von Schuckmann, K. et al., 2016 (see footnote 9).

[17] Intergovernmental Panel on Climate Change, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, https://www.ipcc.ch/srocc/.

heat sequestration into the ocean below 700 m depth has occurred over the past six decades and is linked to an increase in OHC trends over time. Ocean warming rates for the 0–2 000 m depth layer reached rates of 1.2 (0.8) ± 0.2 Wm^{-2} over the period 2010–2019. Below 2 000 m depth, the ocean also warmed, albeit at the lower rate of 0.07 ± 0.04 Wm^{-2} from 1991 to 2018.[18]

SEA LEVEL

On average, since early 1993, the altimetry-based global mean rate of sea-level rise has amounted to 3.3 ± 0.3 mm/yr. The rate has also increased over that time. A greater loss of ice mass from the ice sheets is the main cause of the accelerated rise in global mean sea level.[19]

Global mean sea level continued to rise in 2020 (Figure 7, left). A small decrease during the northern hemisphere summer was likely related to La Niña conditions in the tropical Pacific. Interannual changes of global mean sea level around the long-term trend are correlated with El Niño–Southern Oscillation (ENSO) variability (Figure 7, right). During La Niña events, such as that which occurred in late 2020 and the strong La Niña of 2011, shifts in rainfall patterns transfer water mass from the ocean to tropical river basins on land, temporarily reducing global mean sea level. The opposite is observed during El Niño (for example, the strong 2015/2016 El Niño). In 2020, exceptional rainfall across the African Sahel and other regions may also have contributed to a temporary slowing in sea-level rise as flood waters slowly found their way back to the sea. However, by the end of 2020, global mean sea level was rising again.

At the regional scale, sea level continues to rise non-uniformly. The strongest regional trends over the period from January 1993 to June 2020 were seen in the southern hemisphere: east of Madagascar in the Indian Ocean; east of New Zealand in the Pacific Ocean; and east of Rio de la Plata/South America in the South Atlantic Ocean. An elongated eastward pattern was also seen in the North Pacific Ocean. The strong pattern that was seen in the western tropical Pacific Ocean over the first two decades of the altimetry record is now fading, suggesting that it was related to short-term variability. Regional sea-level trends are dominated by variations in ocean heat content.[17] However, in some regions, such as the Arctic, salinity changes due to freshwater input from the melting of ice on land play an important role.

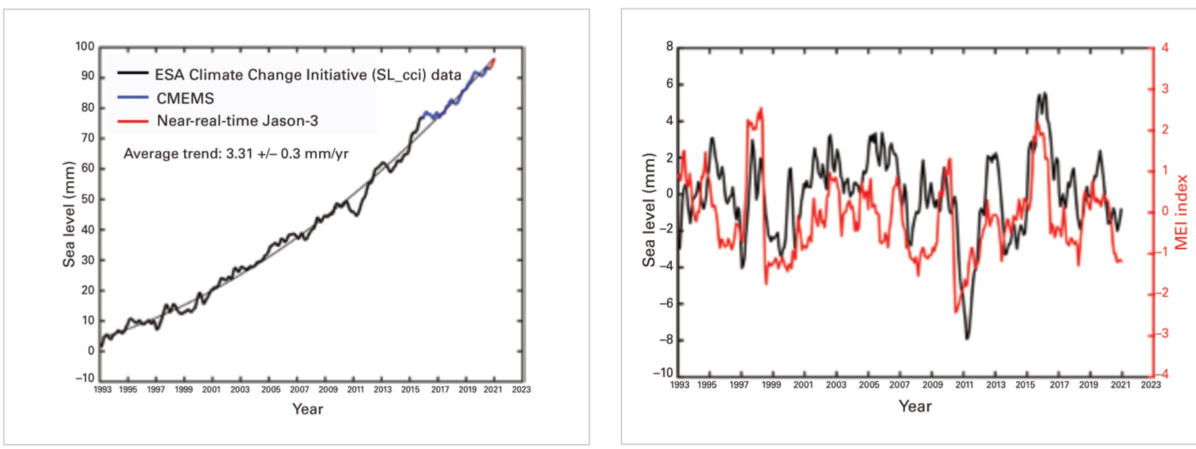

Figure 7. Left: Satellite altimetry-based global mean sea level for January 1993 to January 2021 (last data: 21 January 2021). Data from the European Space Agency Climate Change Initiative Sea Level project (January 1993 to December 2015, thick black curve), data from CMEMS (January 2016 to November 2020, blue curve) and near-real-time altimetry data from the Jason-3 mission beyond November 2020 (red curve). The thin black curve is a quadratic function that best fits the data. Right: Interannual variability of the global mean sea level (with the quadratic function shown in the left-hand panel subtracted) (black curve and left axis) with the multivariate ENSO index (MEI) (red curve and right axis).

[18] Update from Purkey, S.G. and G.C. Johnson, 2010: Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. *Journal of Climate*, 23(23): 6336–6351, https://doi.org/10.1175/2010JCLI3682.1.

[19] WCRP Global Sea Level Budget Group, 2018: Global sea-level budget 1993–present. *Earth System Science Data*, 10(3): 1551–1590, https://doi.org/10.5194/essd-10-1551-2018.

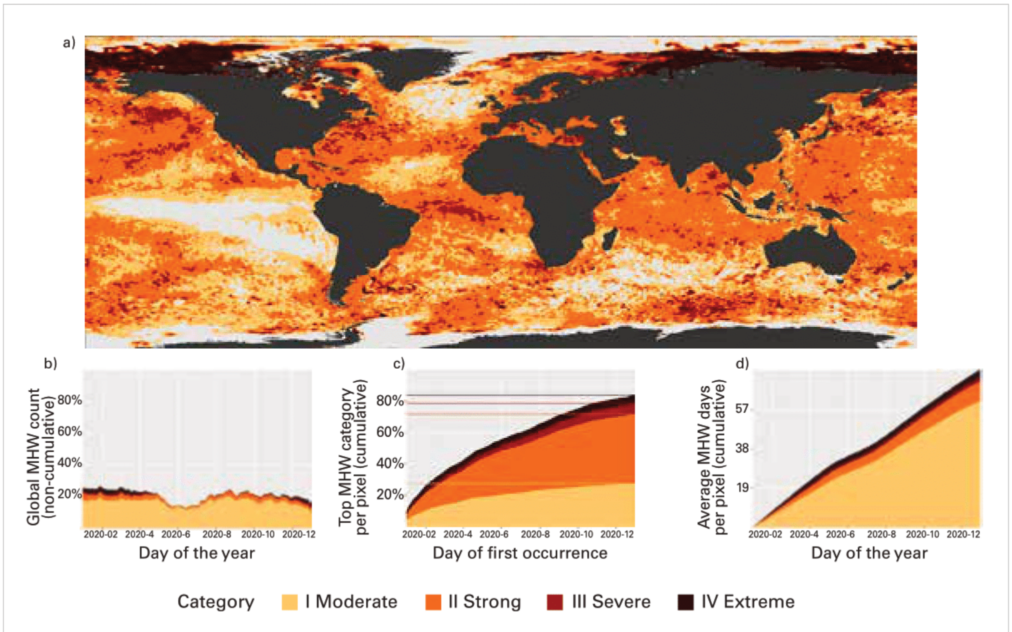

Figure 8. (a) Global map showing the highest MHW category (for definitions, see Marine heatwave data) experienced at each pixel over the course of the year (reference period 1982–2011). Light grey indicates that no MHW occurred in a pixel over the entire year; (b) Stacked bar plot showing the percentage of ocean pixels experiencing an MHW on any given day of the year; (c) Stacked bar plot showing the cumulative percentage of the ocean that experienced an MHW over the year. Note: These values are based on when in the year a pixel first experienced its highest MHW category, so no pixel was counted more than once. Horizontal lines in this figure show the final percentages for each category of MHW; (d) Stacked bar plot showing the cumulative number of MHW days averaged over all pixels in the ocean. Note: This average is calculated by dividing the cumulative number of MHW days per pixel for the entire ocean by the overall number of ocean pixels (~690 000). *Source:* Robert Schlegel

MARINE HEATWAVES

As with heatwaves on land, extreme heat can affect the near-surface layer of the oceans. This situation is called a marine heatwave (MHW), and it can cause a range of consequences for marine life and dependent communities. Satellite retrievals of sea-surface temperature can be used to monitor MHWs. An MHW is categorized here as moderate, strong, severe or extreme (for definitions, see Marine heatwave data).

Much of the ocean experienced at least one 'strong' MHW at some point in 2020 (Figure 8a). Conspicuously absent are MHWs in the Atlantic Ocean south of Greenland and in the eastern equatorial Pacific Ocean. The Laptev Sea experienced a particularly intense MHW from June to December. Sea-ice extent was unusually low in that region, and adjacent land areas experienced heatwaves during the summer (see The Arctic in 2020). Another important MHW to note in 2020 was the return of the semi-persistent warm region in the North-East Pacific Ocean. This event is similar in scale to the original 'blob',[20,21] which developed around 2013, with remnants lasting until 2016.[22] Approximately one fifth of the global ocean was experiencing an MHW on any given day in 2020 (Figure 8b). This percentage is similar to that of 2019, but less than the 2016 peak percentage of 23%. More of the ocean experienced MHWs classified as 'strong' (45%) than 'moderate' (28%). In total, 84% of the ocean experienced at least one MHW during 2020 (Figure 8c); this is similar to the percentage of the ocean that experienced MHWs in 2019 (also 84%), but below the 2016 peak (88%).

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[20] Gentemann, C.L. et al., 2017: Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. *Geophysical Research Letters*, 44(1): 312–319, https://doi.org/10.1002/2016GL071039.

[21] di Lorenzo, E. and N. Mantua, 2016: Multi-Year Persistence of the 2014/15 North Pacific Marine Heatwave. *Nature Climate Change*, 6: 1042–1047, https://doi.org/10.1038/nclimate3082.

[22] Schmeisser, L. et al., 2019: The Role of Clouds and Surface Heat Fluxes in the Maintenance of the 2013–2016 Northeast Pacific Marine Heatwave. *Journal of Geophysical Research: Atmospheres*, 124(20): 10772–10783, https://doi.org/10.1029/2019JD030780.

Figure 9. Left: Surface pH values based on ocean acidification data submitted to the 14.3.1 data portal (http://oa.iode.org) for the period from 1 January 2010 to 8 January 2020. The grey circles represent the calculated pH of data submissions (including all data sets with data for at least two carbonate parameters); the blue circles represent the average annual pH (based on data sets with data for at least two carbonate parameters); the red circles represent the annual minimum pH and the green circles represent the annual maximum pH. Note that the number of stations is not constant with time. Right: Global mean surface pH from E.U. Copernicus Marine Service Information (blue). The shaded area indicates the estimated uncertainty in each estimate.

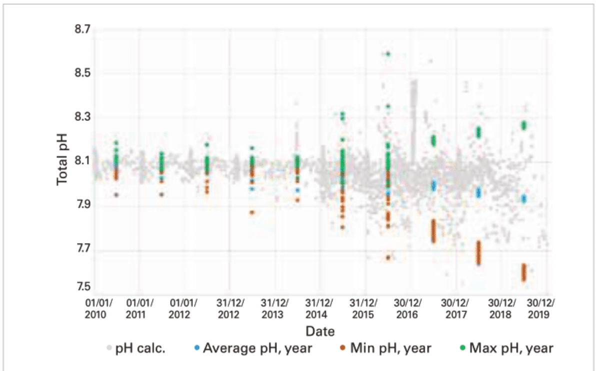
OCEAN ACIDIFICATION

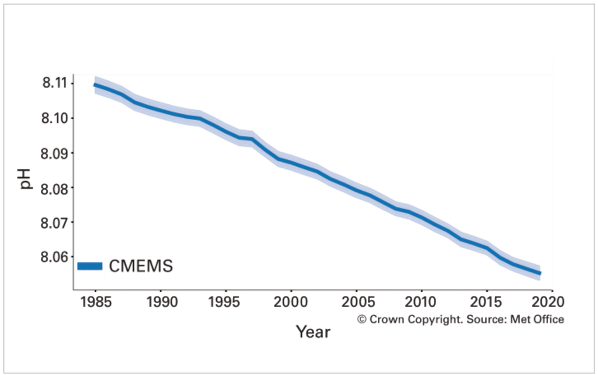
The ocean absorbs around 23% of the annual emissions of anthropogenic CO_2 into the atmosphere,[23] thereby helping to alleviate the impacts of climate change.[24] However, the CO_2 reacts with seawater, lowering its pH. This process, known as ocean acidification, affects many organisms and ecosystem services, threatening food security by endangering fisheries and aquaculture. This is particularly a problem in the polar oceans. It also affects coastal protection by weakening coral reefs, which shield coastlines. As the pH of the ocean declines, its capacity to absorb CO_2 from the atmosphere decreases, diminishing the ocean's capacity to moderate climate change. Regular global observations and measurements of ocean pH are needed to improve the understanding of the consequences of its variations, enable modelling and prediction of change and variability, and help inform mitigation and adaptation strategies.

Global efforts have been made to collect and compare ocean acidification observation data. These data contribute towards achieving Sustainable Development Goal (SDG) 14.3 and can be used to determine its associated SDG Indicator 14.3.1: "Average marine acidity (pH) measured at agreed suite of representative sampling stations". They are summarized in Figure 9 (left) and show an increase of variability (minimum and maximum pH values are highlighted) and a decline in average pH at the available observing sites between 2015 and 2019. The steady global change (Figure 9, right) estimated from a wide variety of sources, including measurements of other variables, contrasts with the regional and seasonal variations in ocean carbonate chemistry seen at individual sites. The increase in the amount of available data highlights the variability and the trend in ocean acidification, as well as the need for sustained long-term observations to better characterize the natural variability in ocean carbonate chemistry.

DEOXYGENATION

Since 1950, the open ocean oxygen content has decreased by 0.5–3%.[17] Oxygen minimum zones, which are permanent features of the open ocean, are expanding.[25] The trend of deoxygenation in the global coastal ocean is still uncertain. Since 1950, the number of hypoxic sites in the global coastal ocean has increased in response to worldwide eutrophication.[26] A quantitative assessment of the severity of





[23] World Meteorological Organization, 2019: *WMO Greenhouse Gas Bulletin: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2018*, No. 15, https://library.wmo.int/index.php?lvl=notice_display&id=21620.

[24] Friedlingstein, P. et al., 2020: Global Carbon Budget 2020. *Earth System Science Data*, 12(4): 3269–3340, https://doi.org/10.5194/essd-12-3269-2020.

[25] Breitburg, D.et al., 2018: Declining oxygen in the global ocean and coastal waters. *Science (New York, N.Y.)*, 359(6371), https://doi.org/10.1126/science.aam7240.

[26] Diaz, R.J. and R. Rosenberg, 2008: Spreading Dead Zones and Consequences for Marine Ecosystems. *Science*, 321(5891): 926–929, https://doi.org/10.1126/science.1156401.

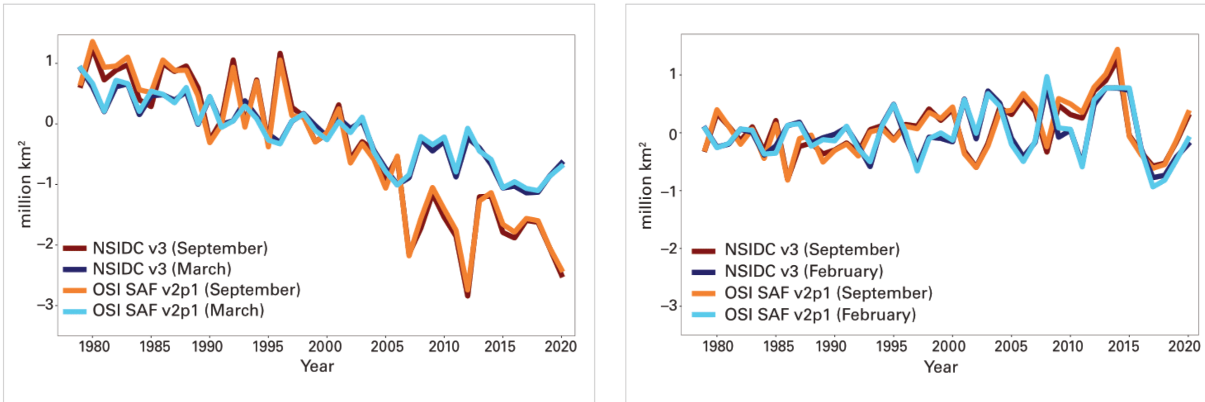


Figure 10. Sea-ice extent difference from the 1981–2010 average in the Arctic (left) and Antarctic (right) for the months with maximum ice cover (Arctic: March; Antarctic: September) and minimum ice cover (Arctic: September; Antarctic: February). *Source:* Data from EUMETSAT OSI SAF v2p1 (Lavergne et al., 2019) and National Snow and Ice Data Centre (NSIDC) v3 (Fetterer et al., 2017) (see reference details in Sea-ice data).

hypoxia on marine life at the global coastal scale requires characterizing the dynamics of hypoxia, for which there is currently insufficient data.

A comprehensive assessment of deoxygenation in the open and coastal ocean would benefit from building a consistent, quality-controlled, open-access global ocean oxygen data set and atlas complying with the FAIR[27] principles. An effort in this direction has been initiated by the Global Ocean Oxygen Network (GO$_2$NE), the International Ocean Carbon Coordination Project (IOCCP), the National Oceanic and Atmospheric Administration (NOAA) and the German Collaborative Research Centre 754 (SFB 754) project. This effort is part of the Global Ocean Oxygen Decade (GOOD) proposal submitted to the United Nations Decade of Ocean Sciences for Sustainable Development.

CRYOSPHERE

The cryosphere is the domain that comprises the frozen parts of the earth. The cryosphere provides key indicators of the changing climate, but it is one of the most under-sampled domains. The major cryosphere indicators used in this report are sea-ice extent, glacier mass balance and mass balance of the Greenland and Antarctic ice sheets. Specific snow events are covered in the High-impact events in 2020 section.

SEA ICE

In the Arctic, the annual minimum sea-ice extent in September 2020 was the second lowest on record, and record low sea-ice extent was observed in the months of July and October. The sea-ice extents in April, August, November, and December were among the five lowest in the 42-year satellite data record. For more details on the data sets used, see Sea-ice data.

In the Arctic, the maximum sea-ice extent for the year was reached on 5 March 2020. At just above 15 million km^2, this was the 10th or 11th (depending on the data set used) lowest maximum extent on record.[28] Sea-ice retreat in late March was mostly in the Bering Sea. In April, the rate of decline was similar to that of recent years, and the mean sea-ice extent for April was between the second and fourth lowest on record, effectively tied with 2016, 2017, and 2018 (Figure 10).

Record high temperatures north of the Arctic Circle in Siberia (see The Arctic in 2020) triggered an acceleration of sea-ice melt in the East Siberian and Laptev Seas, which continued well into July. The sea-ice extent for July was the lowest on record (7.28 million km^2).[29] The sea-ice retreat in the Laptev Sea was the earliest observed in the satellite era. Towards the end of July, a cyclone entered the Beaufort Sea and spread

[27] FAIR principles: https://www.go-fair.org/fair-principles/

[28] http://nsidc.org/arcticseaicenews/2020/03/

[29] https://cryo.met.no/en/arctic-seaice-summer-2020, https://nsidc.org/arcticseaicenews/2020/08/steep-decline-sputters-out/

the sea ice out, temporarily slowing the decrease of the ice extent. In mid-August, the area affected by the cyclone melted rapidly, which, combined with the sustained melt in the East Siberian and Laptev Seas, made the August extent the 2nd or 3rd lowest on record.

The 2020 Arctic sea-ice extent minimum was observed on 15 September to be 3.74 million km^2, marking only the second time on record that the Arctic sea-ice extent shrank to less than 4 million km^2. Only 2012 had a lower minimum extent at 3.39 million km^2. Vast areas of open ocean were observed in the Chukchi, East Siberian, Laptev, and Beaufort Seas, notwithstanding a tongue of multi-year ice that survived the 2020 melt season in the Beaufort Sea (Figure 13).[30]

Refreeze was slow in late September and October in the Laptev and East Siberian Seas, probably due to the heat accumulated in the upper ocean since the early retreat in late June. The Arctic sea-ice extent was the lowest on record for October and November. December sea-ice growth was faster than average, but the extent remained the second or third lowest on record for the month.

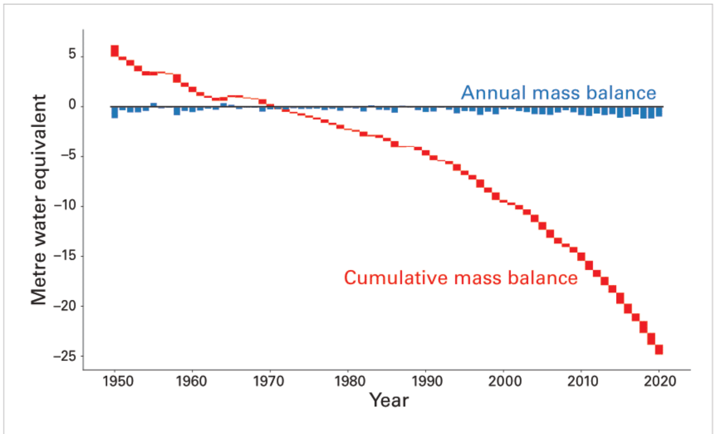
Interannual variability in the annual mean extent of Antarctic sea ice has increased since 1979. For the first 20 years of measurements from 1979 to 1999, there was no significant trend; however, around 2002, the total extent began to increase, reaching a maximum of 12.8 million km^2 in 2014. This was followed by a remarkable decrease over the next three years to a record minimum of 10.7 million km^2 in 2017. The decrease occurred in all sectors but was greatest in the Weddell Sea sector.

In 2020, the Antarctic sea ice extent increased to 11.5 million km^2, only 0.14 million km^2 below the long-term mean. Indeed, extents were close to the long-term mean in all sectors. The Bellingshausen Sea sector had its lowest extent on record in July 2020, but the extent was closer to the mean later in the year.

The Antarctic sea-ice extent in January 2020 showed only a modest increase from the very low values of the previous years, but February 2020 saw a return to less extreme conditions. During the autumn and winter of 2020, the Antarctic sea-ice extent was mostly close to the long-term mean but with positive ice extent anomalies near the maximum in September and October.

The minimum Antarctic sea ice extent in 2020 was around 2.7 million km^2. This occurred between 19 February and 2 March (depending on the data set) and was the seventeenth lowest minimum in the record. It reflected the gradual increase from the record minimum extent of 2.08 million km^2 on 1 March 2017. The maximum extent of the Antarctic sea ice in 2020 was around 19 million km^2 and was observed between 26 and 28 September. This was the thirteenth largest extent in the 42-year record.

Figure 11. Annual (blue) and cumulative (red) mass balance of reference glaciers with more than 30 years of ongoing glaciological measurements. Global mass balance is based on an average for 19 regions to minimize bias towards well-sampled regions. Annual mass changes are expressed in metre water equivalent (m w.e.), which corresponds to tons per square metre (1 000 kg m^{-2}). *Source:* World Glacier Monitoring Service, 2021, updated



GLACIERS

Glaciers are formed from snow that has compacted to form ice, which can deform and flow downhill to lower, warmer altitudes, where it melts, or if the glacier terminates in the ocean, breaks up, forming icebergs. Glaciers are sensitive to changes in temperature, precipitation and incoming solar radiation, as well as other factors, such as changes in basal lubrication or the loss of buttressing ice shelves.

According to the World Glacier Monitoring Service (Figure 11), in the hydrological year 2018/2019, the roughly 40 glaciers with

[30] https://cryo.met.no/en/arctic-seaice-september-2020

long-term observations experienced an ice loss of 1.18 metre water equivalent (m w.e.), close to the record loss set in 2017/2018. Despite the global pandemic, observations for 2019/2020 were able to be collected for the majority of the important glacier sites worldwide, although some data gaps will be inevitable. Preliminary results for 2020, based on a subset of evaluated glaciers, indicate that glaciers continued to lose mass in the hydrological year 2019/2020. However, mass balance was slightly less negative, with an estimated ice loss of 0.98 m w.e.

The lower rates of glacier mass change are attributed to more moderate climate forcing in some regions, for example in Scandinavia, High Mountain Asia and, to a lesser extent, North America. Lower rates are in some cases explained by high winter precipitation. Most other regions, such as the European Alps or New Zealand, showed strong glacier mass loss, albeit less than in the two preceding years. In contrast, there are indications that glaciers in the Arctic, which account for a large area, were subject to substantially increased melting, but data are still too scarce to establish the overall signal. Although the hydrological year 2019/2020 was characterized by somewhat less negative glacier mass balances in many parts of the Earth, there is a clear trend towards accelerating glacier mass loss in the long term, which is also confirmed by large-scale remote sensing studies. Eight out of the ten most negative mass balance years have been recorded since 2010.

ICE SHEETS

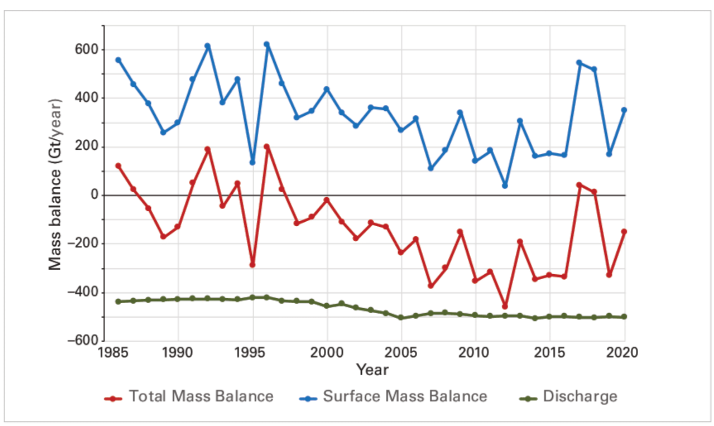
Despite the exceptional warmth in large parts of the Arctic, in particular the very unusual temperatures that were observed in eastern Siberia, temperatures over Greenland in 2020 were close to the long-term mean (Figure 2). The Greenland ice sheet ended the September 2019 to August 2020 season with an overall loss of 152 Gt of ice. This loss was a result of surface melting, the discharge of icebergs and the melting of glacier tongues by warm ocean water (Figure 12) and although significant, was less than the loss of ice in the previous year (329 Gt).

Changes in the mass of the Greenland ice sheet reflect the combined effects of the surface mass balance (SMB) – defined as the difference between snowfall and run-off from the ice sheet, which is always positive at the end of the year – and mass losses at the periphery from the calving of icebergs and the melting of glacier tongues that meet the ocean. The 2019/2020 Greenland SMB was +349 Gt of ice, which is close to the 40-year average of +341 Gt. However, ice loss due to iceberg calving was at the high end of the 40-year satellite record. The Greenland SMB record is now four decades long and, although it varies from one year to another, there has been an overall decline in the average SMB over time (Figure 12). In the 1980s and 1990s, the average SMB gain was about +416 Gt/year. It fell to +270 Gt/year in the 2000s and +260 Gt/year in the 2010s.

The GRACE satellites and the follow-on mission GRACE-FO measure the tiny change of the gravitational force due to changes in the amount of ice. This provides an independent measure of the total mass balance. Based on this data, it can be seen that the Greenland ice sheet lost about 4 200 Gt from April 2002 to August 2019, which contributed to a sea-level rise of slightly more than 1 cm. This is in good agreement with the mass balance from SMB and discharge, which was 4 261 Gt during the same period.

The 2019/2020 melt season on the Greenland ice sheet started on 22 June, 10 days later than the 1981–2020 average. As in previous seasons, there were losses along the Greenlandic west coast and gains in the east. In mid-August, unusually large storms

Figure 12. Components of the total mass balance of the Greenland ice sheet for the period 1986–2020. Blue: surface mass balance (http://polarportal.dk/en/greenland/surface-conditions/), green: discharge, red: total mass balance (the sum of the surface mass balance and discharge). *Source:* Mankoff, K.D. et al., 2020: Greenland Ice Sheet solid ice discharge from 1986 through March 2020. *Earth System Science Data*, 12(2): 1367–1383, https://doi.org/10.5194/essd-12-1367-2020.



The Arctic in 2020

The Arctic has been undergoing drastic changes as the global temperature has increased. Since the mid-1980s, Arctic surface air temperatures have warmed at least twice as fast as the global average, while sea ice, the Greenland ice sheet and glaciers have declined over the same period and permafrost temperatures have increased. This has potentially large implications not only for Arctic ecosystems, but also for the global climate through various feedbacks.[a]

In 2020, the Arctic stood out as the region with the largest temperature deviations from the long-term average. Contrasting conditions of ice, heat and wildfires were seen in the eastern and western Arctic (Figure 13). A strongly positive phase of the Arctic Oscillation during the 2019/2020 winter set the scene early in the year, with higher-than-average temperatures across Europe and Asia and well-below-average temperatures in Alaska, a pattern which persisted throughout much of the year.

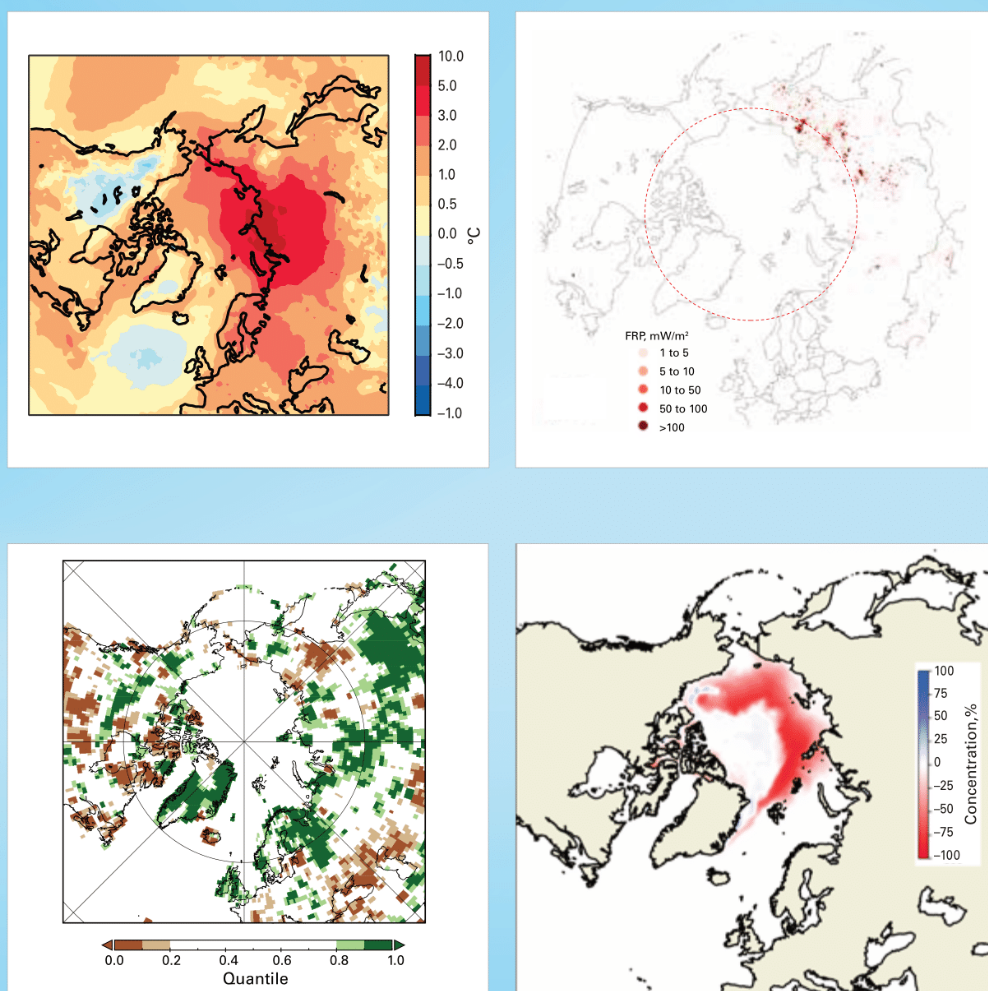


Figure 13. Top left: Temperature anomalies for the Arctic relative to the 1981–2010 long-term average from the ERA5 reanalysis for 2020. *Source:* Copernicus Climate Change Service, ECMWF

Top right: Fire Radiative Power, a measure of heat output from wildfires, in the Arctic Circle between June and August 2020. *Source:* Copernicus Atmosphere Monitoring Service, ECMWF

Bottom left: Total precipitation in 2020, expressed as a percentile of the 1951–2010 reference period, for areas that would have been in the driest 20% (brown) and wettest 20% (green) of years during the reference period, with darker shades of brown and green indicating the driest and wettest 10%, respectively. *Source:* Global Precipitation Climatology Centre (GPCC)

Bottom right: Sea-ice concentration anomaly for September 2020. *Source:* EUMETSAT OSI SAF v2p1 data, with research and development input from the European Space Agency Climate Change Initiative (ESA CCI)

[a] Intergovernmental Panel on Climate Change, 2019: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, https://www.ipcc.ch/srocc/.

In a large region of the Siberian Arctic, temperature anomalies for 2020 were more than 3 °C, and in its central coastal parts, more than 5 °C above average (Figure 13). A preliminary record temperature of 38 °C was set for north of the Arctic Circle, on 20 June in Verkhoyansk,[b] during a prolonged heatwave. Heatwaves and heat records were also observed in other parts of the Arctic (see High-impact events in 2020), and extreme heat was not confined to the land. A marine heatwave affected large areas of the Arctic Ocean north of Eurasia (Figure 8). Sea ice in the Laptev Sea, offshore from the area of highest temperature anomalies on land, was unusually low through the summer and autumn. Indeed, the sea-ice extent was particularly low along the Siberian coastline, with the Northern Sea Route ice-free or close to ice-free from July to October. The high spring temperatures also had a significant effect on other parts of the cryosphere. June snow cover was the lowest for the Eurasian Arctic in the 54-year satellite record despite the region having a larger-than-average extent as late as April.[c]

Although the Arctic was predominantly warmer than average for this period, some regions, including parts of Alaska and Greenland, saw close to average or below-average temperatures. As a result, the 2019/2020 surface mass balance for Greenland was close to the 40-year average. Nevertheless, the decline of the Greenland ice sheet continued during the 2019/2020 season, but the loss was below the typical amounts seen during the last decade (see Cryosphere). Sea-ice conditions along the Canadian archipelago were close to average at the September minimum, and the western passage remained closed.[d]

The wildfire season in the Arctic during 2020 was particularly active, but with large regional differences. The region north of the Arctic circle saw the most active wildfire season in an 18-year data record, as estimated in terms of fire radiative power and CO_2 emissions released from fires. The main activity was concentrated in the eastern Siberian Arctic, which was also drier than average. Regional reports[e] for eastern Siberia indicate that the forest fire season started earlier than average, and for some regions ended later, resulting in long-term damage to local ecosystems. Alaska, as well as the Yukon and the Northwest Territories, reported fire activity that was well below average.

[b] https://public.wmo.int/en/media/news/reported-new-record-temperature-of-38%C2%B0c-north-of-arctic-circle

[c] Mudryk, L.E. et al., 2020: *Arctic Report Card 2020: Terrestrial Snow Cover. United States. National Oceanic and Atmospheric Administration.* Office of Oceanic and Atmospheric Research University of Toronto. Department of Physics Ilmatieteen laitos (Finland) / Finnish Meteorological Institute, https://doi.org/10.25923/P6CA-V923.

[d] Arctic Climate Forum, https://arctic-rcc.org/sites/arctic-rcc.org/files/presentations/acf-fall-2020/2%20-%20Day%202%20-%20ACF-6_Arctic_summary_MJJAS_2020_v2.pdf

[e] Arctic Climate Forum, https://arctic-rcc.org/sites/arctic-rcc.org/files/presentations/acf-fall-2020/3%20-%20Day%201-%20ACF%20October%202020%20Regional%20Overview%20Summary%20with%20extremes%20-281020.pdf

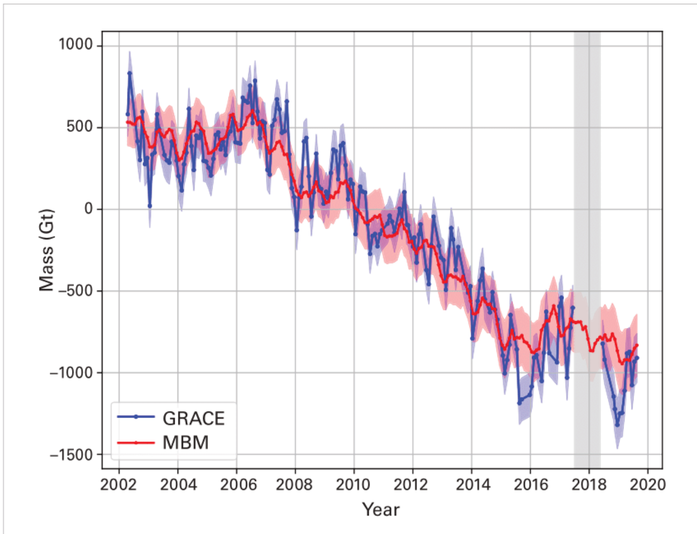


Figure 14. Comparison of Antarctic ice sheet mass changes from GRACE/GRACE-FO satellite gravimetry (blue) and the mass budget method (MBM) (red). This comparison highlights the large interannual variability in mass change, the relatively large uncertainties in these two methods, and their occasional disagreement. *Source:* Velicogna et al., 2020 (see reference details in Antarctic ice sheet data)

brought four times the normal monthly precipitation to western Greenland, most of which fell as snow that temporarily stopped the net loss of ice and was decisive in reducing the amount of melt; this was quite different from the situation in the previous season (2018/2019), in which there were extended high pressure periods and large amounts of sunshine, which significantly increased the summer melt.

There is no routine reporting of the annual mass balance for the Antarctic ice sheet, and reported mass changes typically have a latency of several years. This is because multiple data sets must be combined to reduce uncertainty and bias in mass-change estimates on the continental scale.

Antarctica has exhibited a strong mass loss trend since the late 1990s. This trend accelerated around 2005, and currently, Antarctica loses approximately 175 to 225 Gt per year. Nearly 90% of the acceleration of this trend is due to the increasing flow rates of major glaciers in West Antarctica and the Antarctic Peninsula.[17] This is in contrast to the Greenland ice sheet, where losses from surface melting are of comparable magnitude to those from glacier dynamics. The main driver of faster glacier flow in Antarctica has been enhanced sub-sea melting of fringing ice shelves, with a secondary driver being abrupt ice-shelf collapse due to localized surface melting on the Antarctic Peninsula.[39] This glacier-dynamic response to climate and ocean forcing is strongly controlled by thresholds (ice shelf collapse) and strongly modulated by positive feedbacks in flow. As a result, Antarctica's interannual dynamic losses are largely uncoupled from fluctuations in weather on annual timescales.

Superimposed on this sustained mass loss trend is a large interannual variability in snowfall that fluctuates by several hundred gigatons (Figure 14) around an average of approximately 2 300 Gt to 2 500 Gt per year[31] and has no clear trend over recent decades.[32] These large fluctuations are dominated spatially and temporally by occasional extreme snowfall events.[33] Instrumental observations of snowfall on the continent are extremely scarce, however, and ice-sheet mass changes are instead calculated retrospectively from satellite-observed changes in flow rate (the mass budget method), the gravity field or surface height, combined with modelled surface mass balance, near-surface snow density and isostatic rebound, respectively. Each of these three sets of observations and associated model inputs contains significant uncertainties and potential biases, and the results reported by these techniques do not always agree within their uncertainties.[34] Consensus on Antarctic mass changes therefore emerges only from a detailed inter-comparison of this suite of methods, with careful consideration of their respective strengths and weaknesses.[39,43] No such consensus value is available yet for the 2019/2020 period.

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[31] Mottram, R. et al., 2020: What Is the Surface Mass Balance of Antarctica? An Intercomparison of Regional Climate Model Estimates. *The Cryosphere Discussions*, 1–42, https://doi.org/10.5194/tc-2019-333.

[32] King, M.A. and C.S. Watson, 2020: Antarctic Surface Mass Balance: Natural Variability, Noise, and Detecting New Trends. *Geophysical Research Letters*, 47(12): e2020GL087493, https://doi.org/10.1029/2020GL087493.

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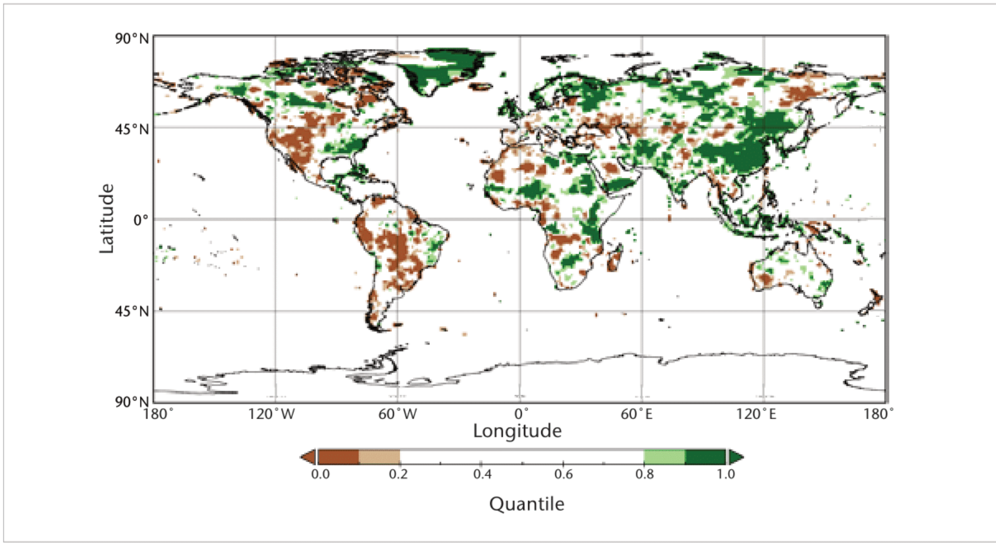
[34] Shepherd, A. et al., 2018: Mass Balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature*, 558(7709): 219–222, https://doi.org/10.1038/s41586-018-0179-y.

PRECIPITATION

Annual precipitation totals in monsoon-influenced regions in North America, Africa, South-West Asia and South-East Asia were unusually high in 2020 (Figure 15, top), as were extreme daily totals (expressed as the 95th percentile of daily totals) (Figure 15, bottom). The African Monsoon extended farther north into the Sahel region than usual. Monsoon seasonal totals in India were 109% of the long-term mean, the third highest seasonal total after 1994 and 2019. East Asia experienced abnormally high annual and extreme daily rainfall totals.

In other regions, the extreme daily totals (95th percentile of daily precipitation amounts) were lower than the long-term mean (Figure 15, bottom), for example, the Maritime Continent (incorporating Indonesia, Papua New Guinea and the Philippines, as well as other islands in the region), Central and North-West Africa, large areas of the Americas and Central and West Europe.



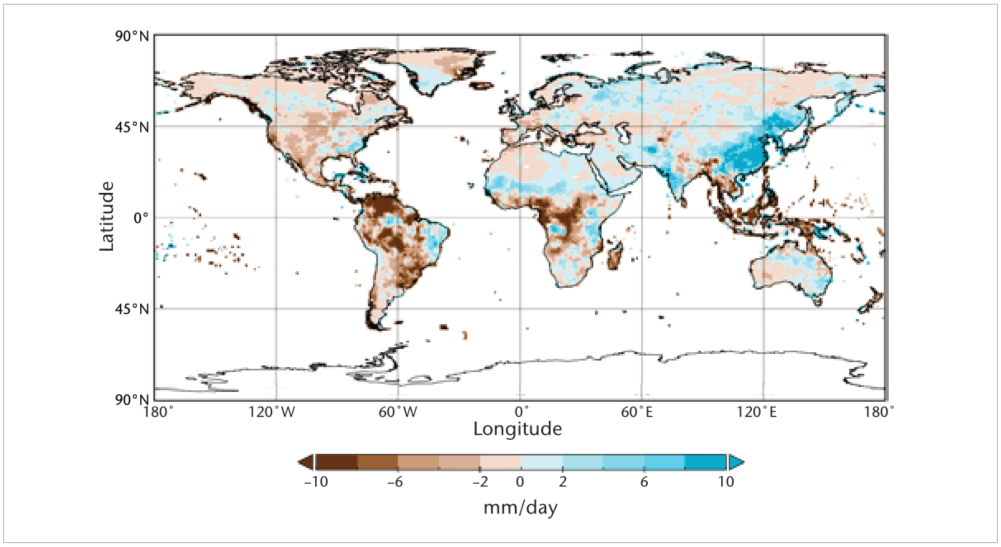


Figure 15. Top: Total precipitation in 2020, expressed as a percentile of the 1951–2010 reference period. The shaded areas are those with precipitation totals in the driest 20% (brown) and wettest 20% (green) of years during the reference period, with darker shades of brown and green indicating the driest and wettest 10%, respectively.
Note: A longer reference period is used here because precipitation is more variable, and a longer period allows a more reliable long-term average to be calculated.
Bottom: Difference between the observed 95th percentile of daily precipitation total in 2020 and the long-term mean based on the 1982–2016 (full year) period. Blue indicates more extreme daily precipitation events than the long-term mean, and brown indicates fewer extreme daily precipitation events than the long-term mean.
Note: The period used here is the full length of the global daily precipitation data set.
Source: GPCC, Deutscher Wetterdienst, Germany

DRIVERS OF SHORT-TERM CLIMATE VARIABILITY

There are many different natural phenomena, often referred to as climate patterns or climate modes, that affect weather at timescales ranging from days to several months. Surface temperatures change relatively slowly over the ocean, so recurring patterns in sea-surface temperature can be used to understand, and in some cases, predict the more rapidly changing patterns of weather over land on seasonal timescales. Similarly, albeit at a faster rate, known pressure changes in the atmosphere can help explain certain regional weather patterns.

In 2020, the El Niño–Southern Oscillation (ENSO) and the Arctic Oscillation (AO) each contributed to weather and climate events in different parts of the world. The Indian Ocean Dipole, which played a key role in the events of 2019, was near-neutral for much of 2020.

EL NIÑO–SOUTHERN OSCILLATION

ENSO is one of the most important drivers of year-to-year variability in weather patterns around the world. It is linked to hazards such as heavy rains, floods, and drought. El Niño, characterized by higher-than-average sea-surface temperatures in the eastern Pacific and a weakening of the trade winds, typically has a warming influence on global temperatures. La Niña, which is characterized by below-average sea-surface temperatures in the central and eastern Pacific and a strengthening of the trade winds, has the opposite effect.

Sea-surface temperatures at the end of 2019 were close to or exceeded El Niño thresholds in the Niño 3.4 region.[4] These temperatures persisted into the early months of 2020, but the event did not strengthen, and sea-surface temperature anomalies in the eastern Pacific fell in March. After a six-month period of neutral conditions – that is, sea-surface temperatures within 0.5 °C of normal – the cool-phase, La Niña, developed in August and strengthened through the northern hemisphere autumn to moderate strength (1.0–1.5 °C below normal). The atmosphere also responded with stronger-than-average trade winds, indicating a coupling with the sea-surface temperatures. La Niña conditions are associated with above-average hurricane activity in the North Atlantic, which experienced a record number of named tropical storms during its 2020 hurricane season, and also with above-average rainfall in Australia, which ended the year with its fourth wettest December on record.

ARCTIC OSCILLATION

AO is a large-scale atmospheric pattern that influences weather throughout the northern hemisphere. The positive phase is characterized by lower-than-average air pressure over the Arctic and higher-than-average pressure over the northern Pacific and Atlantic Oceans. The jet stream is parallel to the lines of latitude and farther north than average, locking up cold Arctic air, and storms can be shifted northward of their usual paths. The mid-latitudes of North America, Europe, Siberia, and East Asia generally see fewer cold air outbreaks than usual during the positive phase of AO. A negative AO has the opposite effect and is associated with a more meandering jet stream and cold air spilling south into the mid-latitudes.

AO was strongly positive during the northern hemisphere 2019/2020 winter and in February was the strongest it had been since January 1993. This contributed to the warmest winter on record for Asia and Europe and the sixth warmest winter on record for the contiguous United States; at the same time, Alaska experienced its coldest winter in more than two decades. By containing cold air in the polar region through the entire winter, the positive AO also contributed to a relatively rare and record-large Arctic ozone hole in March (see Stratospheric ozone and ozone-depleting gases). Additionally, the positive winter phase of AO has been linked to low sea-ice extent the following summer[35] (see Sea ice). AO was strongly positive in November but rapidly declined to large negative values in December and in early 2021.

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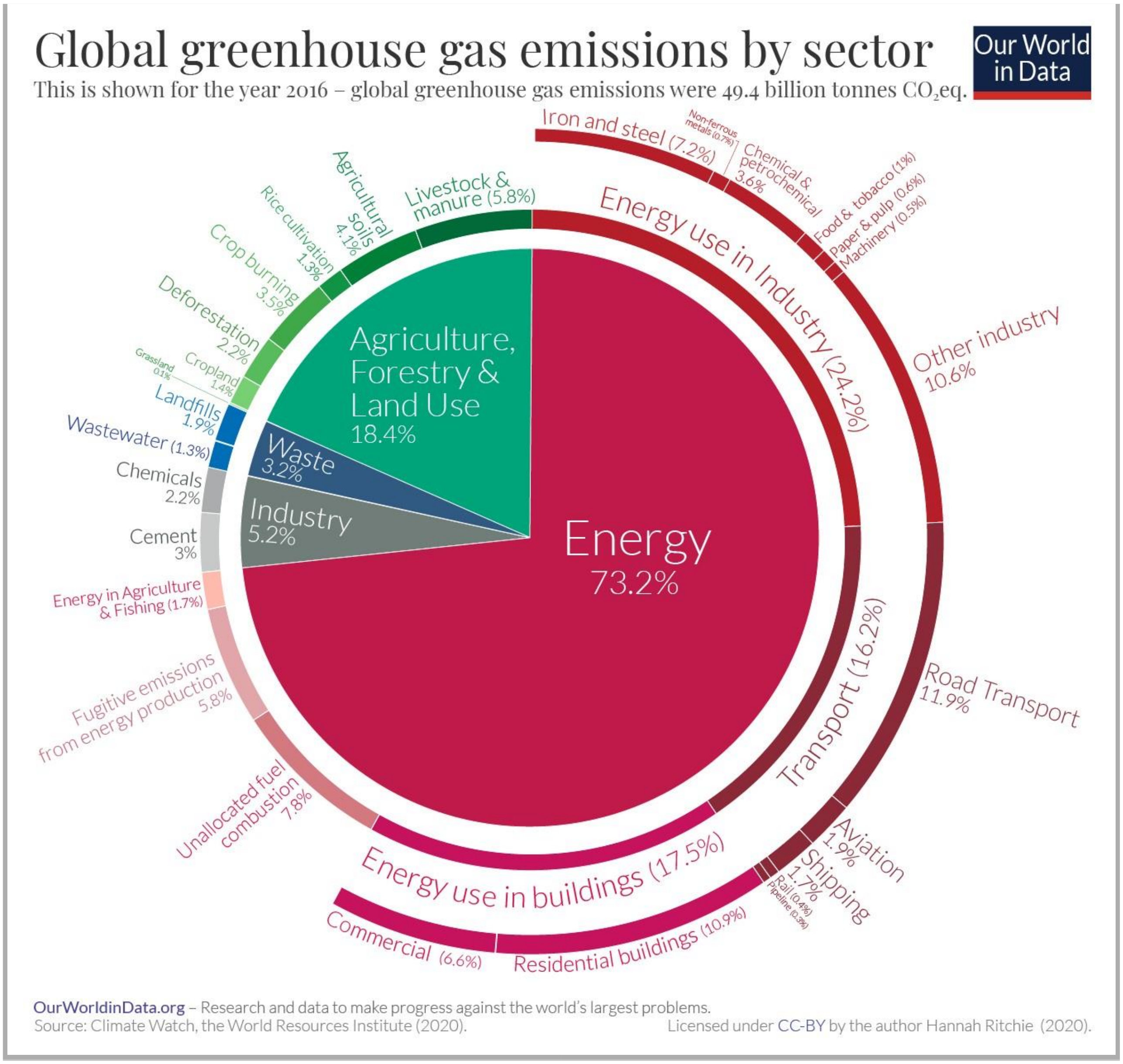
[35] Rigor, I.G. et al., 2002: Response of Sea Ice to the Arctic Oscillation. *Journal of Climate*, 15(18): 2648–2663, https://doi.org/10.1175/1520-0442(2002)015%3c2648:ROSITT%3e2.0.CO;2.

[Climate Change 2022: Impacts, Adaptation & Vulnerability - Full video (https://youtu.be/SDRxfuEvqGg)](https://youtu.be/SDRxfuEvqGg)

Sector by sector: where do global greenhouse gas emissions come from?

Globally, we emit around 50 billion tonnes of greenhouse gases each year. Where do these emissions come from? We take a look, sector-by-sector.

by Hannah Ritchie
September 18, 2020



To prevent severe climate change we need to rapidly reduce global greenhouse gas emissions. The world emits around 50 billion tonnes of greenhouse gases each year *[measured in carbon dioxide equivalents (CO_2eq)]*.[1]

To figure out how we can most effectively reduce emissions and what emissions *can* and *can't* be eliminated with current technologies, we need to first understand where our emissions come from.

In this post I present only one chart, but it is an important one – it shows the breakdown of global greenhouse gas emissions in 2016.[2] This is the latest breakdown of global emissions by sector, published by Climate Watch and the World Resources Institute.[3,4]
The overall picture you see from this diagram is that almost three-quarters of emissions come from energy use; almost one-fifth from agriculture and land use *[this increases to one-quarter when we consider the food system as a whole – including processing, packaging, transport and retail]*; and the remaining 8% from industry and waste.

To know what's included in each sector category, I provide a short description of each. These descriptions are based on explanations provided in the IPCC's Fifth Assessment Report AR5) and a methodology paper published by the *World Resources Institute*.[5,6]

Emissions come from many sectors: we need many solutions to decarbonize the economy

It is clear from this breakdown that a range of sectors and processes contribute to global emissions. This means there is no single or simple solution to tackle climate change. Focusing on electricity, or transport, or food, or deforestation alone is insufficient.

Even within the energy sector – which accounts for almost three-quarters of emissions – there is no simple fix. Even if we could fully decarbonize our electricity supply, we would also need to electrify all of our heating and road transport. And we'd still have emissions from shipping and aviation – which we do not yet have low-carbon technologies for – to deal with.

To reach net-zero emissions we need innovations across many sectors. Single solutions will not get us there.

Let's walk through each of the sectors and sub-sectors in the pie chart, one-by-one.

Energy (electricity, heat and transport): 73.2%

Energy use in industry: 24.2%

Iron and Steel (7.2%): energy-related emissions from the manufacturing of iron and steel.

Chemical & petrochemical (3.6%): energy-related emissions from the manufacturing of fertilizers, pharmaceuticals, refrigerants, oil and gas extraction, etc.

Food and tobacco (1%): energy-related emissions from the manufacturing of tobacco products and food processing (the conversion of raw agricultural products into their final products, such as the conversion of wheat into bread).

Non-ferrous metals: 0.7%: Non-ferrous metals are metals which contain very little iron: this includes aluminium, copper, lead, nickel, tin, titanium and zinc, and alloys such as brass. The manufacturing of these metals requires energy which results in emissions.

Paper & pulp (0.6%): energy-related emissions from the conversion of wood into paper and pulp.

Machinery (0.5%): energy-related emissions from the production of machinery.

Other industry (10.6%): energy-related emissions from manufacturing in other industries including mining and quarrying, construction, textiles, wood products, and transport equipment (such as car manufacturing).

Transport: 16.2%

This includes a small amount of electricity (indirect emissions) as well as all direct emissions from burning fossil fuels to power transport activities. These figures do not include emissions from the manufacturing of motor vehicles or other transport equipment – this is included in the previous point ‘Energy use in Industry’.

Road transport (11.9%): emissions from the burning of petrol and diesel from all forms of road transport which includes cars, trucks, lorries, motorcycles and buses. Sixty percent of road transport emissions come from passenger travel (cars, motorcycles and buses); and the remaining forty percent from road freight (lorries and trucks). This means that, if we could electrify the whole road transport sector, and transition to a fully decarbonized electricity mix, we could feasibly reduce global emissions by 11.9%.

Aviation (1.9%): emissions from passenger travel and freight, and domestic and international aviation. 81% of aviation emissions come from passenger travel; and 19% from freight.[7] From passenger aviation, 60% of emissions come from international travel, and 40% from domestic.

Shipping (1.7%): emissions from the burning of petrol or diesel on boats. This includes both passenger and freight maritime trips.

Rail (0.4%): emissions from passenger and freight rail travel.

Pipeline (0.3%): fuels and commodities (e.g. oil, gas, water or steam) often need to be transported (either within or between countries) via pipelines. This requires energy inputs, which results in emissions. Poorly constructed pipelines can also leak, leading to direct emissions of methane to the atmosphere – however, this aspect is captured in the category 'Fugitive emissions from energy production'.

Energy use in buildings: 17.5%

Residential buildings (10.9%): energy-related emissions from the generation of electricity for lighting, appliances, cooking etc. and heating at home.

Commercial buildings (6.6%): energy-related emissions from the generation of electricity for lighting, appliances, etc. and heating in commercial buildings such as offices, restaurants, and shops.

Unallocated fuel combustion (7.8%)

Energy-related emissions from the production of energy from other fuels including electricity and heat from biomass; on-site heat sources; combined heat and power (CHP); nuclear industry; and pumped hydroelectric storage.

Fugitive emissions from energy production: 5.8%

Fugitive emissions from oil and gas (3.9%): fugitive emissions are the often-accidental leakage of methane to the atmosphere during oil and gas extraction and transportation, from damaged or poorly maintained pipes. This also includes flaring – the intentional burning of gas at oil facilities. Oil wells can release gases, including methane, during extraction – producers often don't have an existing network of pipelines to transport it, or it wouldn't make economic sense to provide the infrastructure needed to effectively capture and transport it. But under environmental regulations they need to deal with it somehow: intentionally burning it is often a cheap way to do so.

Fugitive emissions from coal (1.9%): fugitive emissions are the accidental leakage of methane during coal mining.

Energy use in agriculture and fishing (1.7%)

Energy-related emissions from the use of machinery in agriculture and fishing, such as fuel for farm machinery and fishing vessels.

Direct Industrial Processes: 5.2%

Cement (3%): carbon dioxide is produced as a byproduct of a chemical conversion process used in the production of clinker, a component of cement. In this reaction, limestone ($CaCO_3$) is converted to lime (CaO), and produces CO_2 as a byproduct. Cement production also produces emissions from energy inputs – these related emissions are included in 'Energy Use in Industry'.

Chemicals & petrochemicals (2.2%): greenhouse gases can be produced as a byproduct from chemical processes – for example, CO_2 can be emitted during the production of ammonia, which is used for purifying water supplies, cleaning products, and as a refrigerant, and used in the production of many materials, including plastic, fertilizers, pesticides, and textiles. Chemical and petrochemical manufacturing also produces emissions from energy inputs – these related emissions are included in 'Energy Use in Industry'.

Waste: 3.2%

Wastewater (1.3%): organic matter and residues from animals, plants, humans and their waste products can collect in wastewater systems. When this organic matter decomposes it produces methane and nitrous oxide.

Landfills (1.9%): landfills are often low-oxygen environments. In these environments, organic matter is converted to methane when it decomposes.

Agriculture, Forestry and Land Use: 18.4%

Agriculture, Forestry and Land Use directly accounts for 18.4% of greenhouse gas emissions. The food system as a whole – including refrigeration, food processing, packaging, and transport – accounts for around one-quarter of greenhouse gas emissions. We look at this in detail **here**.

Grassland (0.1%): when grassland becomes degraded, these soils can lose carbon, converting to carbon dioxide in the process. Conversely, when grassland is restored (for example, from cropland), carbon can be sequestered. Emissions here therefore refer to the net balance of these carbon losses and gains from grassland biomass and soils.

Cropland (1.4%): depending on the management practices used on croplands, carbon can be lost or sequestered into soils and biomass. This affects the balance of carbon dioxide emissions: CO_2 can be emitted when croplands are degraded; or sequestered when they are restored. The net change in carbon stocks is captured in emissions of carbon dioxide. This does not include grazing lands for livestock.

Deforestation (2.2%): net emissions of carbon dioxide from changes in forestry cover. This means reforestation is counted as 'negative emissions' and deforestation as 'positive emissions'. Net forestry change is therefore the difference between forestry loss and gain. Emissions are based on lost carbon stores from forests and changes in carbon stores in forest soils.

Crop burning (3.5%): the burning of agricultural residues – leftover vegetation from crops such as rice, wheat, sugar cane, and other crops – releases carbon dioxide, nitrous oxide and methane. *Farmers often burn crop residues after harvest to prepare land for the resowing of crops.*

Rice cultivation (1.3%): flooded paddy fields produce methane through a process called 'anaerobic digestion'. Organic matter in the soil is converted to methane due to the low-oxygen environment of waterlogged rice fields. 1.3% seems substantial, but it's important to put this into context: rice accounts for around one-fifth of the world's supply of calories, and is a staple crop for billions of people globally.[8]

Agricultural soils (4.1%): Nitrous oxide – a strong greenhouse gas – is produced when synthetic nitrogen fertilizers are applied to soils. This includes emissions from agricultural soils for all agricultural products – including food for direct human consumption, animal feed, biofuels and other non-food crops (such as tobacco and cotton).

Livestock & manure (5.8%): animals (mainly ruminants, such as cattle and sheep) produce greenhouse gases through a process called 'enteric fermentation' – when microbes in their digestive systems break down food, they produce methane as a by-product. This means beef and lamb tend to have a high carbon footprint, and eating less is an effective way to reduce the emissions of your diet.

Nitrous oxide and methane can be produced from the decomposition of animal manures under low oxygen conditions. This often occurs when large numbers of animals are managed in a confined area (such as dairy farms, beef feedlots, and swine and poultry farms), where manure is typically stored in large piles or disposed of in lagoons and other types of manure management systems 'Livestock' emissions here include direct emissions from livestock only- they do not consider impacts of land use change for pasture or animal feed.

U.S. Energy Information Administration

NATURAL GAS EXPLAINED

NATURAL GAS AND THE ENVIRONMENT

BASICS

Natural gas has many qualities that make it an efficient, relatively clean burning, and economical energy source. However, the production and use of natural gas have some environmental and safety issues to consider.

Natural gas is a relatively clean burning fossil fuel

Burning natural gas for energy results in fewer emissions of nearly all types of air pollutants and carbon dioxide (CO_2) than burning coal or petroleum products to produce an equal amount of energy. About 117 pounds of CO_2 are produced per million British thermal units (MMBtu) equivalent of natural gas compared with more than 200 pounds of CO_2 per MMBtu of coal and more than 160 pounds per MMBtu of distillate fuel oil. The clean burning properties of natural gas have contributed to increased natural gas use for electricity generation and as a transportation fuel for fleet vehicles in the United States.

Natural gas is mainly methane—a strong greenhouse gas

Some natural gas leaks into the atmosphere from oil and natural gas wells, storage tanks, pipelines, and processing plants. The U.S. Environmental Protection Agency estimates that in 2019, methane emissions from natural gas and petroleum systems and from abandoned oil and natural gas wells were the source of about 29% of total U.S. methane emissions and about 3% of total U.S. greenhouse gas emissions.[1] The oil and natural gas industry takes steps to prevent natural gas leaks.

Natural gas exploration, drilling, and production affects the environment

When geologists explore for natural gas deposits on land, they may disturb vegetation and soil with their vehicles. Drilling a natural gas well on land may require clearing and leveling an area around the well site. Well drilling activities produce air pollution and may disturb people, wildlife, and water resources. Laying pipelines that transport natural gas from wells usually requires clearing land to bury the pipe. Natural gas production can also produce large volumes of contaminated water. This water requires proper handling, storage, and treatment so that it does not pollute land and other waters. Natural gas wells and pipelines often have engines to run equipment and compressors, which produce air pollutants and noise.

In areas where natural gas is produced at oil wells but is not economical to transport for sale or contains high concentrations of hydrogen sulfide (a toxic gas), it is burned (flared) at well sites. Natural gas flaring produces CO_2, carbon monoxide, sulfur dioxide, nitrogen oxides, and many other compounds, depending on the chemical composition of the natural gas and on how well the natural gas burns in the flare. However, flaring is safer than releasing natural gas into the air and results in lower overall greenhouse gas emissions because CO_2 is not as strong a greenhouse gas as methane.

BIOFUELS EXPLAINED

BIOFUELS AND THE ENVIRONMENT

BASICS

Biofuels may have fewer effects on the environment than fossil fuels

Production and use of biofuels is considered by the U.S. government to have fewer or lower negative effects on the environment compared to fossil-fuel derived fuels. There are also potential national economic and security benefits when biofuel use reduces the need to import petroleum fuels. Government programs that promote and/or require biofuels use, such as the U.S. Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS), define the types of biofuels and processes or low-carbon pathways by which biofuels can be produced in order for them to qualify for use under the programs. While biofuels have environmental benefits, their production and use do have effects on the environment.

Pure ethanol and biodiesel are nontoxic and biodegradable, and if spilled, they break down into harmless substances. However, fuel ethanol contains denaturants to make fuel ethanol undrinkable. Similar to petroleum fuels, biofuels are flammable (especially ethanol) and must be transported carefully.

When burned, pure biofuels generally produce fewer emissions of particulates, sulfur dioxide, and air toxics than their fossil-fuel derived counterparts. Biofuel-petroleum blends also generally result in lower emissions relative to fuels that do not contain biofuels. Biodiesel combustion may result in slightly higher amounts of nitrogen oxides relative to petroleum diesel.

Ethanol and ethanol-gasoline mixtures burn cleaner and have higher octane levels than gasoline that does not contain ethanol, but they also have higher evaporative emissions from fuel tanks and dispensing equipment. These evaporative emissions contribute to the formation of harmful, ground-level ozone and smog. Gasoline requires extra processing to reduce evaporative emissions before blending with ethanol.

Burning biofuels results in emissions of carbon dioxide (CO_2), a greenhouse gas. However, according to international convention, CO_2 emissions from biofuel combustion are excluded from national greenhouse gas emissions inventories because growing the biomass feedstocks used for biofuel production may offset the CO_2 produced when biofuels are burned.

The effect that biofuel use has on net CO_2 emissions depends on how the biofuels are produced and whether or not emissions associated with cropland cultivation are included in the calculations. Growing plants for fuel is a controversial topic because some people believe the land, fertilizers, and energy used to grow biofuel crops should be used to grow food crops instead. In some parts of the world, large areas of natural vegetation and forests have been cleared or burned to grow soybeans and palm oil trees to make biodiesel. The processes for producing ethanol, renewable diesel, renewable heating oil, and renewable aviation fuel require a heat source, and most producers of these biofuels currently use fossil fuels. Some U.S. ethanol producers burn corn stalks for heat and ethanol producers in Brazil use sugar cane stalks (called bagasse) to produce heat and electricity.

The U.S. government is supporting efforts to produce biofuels with methods that use less energy than conventional fermentation and that use *cellulosic* biomass, which requires less cultivation, fertilizer, and pesticides than corn or sugar cane. *Cellulosic ethanol* feedstock includes native prairie grasses, fast-growing trees, sawdust, and even waste paper. However, there is currently no commercial cellulosic ethanol production in the United States because of technical and economic challenges.

Lipid feedstocks—waste/used cooking oil and animal fats/tallow and grease—have relatively low carbon intensities as feedstocks for biofuels production and they have been used to meet the targets for advanced biofuels under the federal RFS program. The total process (or life-cycle) emissions for lipid feedstocks are low because lipids were previously used for another purpose and the emissions related to transportation of these biofuels feedstocks only account for emissions that occur after the waste oil/grease is collected. Because of their potentially lower carbon intensities, some state governments provide more support for biofuels production from lipid feedstocks than for raw, unused vegetable oil feedstocks. In California, lipids account for the majority of the feedstocks for U.S. non-fuel ethanol biofuels production and also for the majority of credits generated under California's LCFS. The federal RFS currently does not differentiate between lipid and vegetable oil feedstocks as it does with cellulosic and other renewable fuels. At scale, hydrogenated lipid-based biofuels production requires a significant amount of hydrogen, which if produced from fossil fuels, may increase process emissions and thus increase their carbon intensity.

Last updated: April 13, 2022

U.S. Energy Information Administration

BIOMASS EXPLAINED

BIOMASS AND THE ENVIRONMENT

BASICS

Using biomass for energy has positive and negative effects

Biomass and biofuels made from biomass are alternative energy sources to fossil fuels—coal, petroleum, and natural gas. Burning either fossil fuels or biomass releases carbon dioxide (CO_2), a greenhouse gas. However, the plants that are the source of biomass for energy capture almost the same amount of CO_2 through photosynthesis while growing as is released when biomass is burned, which can make biomass a carbon-neutral energy source.[1]

Burning wood

Using wood, wood pellets, and charcoal for heating and cooking can replace fossil fuels and may result in lower CO_2 emissions overall. Wood can be harvested from forests, from woodlots that have to be thinned, or from urban trees that fall down or have to be cut down.

Wood smoke contains harmful pollutants such as carbon monoxide and particulate matter. Modern wood-burning stoves, pellet stoves, and fireplace inserts can reduce the amount of particulates from burning wood. Wood and charcoal are major cooking and heating fuels in poor countries, but if people harvest the wood faster than trees can grow, it causes deforestation. Planting fastgrowing trees for fuel and using fuel-efficient cooking stoves can help slow deforestation and improve the environment.

Burning municipal solid waste (MSW) or wood waste

Burning municipal solid waste (MSW), or *garbage*, in waste-to-energy plants could result in less waste buried in landfills. On the other hand, burning garbage produces air pollution and releases the chemicals and substances in the waste into the air. Some of these chemicals, which are mostly related to the combustion of non-biomass materials in garbage, can be hazardous to people and the environment if they are not properly controlled.

The U.S. Environmental Protection Agency (EPA) applies strict environmental rules to waste-to-energy plants, which require waste-to-energy plants to use air pollution control devices such as scrubbers, fabric filters, and electrostatic precipitators to capture air pollutants.

Scrubbers clean emissions from waste-to-energy facilities by spraying a liquid into the combustion gases to neutralize the acids present in the stream of emissions. Fabric filters and electrostatic precipitators also remove particles from the combustion gases.

The particles—called fly ash—are then mixed with the ash that is removed from the bottom of the waste-to-energy furnace.

A waste-to-energy furnace burns at high temperatures (1,800°F to 2,000°F), which break down the chemicals in MSW into simpler, less harmful compounds.

Disposing ash from waste-to-energy plants

Ash from waste-to-energy plants can contain high concentrations of various metals that were present in the original waste. Textile dyes, printing inks, and ceramics, for example, may contain lead and cadmium.

Separating waste before burning can solve part of the problem. Because batteries are the largest source of lead and cadmium in municipal waste, they should not be included in regular trash. Florescent light bulbs should also not be put in regular trash because they contain small amounts of mercury.

The EPA tests ash from waste-to-energy plants to make sure that it is not hazardous. The test looks for chemicals and metals that could contaminate ground water. Some MSW landfills use ash that is considered safe as a cover layer for their landfills, and some MSW ash is used to make concrete blocks and bricks.

Collecting landfill gas or biogas

Biogas forms as a result of biological processes in sewage treatment plants, waste landfills, and livestock manure management systems. Biogas is composed mainly of methane (a greenhouse gas) and CO_2. Many facilities that produce biogas capture it and burn the methane for heat or to generate electricity. This electricity is considered renewable and, in many states, contributes to meeting state renewable portfolio standards (RPS). This electricity may replace electricity generation from fossil fuels and can result in a net reduction in CO_2 emissions. Burning methane produces CO_2, but because methane is a stronger greenhouse gas than CO_2, the overall greenhouse effect is lower.

Biofuels

Biofuels are generally cleaner burning than petroleum fuels made from crude oil, but production and use of biofuels do have effects on the environment. Biofuels may be considered carbon-neutral because the plants that are used to make biofuels (such as corn and sugarcane for ethanol and soy beans and oil palm trees for biodiesel) absorb CO_2 as they grow and may offset the CO_2 emissions when biofuels are produced and burned.

U.S. Energy Information Administration

ELECTRICITY EXPLAINED

ELECTRICITY AND THE ENVIRONMENT

BASICS

Although electricity is a clean and relatively safe form of energy when it is used, the generation and transmission of electricity affects the environment. Nearly all types of electric power plants have an effect on the environment, but some power plants have larger effects than others.

The United States has laws that govern the effects that electricity generation and transmission have on the environment. The Clean Air Act regulates air pollutant emissions from most power plants. The U.S. Environmental Protection Agency (EPA) administers the Clean Air Act and sets emissions standards for power plants through various programs such as the Acid Rain Program. The Clean Air Act has helped to substantially reduce emissions of some major air pollutants in the United States.

The effect of power plants on the landscape

All power plants have a physical footprint (the location of the power plant). Some power plants are located inside, on, or next to an existing building, so the footprint is fairly small. Most large power plants require land clearing to build the power plant. Some power plants may also require access roads, railroads, and pipelines for fuel delivery, electricity transmission lines, and cooling water supplies. Power plants that burn solid fuels may have areas to store the combustion ash.

Many power plants are large structures that alter the visual landscape. In general, the larger the structure, the more likely it is that the power plant will affect the visual landscape.

Fossil fuel, biomass, and waste burning power plants

In the United States, about 60% of total electricity generation in 2020 was produced from fossil fuels (coal, natural gas, and petroleum), materials that come from plants (biomass), and municipal and industrial wastes. The substances that occur in combustion gases when these fuels are burned include:

- Carbon dioxide (CO_2)
- Carbon monoxide (CO)

- Sulfur dioxide (SO_2)
- Nitrogen oxides (NOx)
- Particulate matter (PM)
- Heavy metals such as mercury

Nearly all combustion byproducts have negative effects on the environment and human health:

- CO_2 is a greenhouse gas, which contributes to the greenhouse effect.
- SO_2 causes acid rain, which is harmful to plants and to animals that live in water. SO_2 also worsens respiratory illnesses and heart diseases, particularly in children and the elderly.
- NOx contribute to ground-level ozone, which irritates and damages the lungs.
- PM results in hazy conditions in cites and scenic areas and coupled with ozone, contributes to asthma and chronic bronchitis, especially in children and the elderly. Very small, or *fine PM*, is also believed to cause emphysema and lung cancer.
- Heavy metals such as mercury are hazardous to human and animal health.

Power plants reduce air pollution emissions in various ways

Air pollution emission standards limit the amounts of some of the substances that power plants can release into the air. Some of the ways that power plants meet these standards include:

- Burning low-sulfur-content coal to reduce SO_2 emissions. Some coal-fired power plants *cofire* wood chips with coal to reduce SO_2 emissions. Pretreating and processing coal can also reduce the level of undesirable compounds in combustion gases.
- Different kinds of particulate emission control devices treat combustion gases before they exit the power plant:
  - *Bag-houses* are large filters that trap particulates.
  - Electrostatic precipitators use electrically charged plates that attract and pull particulates out of the combustion gas.
  - Wet scrubbers use a liquid solution to remove PM from combustion gas.
- Wet and dry scrubbers mix lime in the fuel (coal) or spray a lime solution into combustion gases to reduce SO_2 emissions. Fluidized bed combustion also results in lower SO_2 emissions.
- NOx emissions controls include low NOx burners during the combustion phase or selective catalytic and non-catalytic converters during the post combustion phase.

Many U.S. power plants produce CO_2 emissions

The electric power sector is a large source of U.S. CO_2 emissions. Electric power sector power plants that burned fossil fuels or materials made from fossil fuels, and some geothermal power plants, were the source of about 28% of total U.S. energy-related CO_2 emissions in 2020.

Some power plants also produce liquid and solid wastes

Ash is the solid residue that results from burning solid fuels such as coal, biomass, and municipal solid waste. *Bottom ash* includes the largest particles that collect at the bottom of the combustion chamber of power plant boilers. *Fly ash* is the smaller and lighter particulates that collect in air emission control devices. Fly ash is usually mixed with bottom ash. The ash contains all the hazardous materials that pollution control devices capture. Many coal-fired power plants store ash sludge (ash mixed with water) in retention ponds. Several of these ponds have burst and caused extensive damage and pollution downstream. Some coal-fired power plants send ash to landfills or sell ash for use in making concrete blocks or asphalt.

Nuclear power plants produce different kinds of waste

Nuclear power plants do not produce greenhouse gases or PM, SO_2, or NOx, but they do produce two general types of radioactive waste:

- Low-level waste, such as contaminated protective shoe covers, clothing, wiping rags, mops, filters, reactor water treatment residues, equipment, and tools, is stored at nuclear power plants until the radioactivity in the waste decays to a level safe for disposal as ordinary trash, or it is sent to a low-level radioactive waste disposal site.
- High-level waste, which includes the highly radioactive spent (used) nuclear fuel assemblies, must be stored in specially designed storage containers and facilities (see Interim storage and final disposal in the United States).

U.S. Energy Information Administration

GEOTHERMAL EXPLAINED

GEOTHERMAL ENERGY AND THE ENVIRONMENT

BASICS

The environmental effects of geothermal energy depend on how geothermal energy is used or how it is converted to useful energy. Direct use applications and geothermal heat pumps have almost no negative effects on the environment. In fact, they can have a positive effect by reducing the use of energy sources that may have negative effects on the environment.

Geothermal power plants have low emission levels

Geothermal power plants do not burn fuel to generate electricity, but they may release small amounts of sulfur dioxide and carbon dioxide. Geothermal power plants emit 97% less acid rain-causing sulfur compounds and about 99% less carbon dioxide than fossil fuel power plants of similar size. Geothermal power plants use scrubbers to remove the hydrogen sulfide naturally found in geothermal reservoirs. Most geothermal power plants inject the geothermal steam and water that they use back into the earth. This recycling helps to renew the geothermal resource and to reduce emissions from the geothermal power plants.

U.S. Energy Information Administration

HYDROPOWER EXPLAINED

HYDROPOWER AND THE ENVIRONMENT

BASICS

Hydropower generators produce clean electricity, but hydropower does affect the environment

Most dams in the United States were built mainly for flood control, municipal water supply, and irrigation water. Although many of these dams have hydroelectric generators, only a small number of dams were built specifically for hydropower generation.

Hydropower generators do not directly emit air pollutants. However, dams, reservoirs, and the operation of hydroelectric generators can affect the environment.

A dam that creates a reservoir (or a dam that diverts water to a run-of-river hydropower plant) may obstruct fish migration. A dam and reservoir can also change natural water temperatures, water chemistry, river flow characteristics, and silt loads. All of these changes can affect the ecology and the physical characteristics of the river. These changes may have negative effects on native plants and on animals in and around the river. Reservoirs may cover important natural areas, agricultural land, or archeological sites. A reservoir and the operation of the dam may also result in the relocation of people. The physical impacts of a dam and reservoir, the operation of the dam, and the use of the water can change the environment over a much larger area than the area a reservoir covers.

Manufacturing the concrete and steel in hydropower dams requires equipment that may produce emissions. If fossil fuels are the energy sources for making these materials, then the emissions from the equipment could be associated with the electricity that hydropower facilities generate. However, given the long operating lifetime of a hydropower plant (50 years to 100 years) these emissions are offset by the emissions-free hydroelectricity.

Greenhouse gases (GHG) such as carbon dioxide and methane form in natural aquatic systems and in human-made water storage reservoirs as a result of the aerobic and anaerobic decomposition of biomass in the water. The exact amounts of GHG that form in and are emitted from hydropower reservoirs is uncertain and depend on many site specific and regional factors.

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SOLAR EXPLAINED

SOLAR ENERGY AND THE ENVIRONMENT

Solar energy technologies and power plants do not produce air pollution or greenhouse gases when operating. Using solar energy can have a positive, indirect effect on the environment when solar energy replaces or reduces the use of other energy sources that have larger effects on the environment. However, there are environmental issues related to the production and use of solar energy technologies.

Solar energy technologies require use of materials, such as metals and glass, that are energy intensive to make. The environmental issues related to the production of these materials could be associated with solar energy systems when conducting life-cycle or so called *cradle-to-grave* environmental analysis. Studies conducted by a number of organizations and researchers have concluded that PV systems can produce the equivalent amount of energy that was used to manufacture the systems within 1 to 4 years. Most PV systems have operating lives of up to 30 years or more.

There are hazardous chemicals used to make photovoltaic (PV) cells and panels that must be carefully handled to avoid release to the environment. Some types of PV cell technologies use heavy metals, and these types of cells and PV panels may require special handling when they reach the end of their useful life. Some solar thermal systems use potentially hazardous fluids to transfer heat, and leaks of these materials could be harmful to the environment. U.S. environmental laws regulate the use and disposal of hazardous materials. The U.S. Department of Energy is supporting various efforts to address *end-of-life* issues related to solar energy technologies, including the recovery and recycling of the materials used to manufacture PV cells and panels. Several states have enacted laws that encourage recycling of PV panels.

As with any type of power plant, large solar power plants can affect the environment at or near their locations. Clearing land for construction and the placement of the power plant may have long-term effects on the habitats of native plants and animals. However, installing solar energy systems on land with marginal agricultural value or integrating solar energy systems on farms may provide a variety of economic and environmental benefits to farmers.

Some solar power plants may require water for cleaning solar collectors and concentrators or for cooling turbine generators. Using large volumes of ground water or surface water for cleaning collectors in some arid locations may affect the ecosystems that depend on these water resources. In addition, the beam of concentrated sunlight a *solar power tower* creates can kill birds and insects that fly into the beam.

U.S. Energy Information Administration

WIND EXPLAINED

WIND ENERGY AND THE ENVIRONMENT

BASICS

Wind is an emissions-free source of energy

Wind is a renewable energy source. Overall, using wind to produce energy has fewer effects on the environment than many other energy sources. Wind turbines do not release emissions that can pollute the air or water (with rare exceptions), and they do not require water for cooling. Wind turbines may also reduce the amount of electricity generation from fossil fuels, which results in lower total air pollution and carbon dioxide emissions.

An individual wind turbine has a relatively small physical footprint. Groups of wind turbines, sometimes called wind farms, are located on open land, on mountain ridges, or offshore in lakes or the ocean.

Wind turbines have some negative effects on the environment

Modern wind turbines can be very large machines, and they may visually affect the landscape. A small number of wind turbines have also caught fire, and some have leaked lubricating fluids, but these occurrences are rare. Some people do not like the sound that wind turbine blades make as they turn in the wind. Some types of wind turbines and wind projects cause bird and bat deaths. These deaths may contribute to declines in the population of species also affected by other human-related impacts. The wind energy industry and the U.S. government are researching ways to reduce the effect of wind turbines on birds and bats.

Most wind power projects on land require service roads that add to the physical effects on the environment. Producing the metals and other materials used to make wind turbine components has impacts on the environment, and fossil fuels may have been used to produce the materials. Although most of the materials used to make wind turbines can be reused or recycled, turbine blades, as most are currently constructed, cannot be recycled. Researchers at the National Renewable Energy Laboratory (NREL) established an approach to manufacturing wind turbine blades, employing a thermoplastic resin system. These thermoplastic resins enable a manufacturing process that allows wind turbine blades to be recycled at their end of life and also reduces the energy required to manufacture blades.

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