Guide to the Science of Climate Change in the 21st Century

Chapter 16
Observations and Impacts of Recent Climate Change – Attribution Science

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Chapter 16.0 Observation and Impacts of Recent Climate Change – Attribution Science

16.1 Attribution

Attribution of climate change, and the known causes of climate change, to changes in the global environment generally, and on specific aspects of the environment both in location and time, is known as the 'attribution science'.

NASA has produced a summary of the observed effects of climate change in a web site titled Global Climate Change, Vital Signs of the Planet, https://climate.nasa.gov/vital-signs/carbon-dioxide/ and https://climate.nasa.gov/effects/. They discuss global temperature rise, warming ocean, shrinking ice sheets, glacial retreat, decreased snow cover, sea level rise, declining Arctic Sea ice, frequent extreme events, ocean acidification, changes in precipitation patterns, more droughts and heat waves, and more frequent, more intense and stronger hurricanes.

The World Meteorological Organization (WMO) recently published (November 1, 2021) their report, State of Global Climate 2021 WMO Provisional report https://reliefweb.int/sites/reliefweb.int/files/resources/WMO%20Provisional%20Report%20on%20the%20State%20of%20the%20Global%20Climate%202021.pdf. They discuss:

- Global climate indicators
  - Baselines
  - Greenhouse gases
  - Temperature
  - Ocean
  - Cryosphere
  - Stratospheric ozone
  - Drivers of short-term variability
- High impact events in 2021
  - Heatwaves and wildfires
  - Cold spells and snow
  - Precipitation
  - Flood
  - Drought
  - Tropical cyclones
  - Severe storms
  - Attribution
- Risks and impacts
  - State of disasters
  - Food security
  - Population displacement

- Climate impacts on ecosystems

The World Meteorological Organization reports that 2021 is one of the seven warmest years on record and that since the 1980's, each decade has been warmer than the previous one, https://public.wmo.int/en/media/press-release/2021-one-of-seven-warmest-years-record-wmo-consolidated-data-shows#:~:text=Since%20the%201980s%2C%20each%20decade,to%20record%20global%20average%20warming.

The World Meteorological Organization has published State of Global Climate 2022 https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate . They state:
'The WMO State of the Global Climate report 2022 focuses on key climate indicators – greenhouse gases, temperatures, sea level rise, ocean heat and acidification, sea ice and glaciers. It also highlights the impacts of climate change and extreme weather.

- Drought, floods and heatwaves affect large parts of the world and the costs are rising
- Global mean temperatures for the past 8 years have been the highest on record
- Sea level and ocean heat are at record levels – and this trend will continue for many centuries
- Antarctic sea ice falls to lowest extent on record
- Europe shatters records for glacier melt

From mountain peaks to ocean depths, climate change continued its advance in 2022. Droughts, floods and heatwaves affected communities on every continent and cost many billions of dollars. Antarctic sea ice fell to its lowest extent on record and the melting of some European glaciers was, literally, off the charts.
The State of the Global Climate 2022 shows the planetary scale changes on land, in the ocean and in the atmosphere caused by record levels of heat-trapping greenhouse gases. For global temperature, 2015-2022 were the eight warmest on record despite the cooling impact of a La Niña event for the past three years. Melting of glaciers and sea level rise - which again reached record levels in 2022 - will continue for up to thousands of years.'

Global warming is causing accelerated global ice loss and sea level increase https://tc.copernicus.org/articles/15/233/2021/. The temperature increase is occurring coincident with increasing concentration of greenhouse gases, GHG's, in the atmosphere. The linkage between temperature increases and GHG increases are obvious when considering the energy budget. The observed consequences or impacts of increased concentration of GHG's in the atmosphere and increased temperature of the atmosphere and land (including oceans) are generally predictable if not quantifiable. They appear to be outside the range of probability associated with naturally occurring variations; that is, naturally occurring extremes. The loss of sea ice, globally, is highlighted in reports such as Carbon Brief 26.09.2023 https://www.carbonbrief.org/exceptional-antarctic-melt-drives-months-of-record-low-global-sea-ice-cover/?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-09-27&utm_campaign=Daily+Briefing+27+09+2023 and https://www.theguardian.com/world/2023/sep/26/antarctic-sea-ice-shrinks-to-lowest-annual-maximum-level-on-record-data-shows .

Peter Brannen in the book titled The Ends of the World provides a readable, scientifically informed description of the evolution of life on Earth and the circumstances that resulted in its evolution, extinction and redevelopment - five times since life on Earth first began. Chapter 8 titled The Near Future provides a particularly clear description of recent human caused impacts on biodiversity and climate change.

Colin P. Summerhayes in the book titled Paleoclimatology from Snowball Earth to the Anthropocene provides a detailed scientific/ technical description of the changing climate of Earth over the past 800 million years including recent human caused impacts.

'Extreme event attribution' is of particular interest and is discussed quite thoroughly in a recent Carbon Brief publication titled 'Mapped: How climate change affects extreme weather around the world' (https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/?utm_campaign=Daily%20Briefing&utm_content=20220805&utm_medium=email&utm_source=Revue%20newsletter) considers 'all' peer reviewed publications on the topic to the end of May 2022. They report extreme weather event attribution studies pertaining to heat, oceans, coral bleaching, sunshine, storm, river flow, drought, wildfire, rain and flooding cold, snow and ice, compound events, atmosphere and ecosystem function. This study found that human-caused climate change made:

- 93% of 152 extreme heat events
- 56% of flooding events and
- 68% of 81 drought events

more likely or more severe.

The World Weather Attribution initiative, (https://www.worldweatherattribution.org/), a collaboration between climate scientists at Imperial College London in the UK, KNMI in the Netherlands, IPSL/LSCE in France, Princeton University and NCAR in the US, ETH Zurich in Switzerland, IIT Delhi in India and climate impact specialists at the Red Cross/ Red Crescent Climate Centre (RCCC) around the world was founded to provide robust assessments on the role of climate change in the aftermath of the event. The Carbon Brief publication, Guest post: Lessons learned from five years of extreme weather 'rapid attribution' describes how this study is performed, (https://www.carbonbrief.org/guest-post-lessons-learned-from-five-years-of-extreme-weather-rapid-attribution/). There is extensive use of historic observations and climate models. This approach is said to be 'scientific' and is only possible when needed information is available.

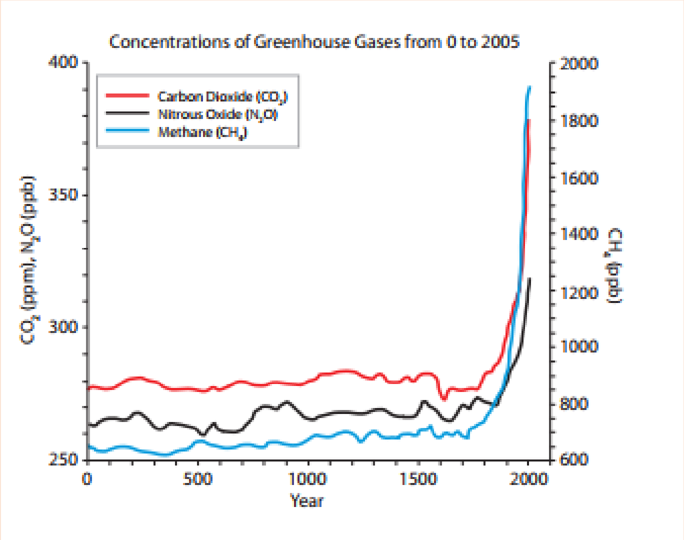
Clearly, most extreme events will not have the needed information to perform the scientific rapid attribution assessment but 'unscientific' assessments will still be made on the basis of the present knowledge of the underlying science.

The discussions that follow introduce attributable impacts of climate change.

16.2 Temperature and Greenhouse Gases

Increases in GHG concentration in Earth's atmosphere, particularly in the past two thousand years as shown in Figure 16.1, was made evident in a variety of proxy data of which the most precise and reliable were the result of ice core sampling in Antarctica and Greenland ice sheets and observations made using modern instrumentation over the past fifty years. The increases since the beginning of the industrial age, considered to be 1850, are rapid and significant. See https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide .

The effects of global warming are more pronounced at the poles in what is called polar amplification, http://www.realclimate.org/index.php/archives/2006/01/polar-amplification/ .



The concentration of carbon dioxide in the atmosphere November 2023 is greater than 420 ppm https://climate.nasa.gov/vital-signs/carbon-dioxide/ .

Figure 16.1 Atmospheric concentrations of greenhouse gases, carbon dioxide, methane, and nitrous oxide over the past 2000 years.
https://www.canr.msu.edu/resources/greenhouse_gas_basics_e3148

The changes in temperature of Earth's atmosphere over the past two thousand years and since 1850 are shown in Figures 16.2 and 16.3.   Recent increases are unusual.

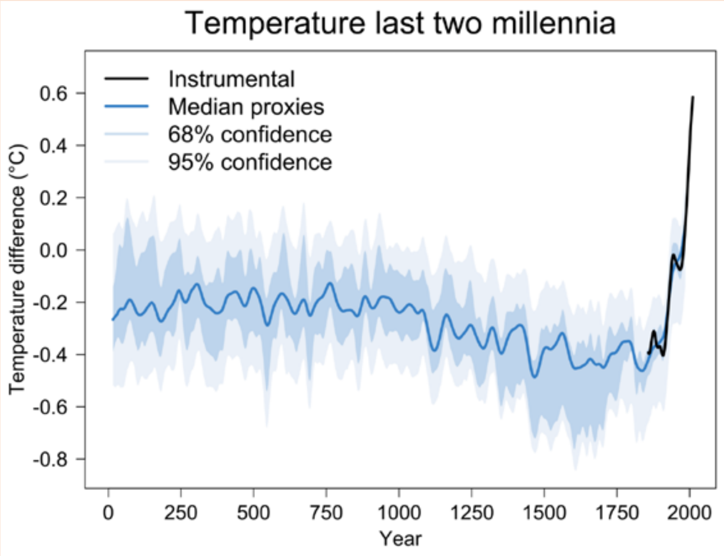


Figure 16.2 Variation of the temperature of Earth's atmosphere over the last two thousand years.

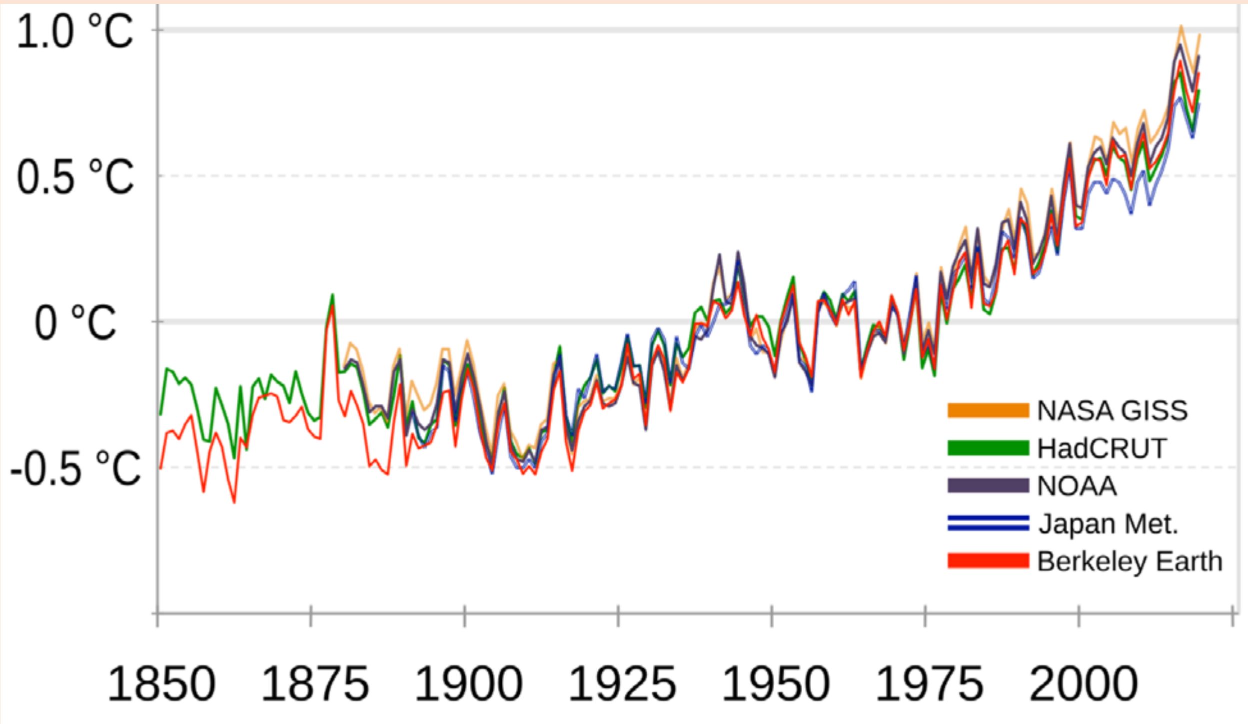


Figure 16.3 Global average temperature change since the beginning of the industrial period. https://earthobservatory.nasa.gov/world-of-change/global-temperatures

The IPCC has updated Figure 16.2 and 16.3 in the recent IPCC AR6 WG1 report, Climate Change: The Physical Science Basis, as shown in Figure 16.4 taken from the Summary for Policy Makers.

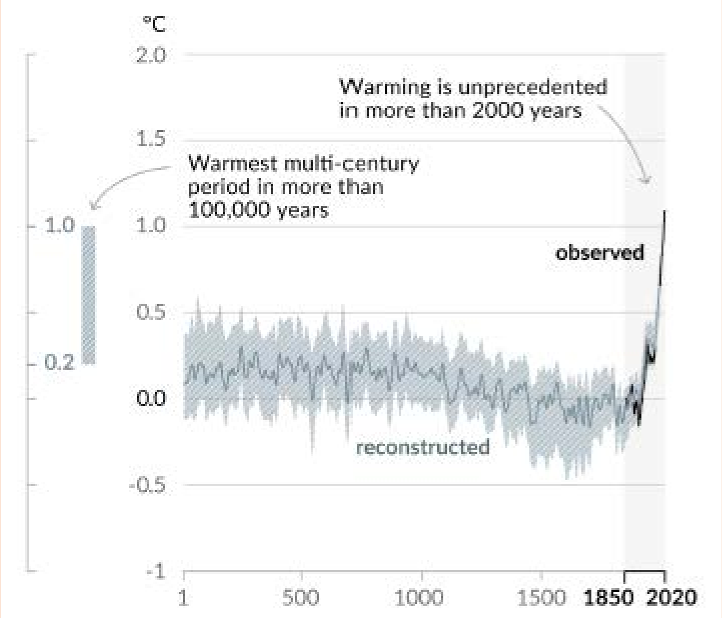
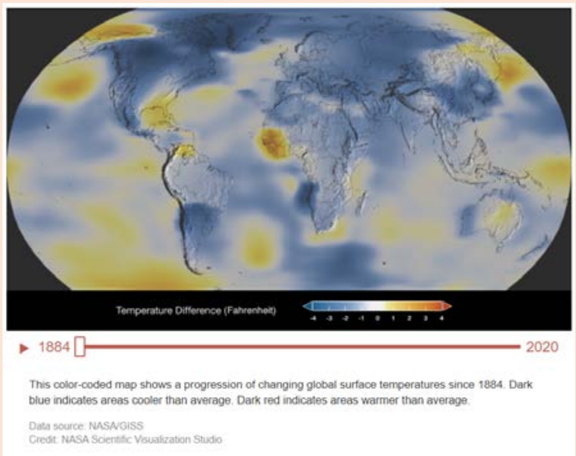


Figure 16.4 Change in global surface temperature (decadal average) as reconstructed (1-2000) and observed (1850-2020), taken from https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

It is important to note that reconstructions of temperatures 100,000 years in the past are less than observed present day temperatures.

NASA, as part of the 'Climate Time Machine', has published an interactive graphic of the map of the world showing how global temperature has varied from 1884 to 2020 https://climate.nasa.gov/interactives/climate-time-machine

Figure 16.5 shows a snapshot of global surface temperatures in 1884 and 2020 taken from the NASA 'Climate Time Machine', interactive graphic of the map of the world showing how global temperature has varied from 1884 to 2020 https://climate.nasa.gov/interactives/climate-time-machine .



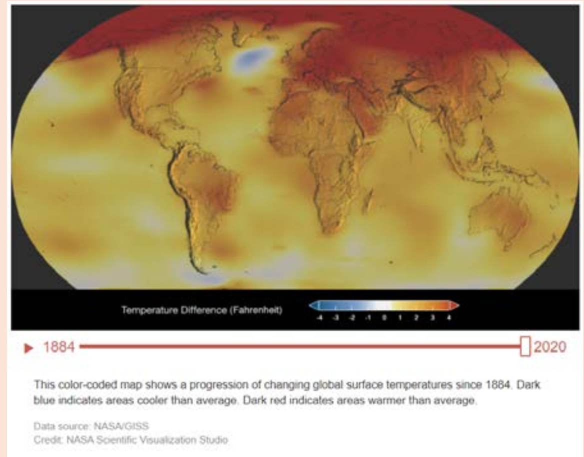


Figure 16.5 Snapshot of global surface temperatures in 1884 and 2020 taken from the NASA 'Climate Time Machine', interactive graphic of the map of the world showing how global temperature has varied from 1884 to 2020 https://climate.nasa.gov/interactives/climate-time-machine .

The Copernicus Climate Change Service reports that the last seven years to 2021 were the world's hottest on record https://climate.copernicus.eu/copernicus-globally-seven-hottest-years-record-were-last-seven.

The World Meteorological Organization reports that July 2023 was the hottest July on record, https://public.wmo.int/en/media/news/july-2023-confirmed-hottest-month-record .

News reports March 2022 report that Antarctica and Arctic hit temperatures 40°C and 30°C hotter than normal https://globalnews.ca/news/8698454/antarctica-arctic-temperatures-records/ and https://www.france24.com/en/science/20220324-polar-regions-record-absurd-high-temperatures-weather-quirk-or-unprecedented-bad-news .

The Guardian newspaper published a synthesis of data published by the Copernicus Climate Change Service (C3C https://climate.copernicus.eu/) which indicates that the summer months of 2023 were the highest ever recorded https://www.theguardian.com/world/2023/sep/06/summer-of-2023-hottest-recorded-in-wake-up-call-to-cut-carbon-emissions?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-09-07&utm_campaign=Daily+Briefing+07+09+2023 . The impacts of the increase in global temperature during the summer months are highlighted in The Guardian article, https://www.theguardian.com/environment/ng-interactive/2023/sep/29/the-hottest-summer-in-human-history-a-visual-timeline .

The Copernicus Climate Change Service also published a graph showing how close the Earth is to realizing global warming of 1.5°C over pre-industrial temperature. This is shown in Figure 18.23 as part of the discussion on Net Zero. The relevance is that once Net Zero emissions is achieved the global warming will stop – particularly if greenhouse gas emissions are totally stopped. The target date for this is 2050. If GHG emissions continue as projected the global temperature in 2050 will be greater than 1.5°C. Go to the figure published by Copernicus at https://climate.copernicus.eu/ .

16.3 Ocean acidification

Approximately 31% of carbon dioxide emissions into the atmosphere are absorbed by the oceans (https://www.ncei.noaa.gov/news/global-ocean-absorbing-more-carbon) This amounts to a fourfold increase in ocean's annual carbon uptake between 1994 to 2007 compared to 1800 to 1994.

The ocean becomes more acidic as it absorbs carbon dioxide, as measured by pH (lower the pH the more acidic the ocean). This is illustrated in Figure 16.6. The carbon dioxide combines with water to form carbonic acid which will ultimately have an impact on aquatic life (shell forming organisms for example). Measurements of pH are taken in oceans over the Earth. Figure 16.7 shows the location of sampling points in the Pacific. Figure 16.8 shows how increases in the concentration of carbon dioxide in the atmosphere correlates with decreases in pH (increased acidity). The acidification of the Arctic Ocean is discussed in a report by the Arctic Monitoring and Assessment Program, AMAP, http://www.amap.no/documents/doc/Arctic-Ocean-Acidification-2013-An-Overview/1061.

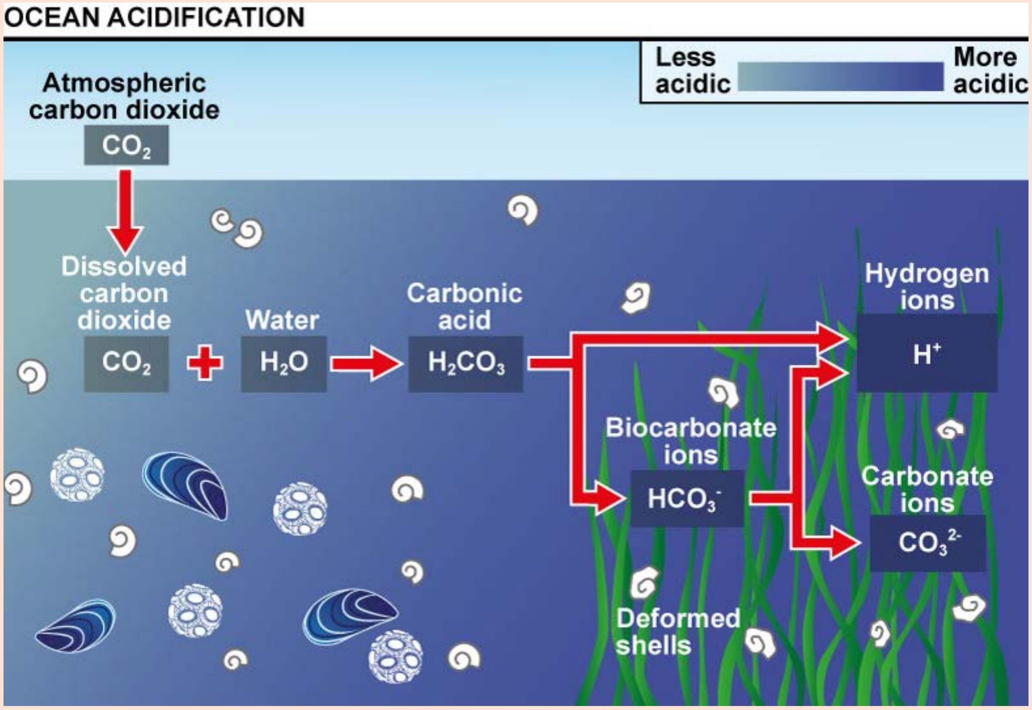


Figure 16.6 Ocean acidification.
https://www.oceanacidification.org.uk/

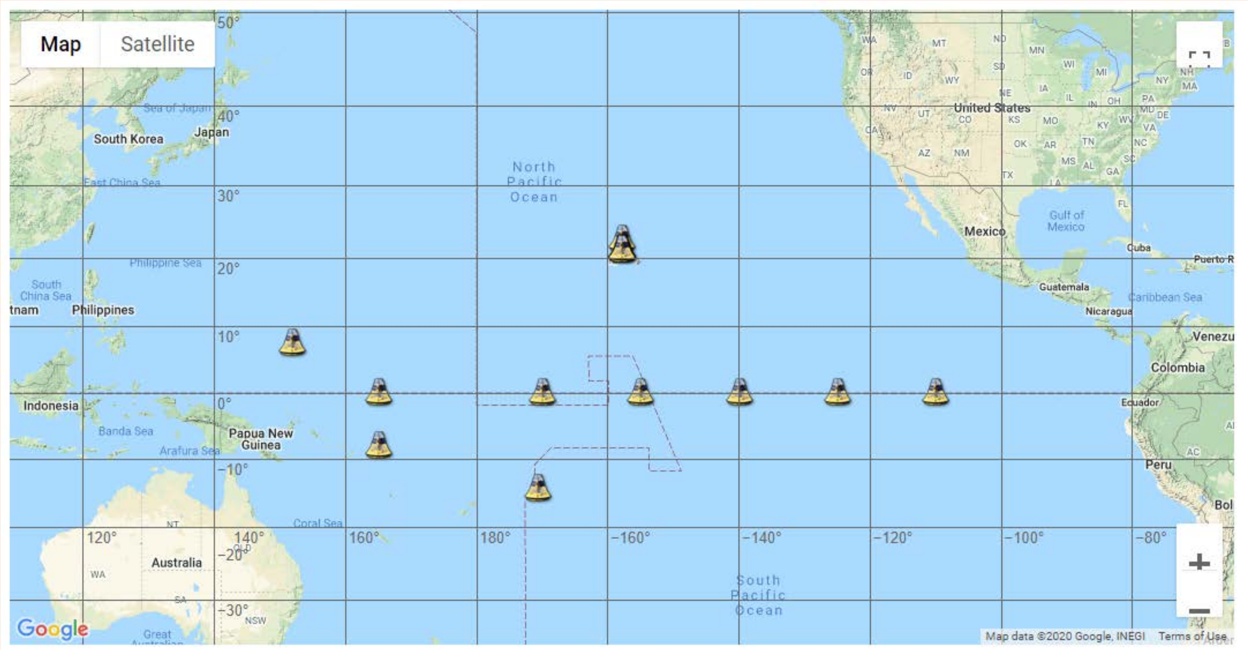


Figure 16.7 Buoys providing real-time data on ocean pH in north Pacific Ocean.
https://www.pacioos.hawaii.edu/projects/acid/

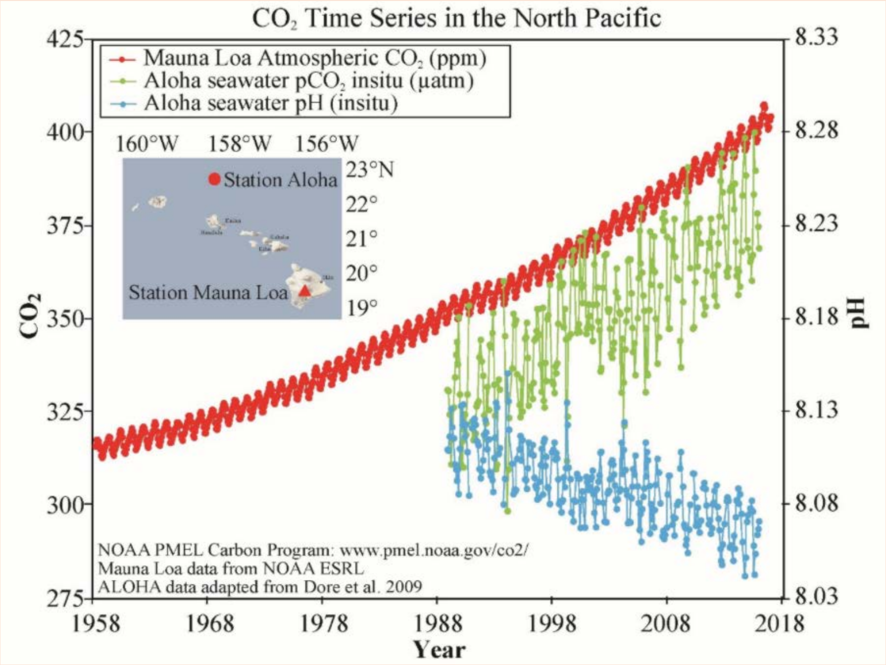


Figure 16.8 Changes in atmospheric carbon dioxide, Mauna Loa, Hawaii and pH of seawater of adjacent Station Aloha. https://en.unesco.org/ocean-acidification

16.4 Arctic

The Arctic is defined by the location of the North Pole (which is in Canada). The location maps shown in Figure 16.9 show that the Arctic is shared by Canada, USA, Denmark, Russia and Sweden and Finland to some extent. Greenland is considered separately.

Figure 16.9 Arctic region location maps.
https://www.arcticcentre.org/EN/arcticregion/Maps/Sea-Ice

The polar regions have experienced much greater temperature increases that the average global temperature (known as Arctic amplification), (https://www.nasa.gov/topics/earth/features/warmingpoles.html#:~:text=Taylor's%20research%20shows%20the%20Earth's, poles%20through%20large%20weather%20systems.&text=But%20the%20poles%20are%20warming, during%20the%20same%20time%20period.)

It is very important to note that the rapid warming being experienced in the Arctic will also affect the melting of the Greenland Ice Field and all ice caps in the Arctic, permafrost and animal habitat both terrestrial and sea.

See Figure 16.10 which shows the departure from average air temperature in the Arctic. Considerable study of the Arctic region has been performed under the auspices of the Arctic Monitoring and Assessment Program, AMAP. They have published a report titled, Snow, Water, Ice and Permafrost in the Arctic (SWIPA) in 2017, http://www.amap.no/swipa which all nations sharing the Arctic have contributed. The World Wildlife Fund has published a report in 2008 titled, Arctic Climate Impact Science – an update since ACIA, https://wwfeu.awsassets.panda.org/downloads/final_climateimpact_22apr08.pdf. The temperature increase has resulted in major changes in sea ice cover, permafrost melt and glacier melt. These effects have impacted wildlife populations. There is also some concern over the volumes of freshwater that are flowing into the Arctic Ocean and the effects this might have on ocean circulation in the north Atlantic.

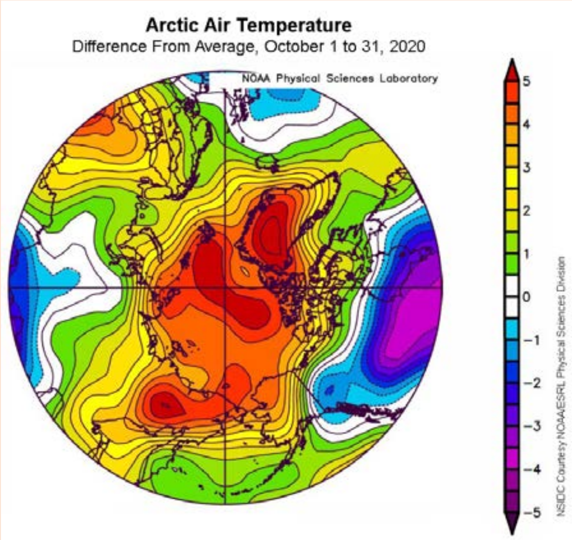


Figure 16.10 Arctic air temperature October 31, 2020. Yellows and reds indicate higher than average temperatures and blues and purples indicate lower than average temperatures. http://nsidc.org/arcticseaicenews/

A recent report from the Norwegian Centre for Climate Services provides an update on how Arctic Sea ice is decreasing and the impacts that this will have on the habitat for such animals as polar bears and walruses (https://www.bjerknes.uib.no/en/article/news/svalbard-have-experienced-warming-4c-last-50-years) where a reference is made to their report, 'Climate in Svalbard 2100'. This study is supported by a recently published paper in the 'communications earth and environment', titled 'Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's last ice area', https://www.nature.com/articles/s43247-021-00197-5?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210702&utm_medium=email&utm_source=Revue%20Daily.

The National Oceanic and Atmospheric Administration, NOAA, has published an Arctic Report Card since 2006; the most recent for 2021 may be found in https://www.arctic.noaa.gov/Report-card. The Report highlights the rapid warming, decline in sea ice extent, decrease in snow cover, accelerated melt of the Greenland ice sheet, retreating glaciers, and species migration resulting from habitat changes. NOAA published the 'Arctic Report Card: Update for 2022, https://arctic.noaa.gov/report-card/report-card-2022/ .

An explanation as to why the Arctic is warming faster than the global average may be found in an article published in the newsletter, Carbon Brief, 11.02.2022 by Dr. Matthew Henry, https://www.carbonbrief.org/guest-post-why-does-the-arctic-warm-faster-than-the-rest-of-the-planet?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220214&utm_medium=email&utm_source=Revue%20Daily. This article is based on a paper titled 'Process Drivers, Inter-Model Spread, and the Path Forward: A Review of Amplified Arctic Warming, by Taylor, Patrick C., et al in the journal Frontiers of Earth Science, 09 February 2022, https://www.frontiersin.org/articles/10.3389/feart.2021.758361/full. The author(s) explain that the amplified Arctic warming is the result of a number of factors including decreased albedo as result of loss of sea ice, lack of strong convective circulation which would have otherwise circulated warm air on the surface to the upper atmosphere, increased warming due to increase in moisture laden air from the equatorial regions to the Arctic where it condenses and releases heat and seasonal differences where the increased heat content of the Arctic ocean (due to effects just listed) tends to result in a warmer winter.

A recent article published Carbon Brief titled 'The Arctic has warmed 'nearly four times faster' than the global average', https://www.carbonbrief.org/the-arctic-has-warmed-nearly-four-times-faster-than-the-global-average/?utm_campaign=Daily%20Briefing&utm_content=20220812&utm_medium=email&utm_source=Revue%20newsletter summarizes an article in the journal Nature Briefing titled 'The Arctic has warmed nearly four times faster than the globe since 1979' https://www.nature.com/articles/s43247-022-00498-3 . A review of several datasets shows that previous estimates underestimated the difference between the temperature increases in the Arctic and the globe indicating that the probable difference is four times.

Mechanisms behind the phenomenon of Arctic amplification including modeling and data analysis efforts and observational elements was published by the American Meteorological Society January 2023 titled 'Atmospheric and Surface Processes, and Feedback Mechanisms Determining Arctic Amplification – A Review of First Results and Prospects' of what they name the $(AC)^3$ Project , https://journals.ametsoc.org/view/journals/bams/104/1/BAMS-D-21-0218.1.xml?tab_body=abstract-display . (Referenced in the newsletter of the Arctic Institute September 7, 2023.) This work is the result of an extensive collaboration with many researchers from several institutes and universities worldwide. It represents the most recent advances on the subject of Arctic amplification. The following figures and table have been extracted from the paper.

Near-surface air temperature—Changes since 1960

The strong increase of the Arctic near-surface air temperature observed over the last decades represents one of the most evident signs of Arctic climate change. The first indications of an amplified warming in the Arctic, as compared to midlatitude, tropical, and global warming, appeared in the mid-1990s (Fig. SB1a). Since then, a gradually increasing divergence between Arctic and non-Arctic average near-surface air temperature has been observed. The strength of the amplified warming depends on the season with the largest warming in winter (Fig. SB1b). The winter of 2017/18 showed the most dramatic indications of amplified warming in the Arctic observed so far, with a 2.8-K-higher temperature compared to the global warming. During the last 30 years, the Arctic has warmed with respect to the proceeding 30-yr period by 0.87–1.63 K, depending on season (Table SB1a). This warming is much stronger than that observed in the midlatitudes, the tropics, and globally. In addition, Table SB1b quantifies the ratios of the averaged warming in the Arctic with respect to the midlatitudes, the tropics, and the global warming, which can be interpreted as Arctic amplification factors. They range between 1.32 and 2.96, depending on the reference region and season with largest values in winter and spring.

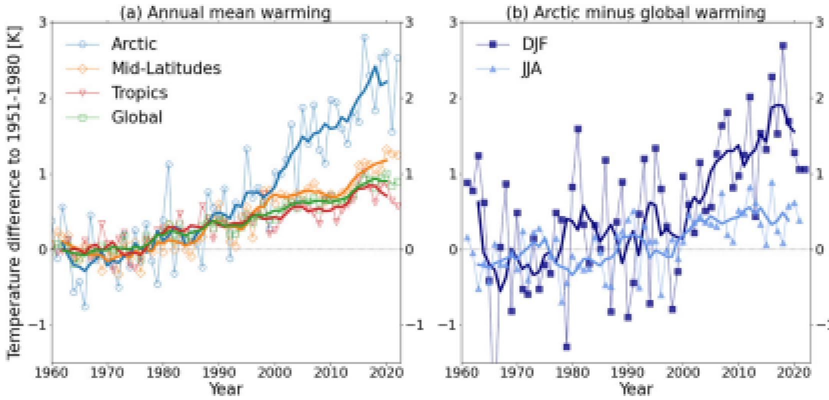


Fig. SB1. Time series of zonally and meridionally averaged, near-surface air temperature differences (anomalies). (a) The annually averaged differences of the near-surface air temperature relative to the corresponding long-term mean over the time period of 1951–80 for the Arctic (60°–90°N), midlatitudes (30°–60°N), tropics (20°S–20°N), and the globe. (b) The difference of the warming in the Arctic shown in (a), and the global average warming for winter (DJF) and summer (JJA). The thick lines in (a) and (b) without symbols indicate 5-yr running averages. The curves for spring (MAM) and fall (SON) are similar to those for DJF and, therefore, have been omitted in (b). The data are provided by the NASA GISTEMP Team, 2020: GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies. Dataset accessed at https://data.giss.nasa.gov/gistemp/ on 8 Jun 2022.

Table SB1. (a) Averaged (1991–2021) increase of the Arctic near-surface air temperature as compared to the reference period of 1951–80. (b) Arctic amplification factors (ratio of averaged warming in the Arctic in relation to midlatitudes, tropics, and the globe). The same data source as in Fig. SB1 has been used.

	Annual	DJF	MAM	JJA	SON
Averaged warming (K)					
Arctic	1.33	1.49	**1.63**	**0.87**	1.33
Midlatitudes	0.71	0.77	0.75	0.66	0.64
Tropics	0.54	0.51	0.55	0.55	0.54
Global	0.60	0.60	0.62	0.58	0.58
Arctic amplification factors (nondimensional)					
Arctic–midlatitudes	1.87	1.94	2.17	**1.32**	2.08
Arctic–tropics	2.46	2.92	**2.96**	1.58	2.46
Arctic–globe	2.22	2.48	2.63	1.50	2.29

They also publish a simplified schematic of important and local and remote processes and feedback mechanisms driving Arctic amplification as shown in the figure below also extracted from the paper.

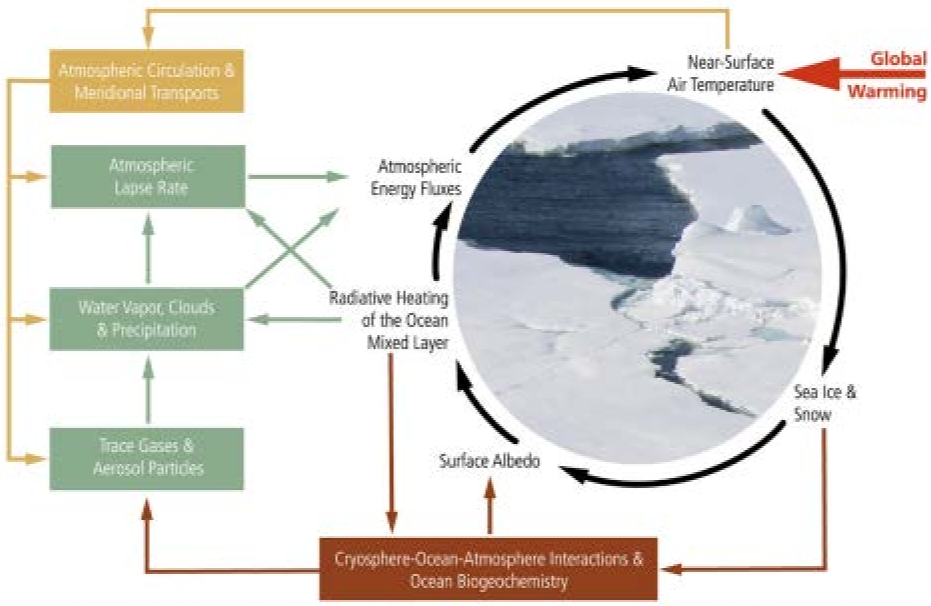


Fig. 1. The (AC)³ simplified schematic of important local and remote processes and feedback mechanisms driving Arctic amplification. The figure illustrates the initial trigger by *global warming* (red), and shows examples of processes/feedback mechanisms such as (i) *surface albedo feedback* (black), (ii) *upper-ocean effects* (brown), (iii) *local atmospheric processes* (green), and (iv) *Arctic–midlatitude linkages* (yellow). Adopted from Wendisch et al. (2017) in modified form.

The International Cryosphere Climate Initiative has published their annual report, State of the Cryosphere 2022 - Growing Losses, Global Impacts https://iccinet.org/statecryo2022/ .   The Arctic is particularly affected with respect to warming, loss of ice sheets and sea-level rise, loss of mountain glaciers and snow, loss of permafrost, loss of Arctic sea-ice and polar ocean acidification (warming and freshening).

The $(AC)^3$ Project provides a clear description of the complexity of Arctic amplification, a deeper understanding of the phenomenon and direction for further investigation. The work continues.

16.4.1 Sea ice

Changes in sea ice extent and thickness in the Arctic are reported by the National Snow and Ice Data Center, NSIDC and the Canadian Ice Service (https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions.html) and by NASA's Ice, Cloud and Land Elevation Satellite-2 (ICESat-2), https://climate.nasa.gov/news/3122/five-facts-to-help-you-understand-sea-ice/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter. Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

Figure 16.11 shows satellite images of the Arctic illustrating how sea ice cover changes from March to September. Figure 16.12 shows a graph indicating that Arctic Sea ice cover is at or near its historical low. Figure 16.13 shows a graph of average monthly Arctic Sea ice extent for the month of October from 1979 to 2020. Note the significant decrease.

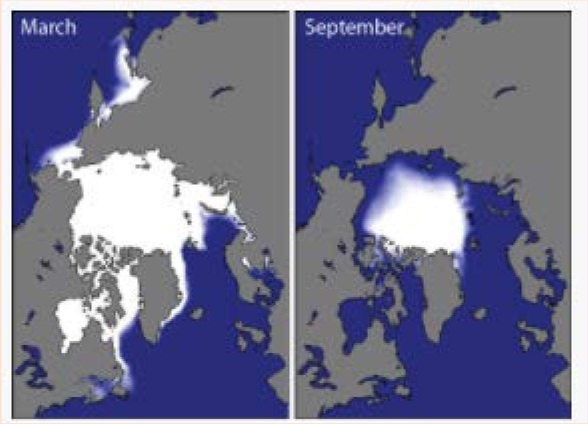


Figure 16.11 Satellite images of Arctic illustrating how sea cover changes from March to September. https://nsidc.org/cryosphere/sotc/sea_ice.html

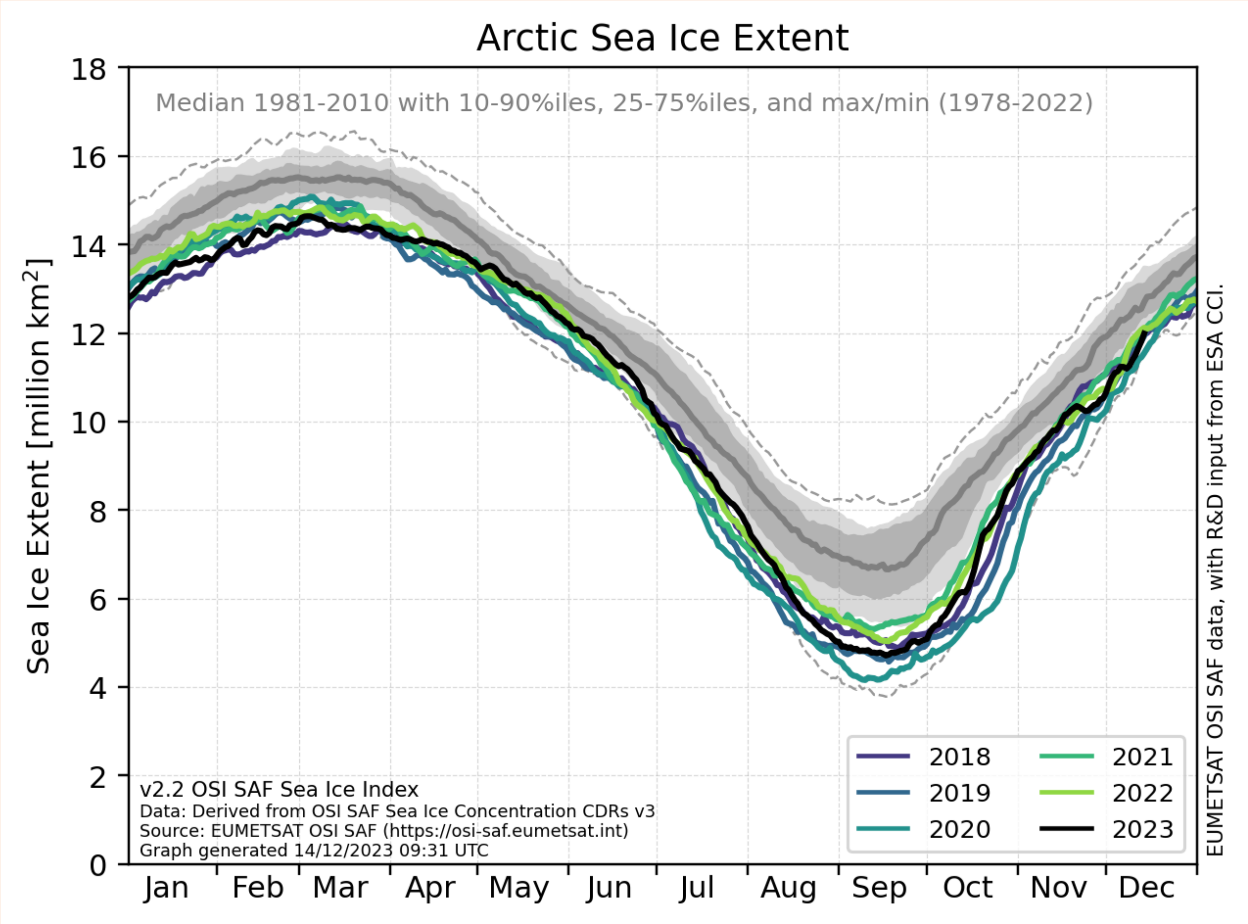


Figure 16.12 Arctic Sea ice extent by month to 2023. http://polarportal.dk/en/sea-ice-and-icebergs/sea-ice-extent0/

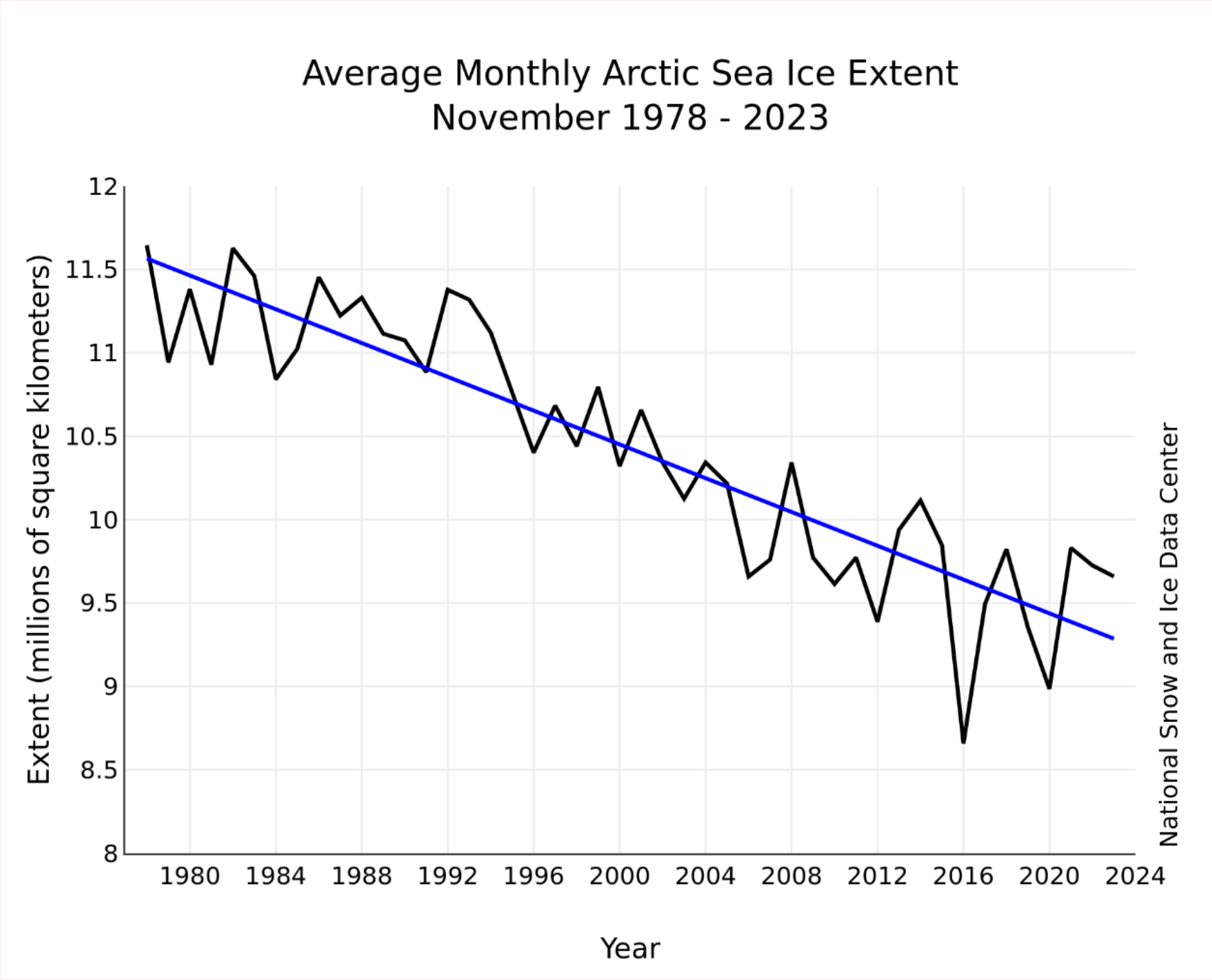


Figure 16.13 Average monthly Arctic Sea ice extent for month of October, 1979 to 2023. http://nsidc.org/arcticseaicenews/ .

The variation in sea ice volume is shown in Figure 16.14 illustrating that 2020 is at or near the historical low. ESA's CryoSat-2 satellite, https://earth.esa.int/web/eoportal/satellite-missions/c-missions/cryosat-2 ,
http://www.esa.int/Applications/Observing_the_Earth/CryoSat ,
https://www.metoffice.gov.uk/research/climate/cryosphere-oceans/sea-ice/measure, and
NASA satellite ICESat-2, https://icesat-2.gsfc.nasa.gov/
https://www.nasa.gov/content/goddard/icesat-2 and
https://svs.gsfc.nasa.gov/4734, measures sea ice thickness.
The downward trend in annual sea ice volume is clear from analysis performed by the Polar Science Center as shown in Figure 16.15.

The significance of sea ice to climate and habitat is discussed by NASA, https://climate.nasa.gov/news/3122/five-facts-to-help-you-understand-sea-ice/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter. They state:

1. The sea ice minimum is declining at the rate of 13% per decade. This is significant because less solar radiation is reflected back to space and warms the water and the atmosphere above it (ice-albedo feedback cycle).
2. Sea ice acts as a blanket separating the ocean from the atmosphere preventing the warmer water from warming the atmosphere above it.
3. Sea ice is the habitat for Arctic Foxes, polar bears, walruses and seals.

They note that sea ice melt has very little impact on sea level rise.

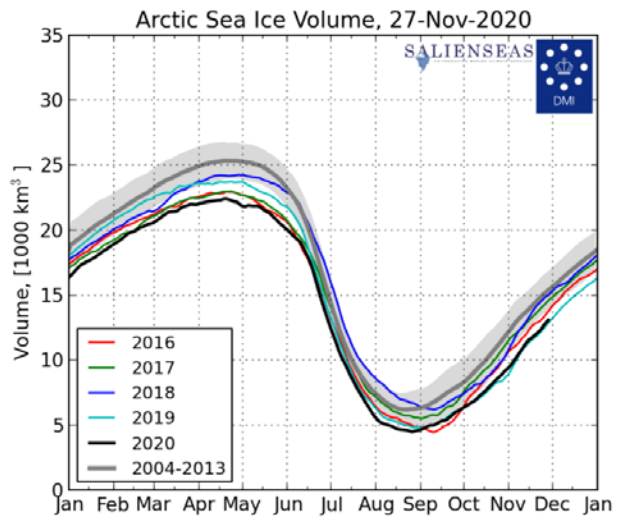


Figure 16.14 Arctic Sea ice volume. http://polarportal.dk/en/sea-ice-and-icebergs/sea-ice-thickness-and-volume/

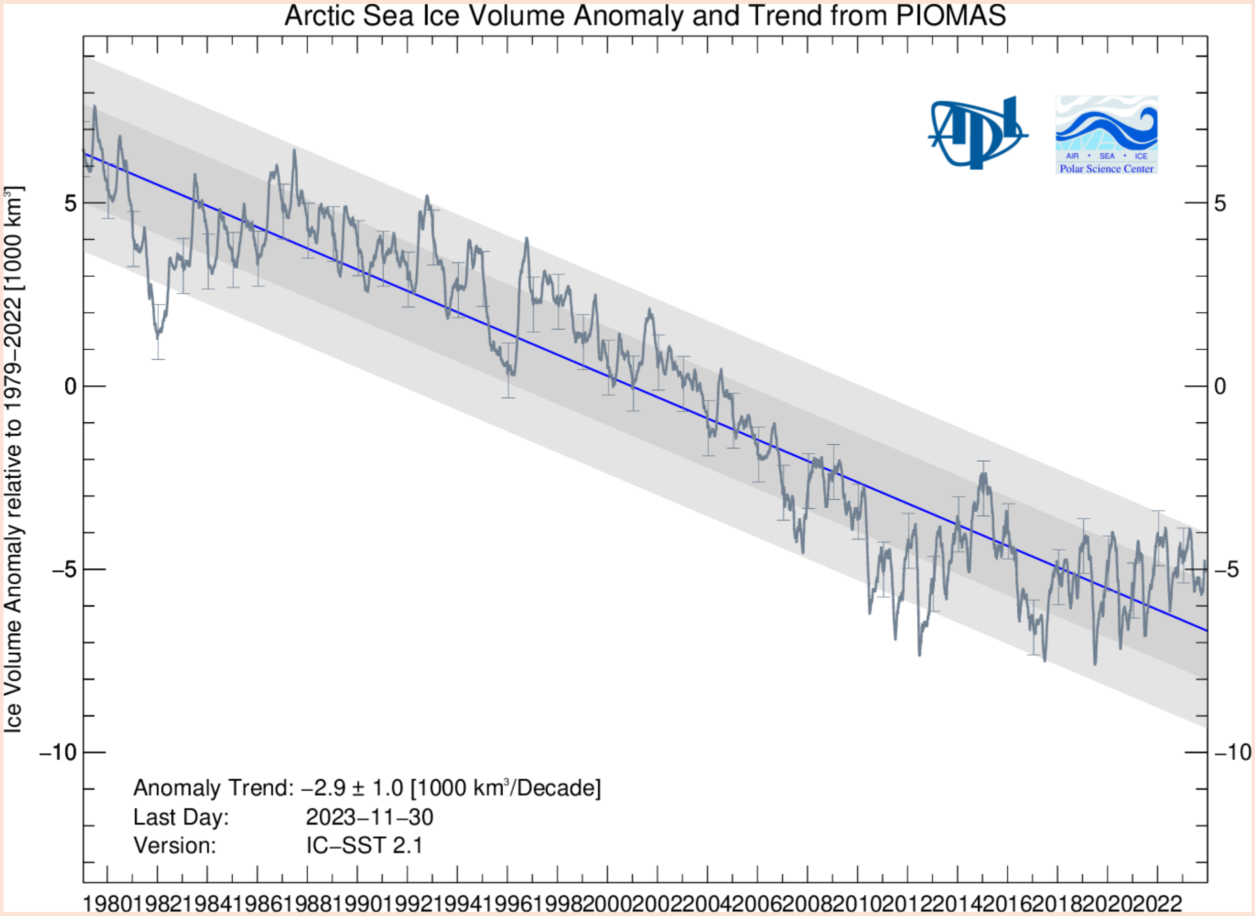


Figure 16.15 Arctic Sea ice volume from analysis by Polar Science Center. http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/

The significance of the seasonal extent of sea ice is the amount of short-wave radiation that will be reflected (albedo) and the effects on natural ecosystems (discussed later). This is illustrated in Figure 16.16. Open ocean has an albedo of 6% and will absorb 94% of short-wave radiation. Bare ice has an albedo of 50% and snow-covered ice (and ground) as high as 90%. The albedo of snow will decrease significantly if there is black carbon and inorganic aerosols in the snow. With the decrease in sea ice extent and observation of black carbon and inorganic aerosols in snow the Arctic region is absorbing much more solar radiation, and is warming. This phenomenon is an example of the positive feedback effect of global warming – temperature increases. The Arctic Monitoring and Assessment Program has published a detailed report on the effects of black carbon and aerosols in their report titled, The Impact of Black Carbon on Arctic Climate, https://www.amap.no/documents/doc/the-impact-of-black-carbon-on-arctic-climate/746.

A recent study published in 'communications earth & environment', documenting the accelerating sea ice loss in the Arctic may be found in https://www.nature.com/articles/s43247-021-00197-5?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210702&utm_medium=email&utm_source=Revue%20Daily . This study is supported by the Norwegian Centre for Climate Services which describes the rate of warming in the Arctic and how the climate has changed in their report titled "Climate in Svalbard 2100" https://www.nature.com/articles/s43247-021-00197-5?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210702&utm_medium=email&utm_source=Revue%20Daily

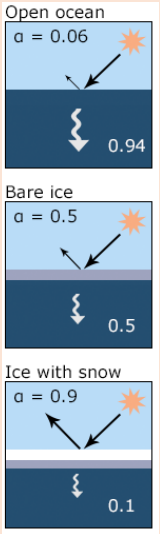


Figure 16.16 Albedo of open ocean, bare ice and snow cover in northern hemisphere. http://nsidc.org/cryosphere/snow/climate.html https://nsidc.org/cryosphere/seaice/processes/albedo.html

Two videos which describe how Arctic Sea ice circulates and moves into the North Atlantic are: Arctic sea ice decline 1984 to 2019, ESRI, https://www.youtube.com/watch?v=C17-Z_sl5cI and Mechanism for Arctic Sea ice decline, Yale, https://www.youtube.com/watch?v=oNTLINqDG_E&feature=youtu.be .

NASA has published an interactive graphic showing how the extent of sea ice has changed from 1979 to present, https://climate.nasa.gov/interactives/climate-time-machine . Figure 16.17 shows a snapshot of sea ice extent in 1979 and in 2020.

Figure 16.17 shows a snapshot of sea ice extent in 1979 and in 2020
https://climate.nasa.gov/interactives/climate-time-machine

16.4.2 Permafrost

National Geographic provides a very good description and discussion of permafrost, https://www.nationalgeographic.org/encyclopedia/permafrost/ . "Permafrost is a permanently frozen layer on or under Earth's surface. It consists of soil, gravel and sand usually bound together by ice. Permafrost usually remains at or below 0°C for a least two years.

Permafrost can be found on land and below the ocean floor. It is found in areas where temperatures rarely rise above freezing. This means permafrost is often found in Arctic regions such as Greenland, Canada, Alaska, Russia, China and Eastern Europe.

Permafrost thickness can range from one metre to more than 1,000 metres. Permafrost covers approximately 22.8 million square kilometres in Earth's Northern Hemisphere. Frozen ground is not always the same as permafrost. A layer of soil that freezes for more than 15 days per year is called "seasonally frozen ground". A layer of soil that freezes between one and 15 days a year is called "intermittently frozen ground".

Permafrost does not always form in one solid sheet. There are two major ways to describe its distribution: continuous and discontinuous.

Continuous permafrost is just what is sounds like: a continuous sheet of frozen material. Continuous permafrost extends under all surfaces except large bodies of water in the area. The part of Russia known as Siberia has continuous permafrost.

Discontinuous permafrost is broken up into separate areas. Some permafrost, in the shadow of a mountain or thick vegetation, stays all year. In other areas of discontinuous permafrost, the summer sun thaws the permafrost for several weeks or months. The land near the southern shore of Hudson Bay, Canada, has discontinuous permafrost."

Permafrost areas in northern hemisphere are shown in Figure 16.18.

The part of the permafrost that thaws in the summer and re-freezes in the winter is called the active layer. The effect of temperature increase is to increase the depth of the active layer and make it structurally weaker. A thicker active layer will re-freeze later in the winter. Thawing permafrost may result in bogs or swamps or the water may drain, lakes or ponds that have formed over permafrost will disappear and the area becomes a grassland (Dr. Vladimir Romanovsky, http://www.sciencepoles.org/interview/the-current-state-of-permafrost). Figure 16.19 illustrates the disruption thawing permafrost may have on infrastructure built on once stable permafrost. The Canadian National Round Table on the Environment and the Economy produced a report titled 'True North: Adapting Infrastructure to Climate Change in Northern Canada' (http://nrt-trn.ca/climate/true-north) in which they describe the impacts thawing permafrost may have and how best to manage them. In many parts of permafrost regions winter roads are constructed over frozen permafrost and ice-covered lakes and rivers (https://www.wilsoncenter.org/article/infographic-above-permafrost-winter-roads) to move goods to northern communities otherwise only accessible by air. The thicker the active layer and the warmer the winter, the later in the season the necessary conditions for winter road construction become available. Permafrost melt on coastal regions may result in substantial erosion as shown in Figure 16.20.

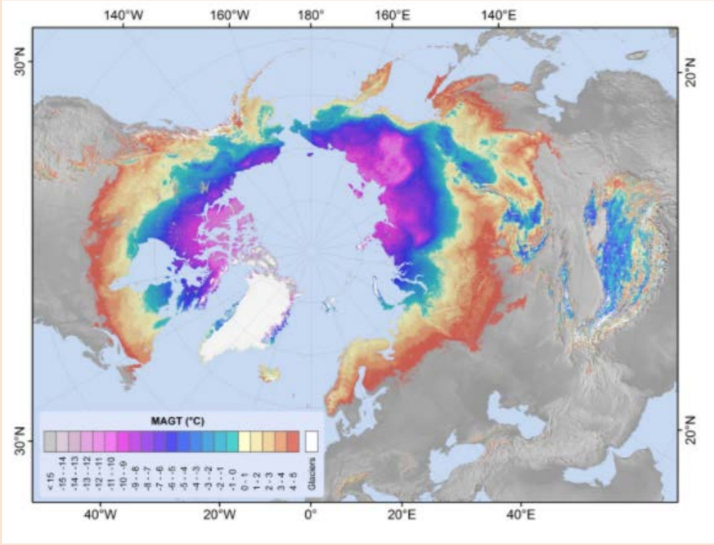


Figure 16.18 Permafrost areas in northern hemisphere.
https://www.sciencedirect.com/science/article/pii/S0012825218305907

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

Figure 16.19 Effect of increasing temperature on Arctic Infrastructure in Canada. http://www.global-greenhouse-warming.com/permafrost.html and https://www.nrcan.gc.ca/the-north/science/permafrost-ice-snow/permafrost/10961

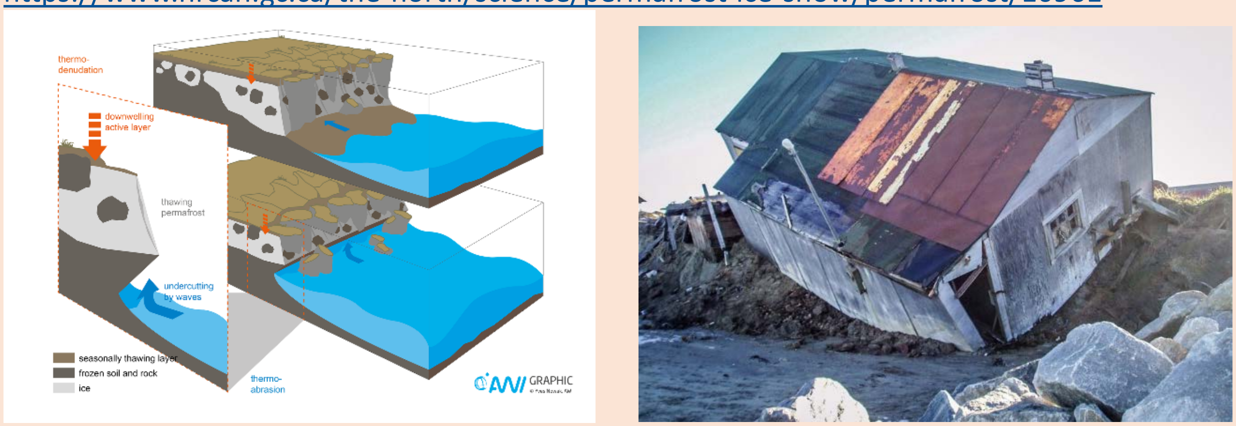


Figure 16.20 Coastal erosion due to permafrost melt. https://skepticalscience.com/The-speed-of-coastal-erosion-in-Eastern-Siberia_AWI.html

16.4.3 Loss and change of habitat

The Arctic ecosystem is being affected by increased temperature. Two of these are:

1. Loss of marine habitat such as required by polar bears and walruses. (http://assets.worldwildlife.org/publications/398/files/original/Effects_of_Climate_Change_on_Polar_Bears_fact_sheet.pdf?1345754206 and https://www.mmc.gov/priority-topics/arctic/climate-change/#:~:text=The%20Arctic%20is%20warming%20at,to%20life%20in%20the%20Arctic.)
2. Arctic cod and changing sea ice. (https://www.frontiersin.org/articles/10.3389/fmars.2019.00179/full)

3. Vegetation typical of more southern latitudes are moving north (https://esajournals.onlinelibrary.wiley.com/doi/10.1890/ES14-00111.1)

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

16.4.4 Transportation

With the decrease in sea ice extent in late summer, shipping through Arctic waters has become possible and economical. Substantial shipping in the Arctic Ocean north of Russia and the shipping route through the islands of northern Canada is now feasible (Shipping route famously named the North-West Passage) and shown in Figure 16.21. There is some dispute over whether Canada has control over these sea routes.

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

Figure 16.21 Northwest passage.
https://en.wikipedia.org/wiki/Territorial_claims_in_the_Arctic

16.4.5 Territorial claims

With the decrease in sea ice and improved transportation access, mineral deposits in the Arctic are becoming economically feasible to exploit. Territorial claims were not considered relevant when the region was inaccessible. Canada, Russia and Denmark are particularly involved and have basically made their 'claims'. Canada has defined the extent of its continental shelf and has made its submissions as shown in Figure 16.22. Others have done the same. These issues have yet to be resolved.

Figure 16.22 Canadian Territorial Claims in Arctic
https://www.un.org/Depts/los/clcs_new/submissions_files/can1_84_2019/CDA_ARC_ES_EN_secured.pdf

16.4.6 Methane and GHG's
As the permafrost thaws the previously frozen organic material in it will decompose releasing carbon dioxide as well as methane, https://www.scientificamerican.com/article/how-much-worse-will-thawing-arctic-permafrost-make-climate-change/.

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

Methane in solid form is found in substantial quantities in permafrost, the ocean floor and several hundreds of meters below the surface called deep methane.   (See essay on methane and frozen ground, https://nsidc.org/cryosphere/frozenground/methane.html and the U.S. Geological Survey Gas Hydrates Project, https://www.usgs.gov/centers/whcmsc/science/us-geological-survey-gas-hydrates-project.)   The methane found on the ocean floor and deep below the surface is fossil methane, methyl clathrates or gas hydrates. Methane from permafrost (near the surface) results from the warming and decomposition of organic matter in the permafrost (along with carbon dioxide). Warming and associated permafrost thawing is having the effect of potentially thawing the deep methane and releasing it to the atmosphere and allowing normal decomposition of permafrost organic material which would result in the release of substantial quantities of carbon dioxide (as well as the methane). This is shown in Figure 16.23. Note that the carbon dioxide would be released from the organic rich top layer of the permafrost (shown in black).

A review of permafrost science in IPCC's AR6 was performed by the Woodell Climate Research Centre, https://www.woodwellclimate.org/review-of-permafrost-science-in-ipccs-ar6/. They report:

- With increasing warming, there is high confidence that thawing permafrost will lead to carbon release. Already, some regions of permafrost are net sources of carbon.

- The losses of permafrost carbon are irreversible at centennial timescales.

- There remains uncertainty on the timing and magnitude of emissions from permafrost.

- The carbon budget is the amount of carbon that can be released without overshooting temperature targets (1.5°C and 2°C) set under the Paris Accord.

- Most climate models still do not include permafrost processes. Nonetheless, the remaining carbon budgets (the amount of carbon that can be released without overshooting temperature targets) featured in AR6 do include emissions from permafrost for the first time.

- This is done using a simplified, preliminary estimate that both assumes a linear relationship between warming and permafrost emissions and excludes a number of critically important thaw processes—notably abrupt thaw (thaw-induced ground collapse that exposes deep permafrost) and fire-permafrost interactions. As a result, the projection (3–41 $GtCO_2$ per 1°C of warming by 2100) is underestimating permafrost carbon emissions potential in the budgets.

The concern is that underestimating GHG production from thawing and decomposing permafrost is the overestimation of how much GHG may be produced by human activities to meet 1.5 °C target.

Figure 16.23 Thawing of permafrost and release of carbon dioxide and methane. http://woodshole.er.usgs.gov/project-pages/hydrates/

An unexpected result of Arctic warming is the creation of methane craters believed to result from catastrophic release of deep (fossil) methane https://www.woodwellclimate.org/arctic-sinkholes-documentary-methane-craters/, as shown in the photograph in Figure 16.24. The amount of fossil methane released is considered significant.

Figure 16.24 Methane crater believed to result from catastrophic release of deep (fossil) methane, https://www.woodwellclimate.org/arctic-sinkholes-documentary-methane-craters/

A paper published in Scientific Reports December 2017 titled ‘Strong geologic methane emissions from discontinuous terrestrial permafrost in the Mackenzie Delta, Canada’ describes how “Arctic permafrost caps vast amounts of old, geologic methane in subsurface reservoirs.” and how “Thawing permafrost opens pathways for the CH4 to migrate to the surface.” https://www.nature.com/articles/s41598-017-05783-2.

Another useful discussion on permafrost or frozen ground including; physics, occurrence, ecology, relationship with people, how it is studied, and formation and occurrence of methane and frozen ground may be found in https://nsidc.org/cryosphere/frozenground/climate.html.

16.4.7 Glaciers

The glaciers on Baffin Island, high in the Canadian Arctic, are disappearing. (https://blogs.agu.org/fromaglaciersperspective/2019/08/22/the-disappearance-of-multiple-baffin-island-glaciers-2002-2019/ and https://www.livescience.com/64602-arctic-baffin-island-ice-photos.html).

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

16.5 Greenland

Greenland is the world's largest island. It is located northeast of Canada and west of Iceland as shown in Figure 16.25. Approximately 79% of its surface is covered by what is known as the Greenland Ice Sheet containing 2,850,000 cubic kilometres of ice. Its thickness varies from 2,000 to 3,000 metres. A large percentage of glaciers in the world are located in Greenland. These glaciers drain the Greenland Ice Sheet. The Greenland Ice Sheet contains sufficient water to raise ocean levels by as much as 7 metres.

The Greenland Ice Sheet is losing mass due to:

- Outlet glaciers calving icebergs into the ocean.
- Melt water from areas adjacent to the ocean surrounding Greenland, draining into moulins, Figure 16.26, which flow to bedrock where the running water lubricates the base of glaciers and increases the speed with which they move into the ocean. The melt water may also flow into sub-glacial lakes and then into the ocean.
- Ice streams, a type of glacier flowing from an ice sheet (not to be confused with water flowing under or over the ice). Ice streams may flow into marine terminating glaciers or directly into the ocean itself. The flow of the ice stream, a type of glacier flowing from an ice sheet, may be slowed by a blocking ice shelf. The Northeast Greenland Ice Stream is shown in Figure 16.27.

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

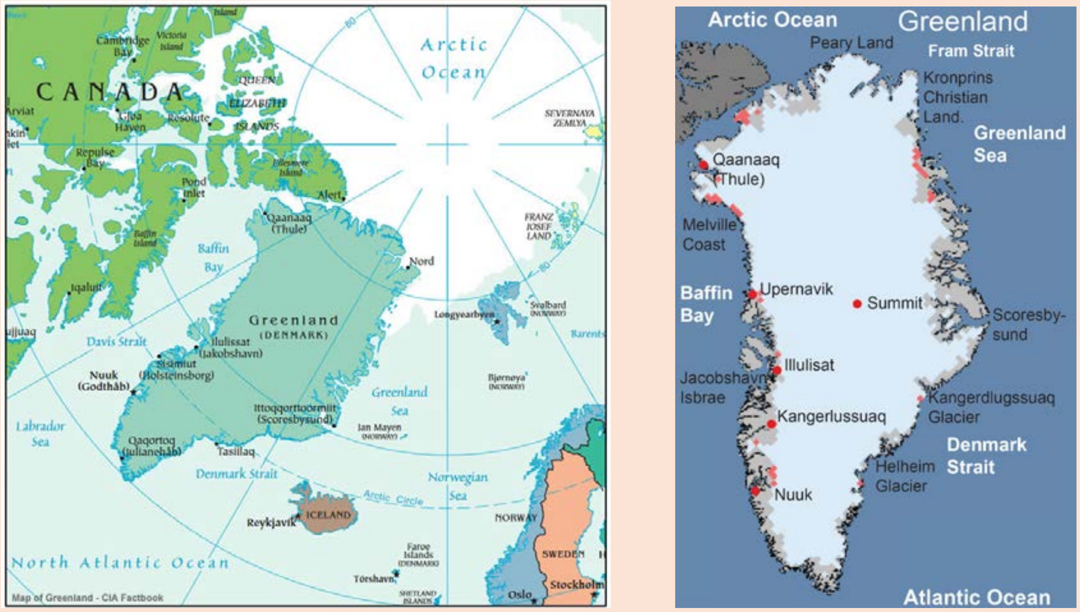


Figure 16.25 Greenland location maps.

Figure 16.26 Melt water on the surface of Greenland ice sheet flowing into a moulin.
https://scitechdaily.com/researchers-investigate-giant-holes-in-greenland-ice-sheet/

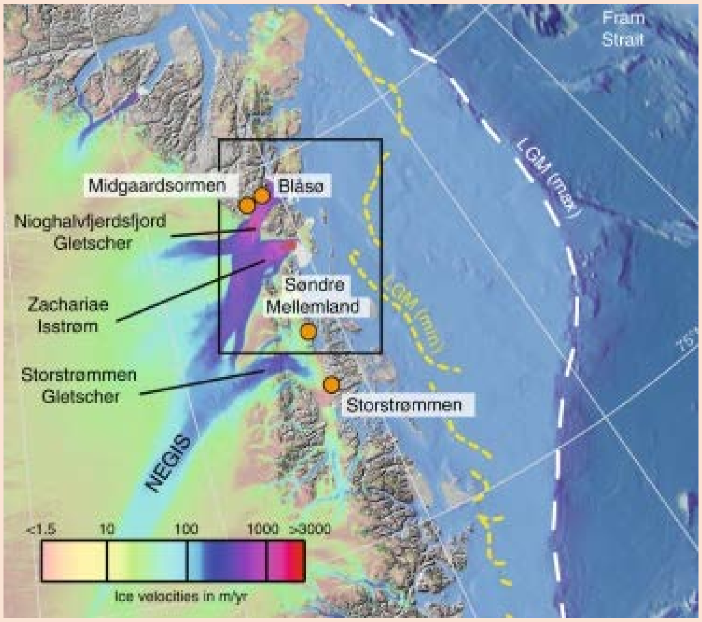


Figure 16.27 Northeast Greenland Ice Stream (NEGIS) dividing into three glaciers which then flow into the ocean.
https://www.nature.com/articles/s41467-018-04312-7

Monitoring of the mass of the Greenland ice sheet has been possible using the NASA/German Aerospace Center's twin Gravity Recovery and Climate Experiment (GRACE) satellites, https://gracefo.jpl.nasa.gov/resources/33/greenland-ice-loss-2002-2016/. The video in this web site illustrates how the Greenland ice mass has been affected by global warming. This has been updated to include 2020, https://grace.jpl.nasa.gov/resources/30/greenland-ice-loss-2002-2020/ . Greenland lost approximately 280 gigatons of ice per year, causing global sea level to rise by 0.8mm per year.

An article published in the journal, Nature Climate Change 29 August 2022 titled 'Greenland ice sheet climate disequilibrium and committed sea-level rise', https://www.nature.com/articles/s41558-022-01441-2?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220830&utm_medium=email&utm_source=Revue%20Daily , reports a study that concludes that sea-level rise by the end of the century due to Greenland ice melt will be 274 ± 68mm regardless of twenty-first-century climate pathways.

16.6 Antarctica

A map of Antarctica is shown in Figure 16.28. The area of Antarctica is 14,200,000 square kilometres of which 98% is covered with ice that averages 1,900 m in thickness.

There is considerable interest in Antarctica from a geopolitical perspective. It is not completely clear why this is the case but several countries have laid claim and manned stations on the continent as shown in Figure 16.29.

Were the Antarctica Ice Sheet to melt the sea level would increase by 60 metres. Melting ice (and icebergs) from Antarctica have contributed 7.2mm to sea level rise since the 1990's when the ice sheets were first monitored by satellite. The average midwinter temperature has increased by approximately 6 degrees Celsius since 1950 or about 1 degree Fahrenheit per decade as reported in an article published in the article, Record warming at the South Pole during the past three decades published in the journal, nature climate change, https://www.nature.com/articles/s41558-020-0815-z.epdf?sharing_token=SseQ9Rv_caI5qpG9C3Q3xdRgN0jAjWel9jnR3ZoTv0NZj9FMZf-OGYzRW4VVW5B-YJpPLoSDHzkgSCgtnA_D7VOLAQT_eO1nfY9N7zyE63wAUmjaOo-pFmfZuxcK4bT0f8eyE3Ih6QIgRJh_gCN-on_wEpfF4LCmY08eMcH6IkXogJEzQ_B0FFFhQG39srbi4Bk2N67Ugctp_0mhlPSSAhii1964yWPJIbOxMmOPX-BoPTtg2GxX5O9mmLePqKXMf2JtQ3hDK0BUk3j7Toir8SHi4TUVT0lIdsTW7uEZymdSvLrGeTX1NiusIAoQxWUu&tracking_referrer=www.scientificamerican.com and referenced in Scientific American, https://www.scientificamerican.com/article/why-is-the-south-pole-warming-so-quickly-its-complicated/.

The mass of the Antarctic ice sheet change is monitored by the GRACE satellite project (https://en.wikipedia.org/wiki/GRACE_and_GRACE-FO and https://grace.jpl.nasa.gov/resources/31/antarctic-ice-loss-2002-2020/). Antarctica has lost approximately 150 gigatons of ice per year resulting in global seal level to rise by 0.4mm per year.

A publication in the journal, Nature Brief, 10 August 2022, provides an update of the extent and seriousness of ice-shelf loss, https://www.nature.com/articles/s41586-022-05037-w . The ice-shelf loss hastens the loss of the ice sheet which flows into the ocean via glaciers at a rate that is slowed by the anchored ice-shelves. The current loss of ice sheet has been accurately assessed as described in a paper, 'Elevation change of the Antarctic Ice Sheet: 1985 to 2020' https://essd.copernicus.org/articles/14/3573/2022/ in which they report a net loss of ice from the ice sheet which would contribute directly to sea-level rise. NASA studies identify how the Antarctic Ice Sheet has been losing mass, https://climate.nasa.gov/news/3206/nasa-studies-find-previously-unknown-loss-of-antarctic-ice/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter

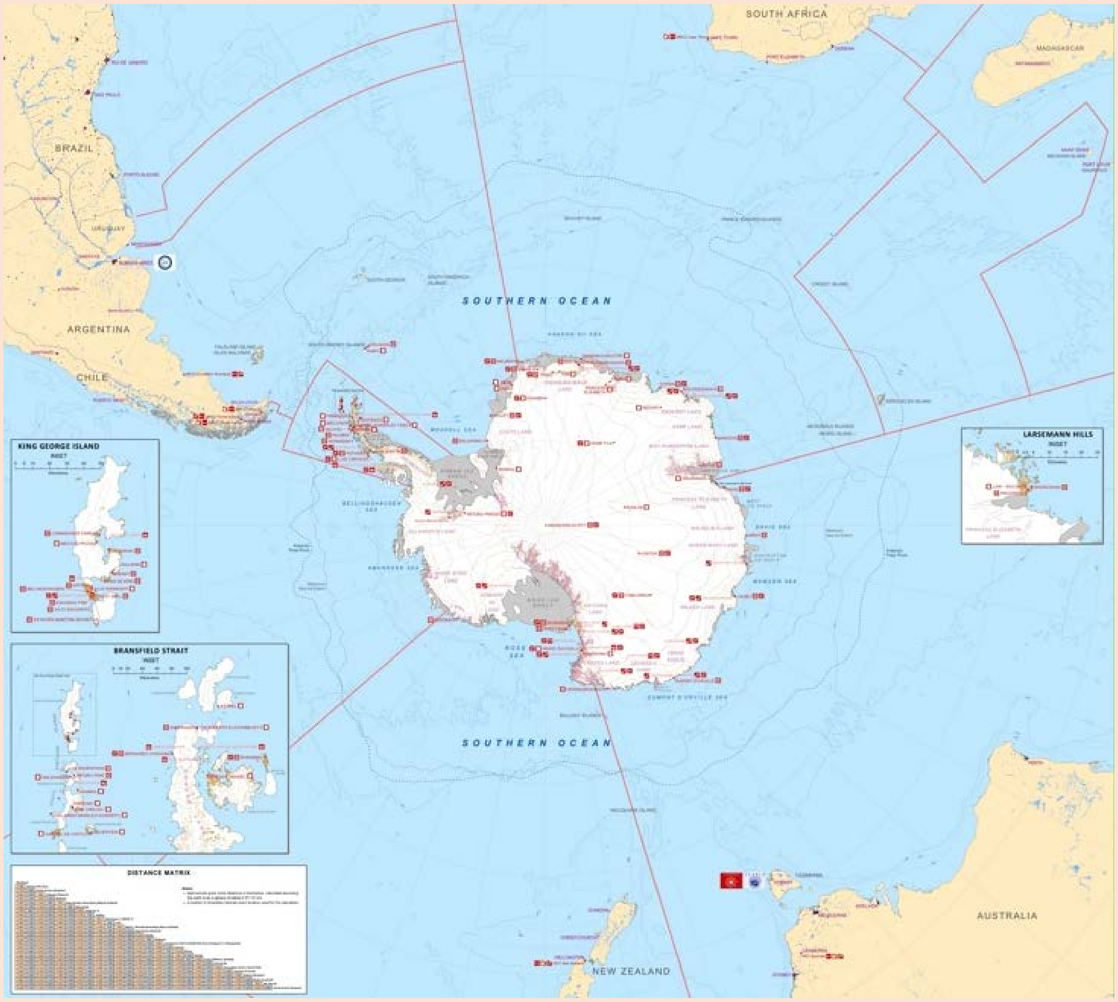


Figure 16.28 Map showing Antarctica relative to South America, Australia and Africa.

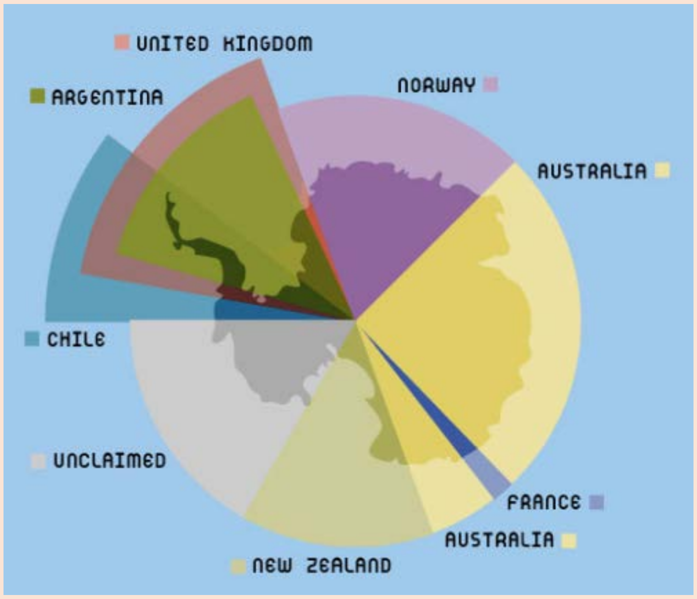


Figure 16.29 Territorial claims in Antarctic.

16.6.1 Loss of ice mass.
See State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

Similar to the Greenland Ice Sheet, Antarctica is losing mass due to:

- Outlet glaciers calving icebergs into the ocean.
- Ice streams (not to be confused with water flowing under or over the ice). Ice streams may flow into marine terminating glaciers or directly into the ocean itself. (The locations of the ice shelves and stations are shown in Figure 16.30.)

Ice shelves play a crucial role in holding back (blocking) glaciers and so controlling the loss of ice mass. Their disappearance does not affect sea level directly because they are floating. However, the more rapid movement of glaciers (non-floating ice) into the ocean will cause sea levels to rise.

The impact of global warming on Antarctica's ice shelves at warming of 1.5C, 2C and 4C is discussed in a recent paper by Dr. Ella Gilbert and C. Kittel published in Geophysical Research Letters, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL091733 and Carbon Brief, https://www.carbonbrief.org/guest-post-the-fate-of-antarctic-ice-shelves-at-1-5c-2c-and-4c-of-warming?utm_campaign=Feed%3A%20carbonbrief%20%28The%20Carbon%20Brief%29&utm_content=20210409&utm_medium=feed&utm_source=feedburner .

Examples of ice shelf break up are Larson C and the terminating ice shelf to Thornthwaites Glacier.

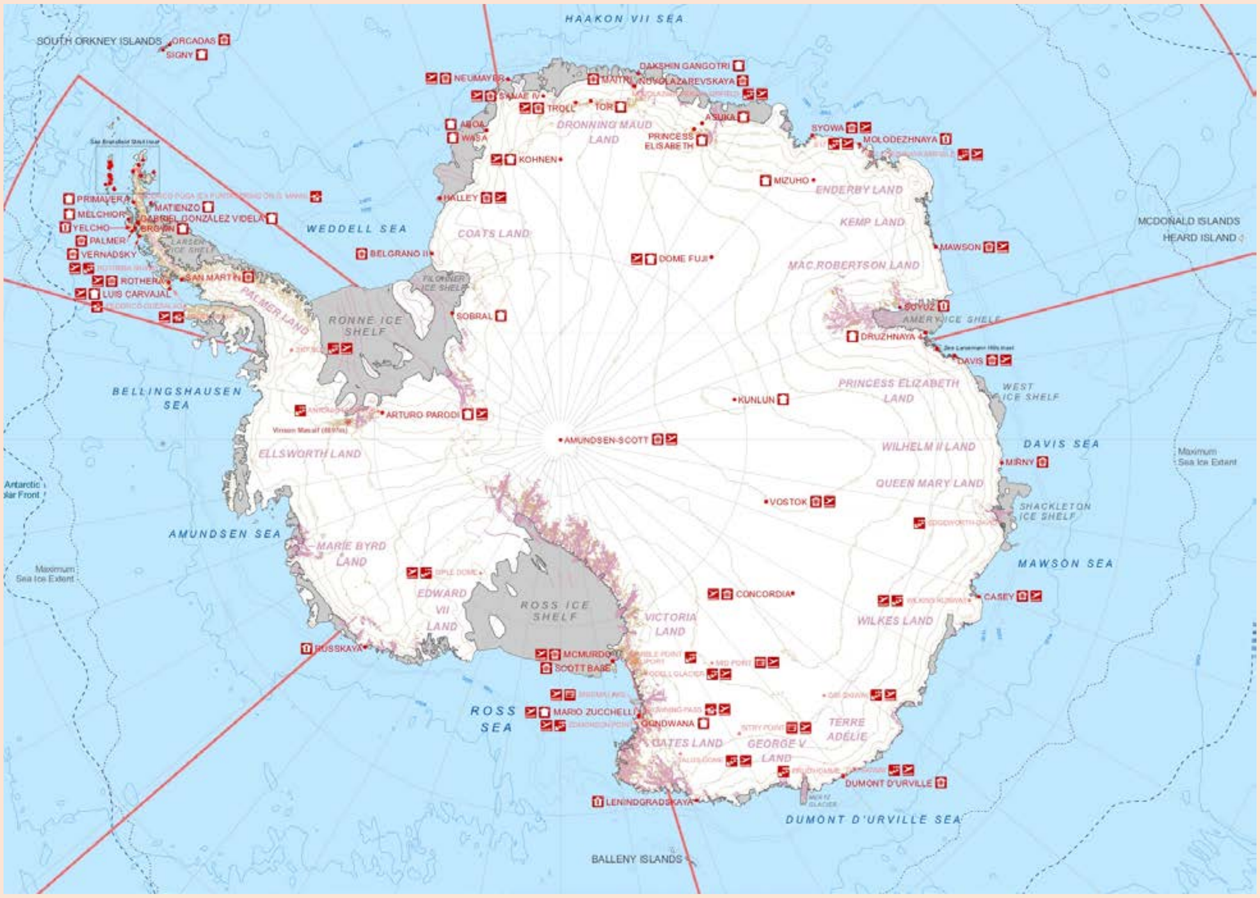


Figure 16.30 Location of the ice shelves and stations on Antarctica.

16.6.2 Break up of Larson C ice shelf

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

One of the most recent collapse of an ice shelf is the Larson C on the Antarctic peninsula (north west corner) as shown in Figure 16.31. The Larson A had broken up in 1995 and the Larson B had broken up in 2002. The Larson C began to break up in 2016. Recent studies have reported that the warming oceans are causing the ice shelves to melt from below. This weakens them structurally and ultimate they break up. A Guest Post in the newsletter Carbon Brief titled, Ranking the reasons why the Larsen C ice shelf is melting, identifies and discusses the most important causes for this breakup, https://www.carbonbrief.org/guest-post-ranking-the-reasons-why-the-larsen-c-ice-shelf-is-melting?utm_campaign=Daily%20Briefing&utm_content=20220419&utm_medium=email&utm

source=Revue%20newsletter. A portion of the shelf Larson C, is an iceberg named A68a which in November, 2020 was about to strike a British Overseas Territory, South Georgia which was expected to have catastrophic effects on the islands king penguin and elephant seal populations. See Figure 16.31. In late January 2021 it broke up. See video.

Breakup of Larson C.

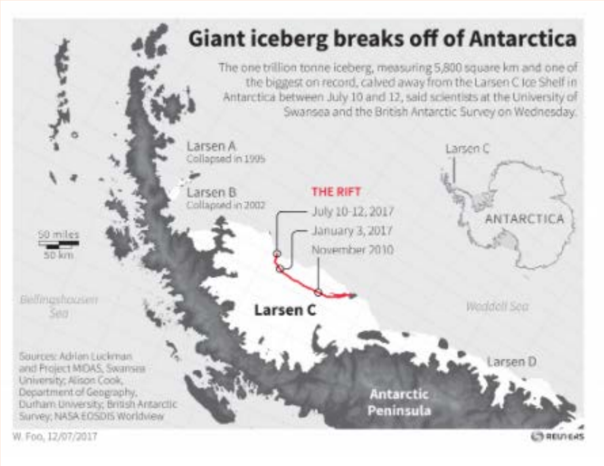


Figure 16.31 Larson C ice shelf on the Antarctic Peninsula.
https://en.wikipedia.org/wiki/Iceberg_A-68

Figure 16.32 King penguin population on South Georgia Island about to be struck by iceberg A68a which had broken away from Larsen C ice shelf, Antarctica.
https://www.ecowatch.com/south-georgia-island-iceberg-collision-2648621635.html?rebelltitem=1#rebelltitem1

16.6.3 Break up of ice shelf at the terminus of Thwaites Glacier in West Antarctica
Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .
The ice shelf blocking Thwaites Glacier (See Figure 16.33) is showing signs of immanent collapse https://climate.to/antarcticas-doomsday-glacier-how-its-collapse-could-trigger-global-floods-and-swallow-islands/?utm_term=&utm_campaign=Climate+To+DSA&utm_source=adwords&utm_medium=ppc&hsa_acc=8742646434&hsa_cam=15307078284&hsa_grp=129385859225&hsa_ad=562837904855&hsa_src=g&hsa_tgt=dsa-19959388920&hsa_kw=&hsa_mt=&hsa_net=adwords&hsa_ver=3&gclid=EAIaIQobChMIhdHhuoOR9QIVQRx9Ch0h9Q7_EAAYASAAEgKMCvD_BwE .

The Thwaites Glacier is also known as the Doomsday Glacier because of the volume of its ice flow, https://thwaitesglacier.org/about/facts. Presently, the flow from the Thwaites Glacier is already responsible for about 4% of global sea level rise https://www.science.org/content/article/ice-shelf-holding-back-keystone-antarctic-glacier-within-years-failure and is steadily increasing.

The stability of the glacier is being threatened by the break up of the ice shelf at its terminus. If this occurred, it is believed that the glacier flow will accelerate – possibly causing the flow of other adjacent glaciers to accelerate as well. A complete breakup of the Thwaites glacier would result in a 0.65 m increase in sea level. A recent paper https://www.nature.com/articles/s41561-022-01019-9 published in the journal Nature Geoscience further discusses the history of advances and retreat of the glacier over the past two hundred years.

Figure 16.33 Location of Thwaites glacier https://thwaitesglacier.org/about/facts

16.6.4 Sea ice
Changes in seasonal sea ice formation and melt as presently experienced is described in an article in Carbon Brief, 26.09.2023, https://www.carbonbrief.org/exceptional-antarctic-melt-drives-months-of-record-low-global-sea-ice-cover/?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-09-27&utm_campaign=Daily+Briefing+27+09+2023 and https://www.theguardian.com/world/2023/sep/26/antarctic-sea-ice-shrinks-to-lowest-annual-maximum-level-on-record-data-shows . September 10, 2023 the sea ice surrounding Antarctic was observed to reach record low http://nsidc.org/arcticseaicenews/ .

16.6.5 Effect of climate change on the ecology of Antarctica
Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

According to a recent paper published in the American Scientist, Ecological responses to climate change on the Antarctic peninsula (https://www.americanscientist.org/article/ecological-responses-to-climate-change-on-the-antarctic-peninsula) is resulting in major ecological shifts which are affecting both penguin and seal populations. The book written by Meridith Hooper titled ‘The Ferocious Summer: Adelie Penguins and the Warming of Antarctica’ provides details of some of the ecological changes that are occurring.

The record low 2022 Antarctic Sea ice led to catastrophic breeding failure of emperor penguins, https://www.nature.com/articles/s43247-023-00927-x .

16.7 Oceans

16.7.1 Warming

Research published in the peer-reviewed journal *Science* in February 2020 found that the world’s oceans are warming at a much faster rate than was previously estimated https://link.springer.com/article/10.1007/s00376-020-9283-7.
According to the paper, the oceans are warming 40 percent faster than they were estimated to by a United Nations panel just five years ago.

The first analysis of recent ocean heat content, OHC, through 2021 is provided in a paper published in a paper titled, ‘Another Record: Ocean Warming Continues through 2021 despite La Nina Conditions’ by Cheng, L. J, and Coauthors, 2022: Another record: Ocean warming continues through 2021 despite La Niña conditions. Adv. Atmos. Sci., https://doi.org/10.1007/s00376-022-1461-3 .   (This paper is an important follow-up to the paper published in 2020.)   The study uses data from the Institute of Atmospheric Physics at the Chinese Academy of Sciences and the National Centers for Environmental Information of the National Oceanic and Atmospheric Administration. They state that “The world ocean in 2021, was the hottest ever recorded by humans, and the 2021 annual OHC value is even higher than last year’s record value – “.   In the introduction to their paper the authors explain: “The increased concentrations of greenhouse gases in the atmosphere from human activities trap heat within the climate system and result in massive changes in the climate system. As a result, outgoing energy from the Earth system is not balancing the incoming solar radiation, thus creating Earth’s Energy Imbalance (EEI) in the climate system – “.

Figure 16.34 shows where heat is stored in the ocean. The zone where most heat is stored will exhibit the greatest temperature changes and thermal expansion. The ocean does not distribute heat energy evenly with depth. It is necessary to measure the temperature changes with depth (temperature profiles).   The changes in ocean heat content from 1955 to 2020 compared to the 1955 to 2006 average from NOAA Climate.gov https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content is illustrated in Figure 16.35.

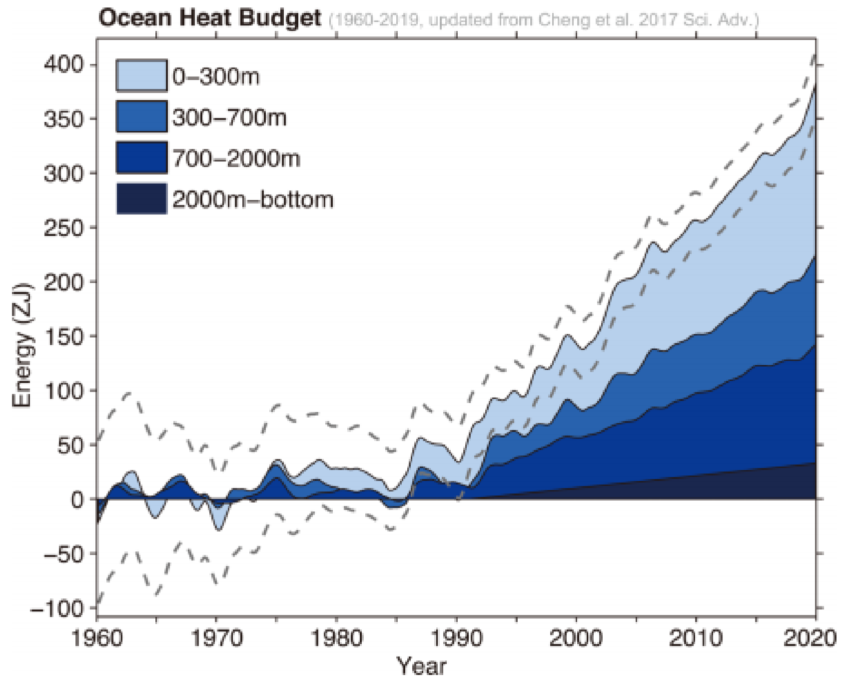


Fig. 2. Ocean heat budget from 1960 to 2019 based on IAP analysis data from 0 to 2000 m, and from Purkey and Johnson (2010) for deep ocean change below 2000 m (units: ZJ). Figure updated from Cheng et al. (2017). The anomalies are related to a 1958–1962 baseline, and the time series are smoothed by LOWESS (locally weighted scatterplot smoothing) with a span width of 24 months. The gray dashed lines are the 95% confidence interval of the total ocean heat budget.

Figure 16.34 Ocean heat content with depth. https://link.springer.com/article/10.1007/s00376-020-9283-7.

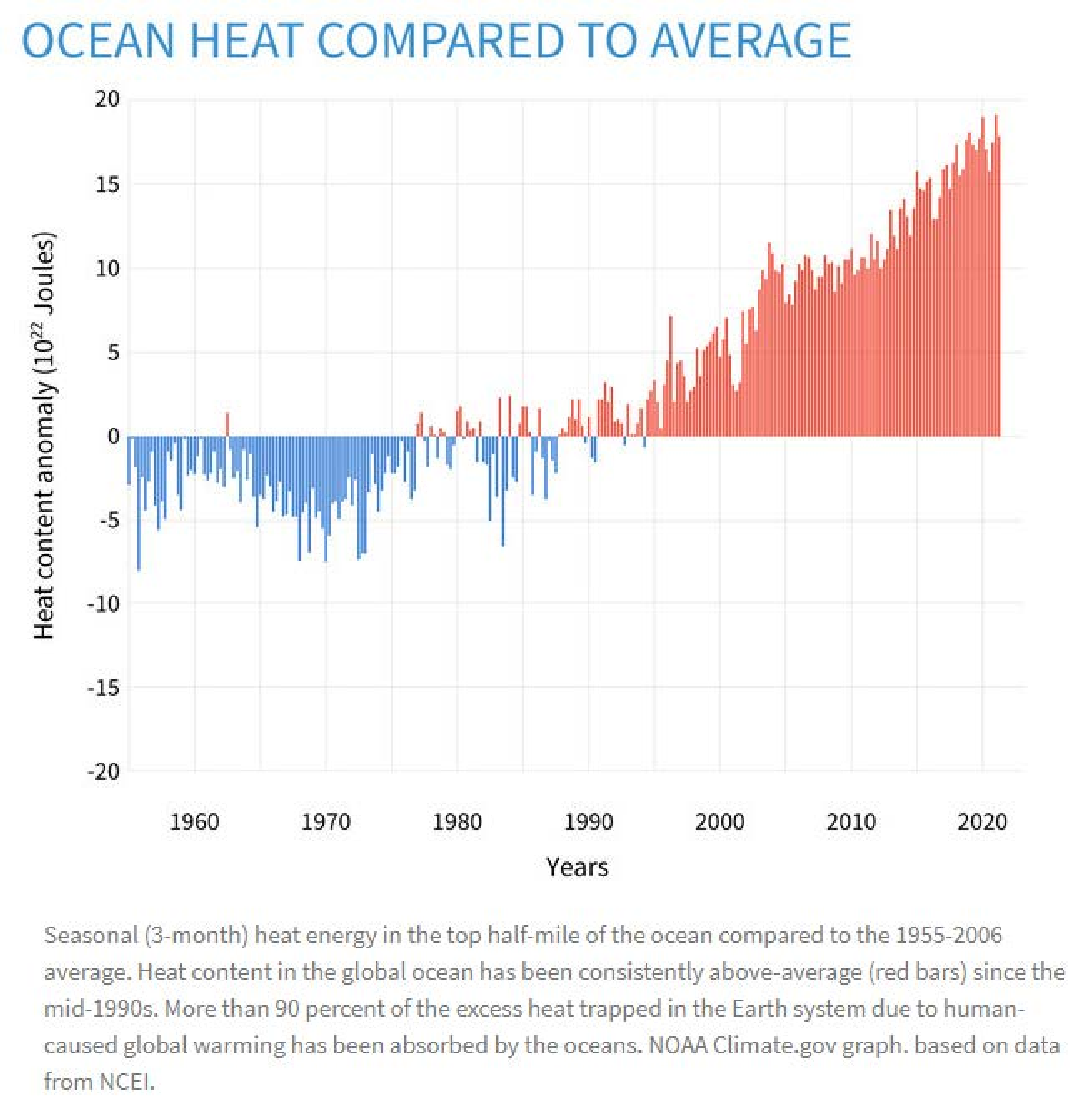
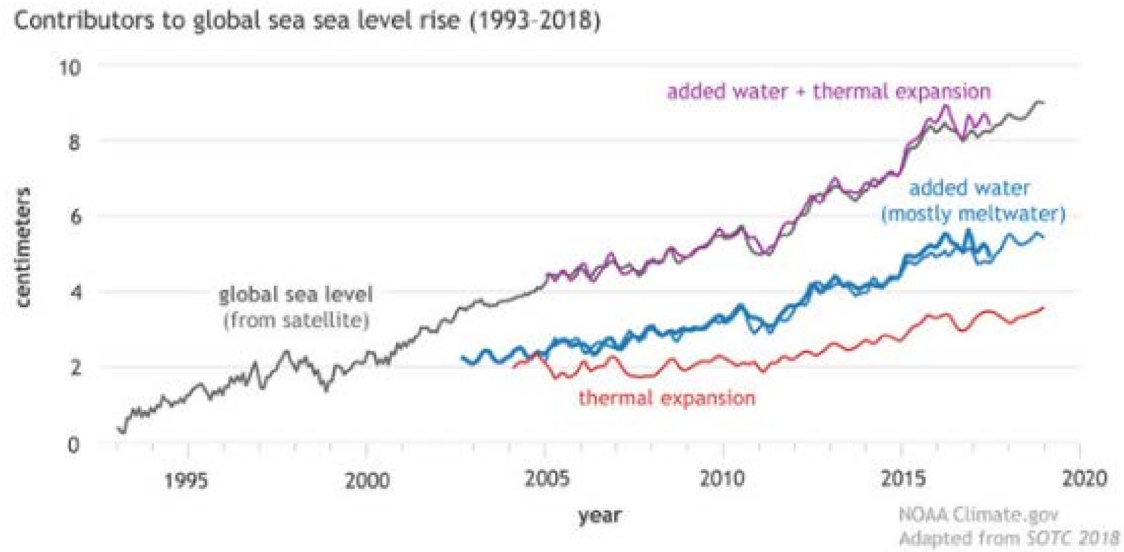


Figure 16.35 Changes in ocean heat content from 1955 to 2020 compared to the 1955 to 2006 average from NOAA Climate.gov https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content. A similar presentation is provided by Cheng, L. J, and Coauthors, 2022, https://doi.org/10.1007/s00376-022-1461-3 reporting data analysis from the Institute of Atmospheric Physics at the Chinese Academy of Sciences.

16.7.2 Sea level

Sea level is increasing as result of ocean thermal expansion or thermosteric change and increased melting of land-based ice such as glaciers and ice sheets as reported by NOAA and illustrated in Figure 16.36. Changes in sea surface height may also result from changes in salt content or salinity known as halosteric change. Steric height is discussed by NASA in https://sealevel.nasa.gov/understanding-sea-level/key-indicators/steric-height.



Observed sea level since the start of the satellite altimeter record in 1993 (black line), plus independent estimates of the different contributions to sea level rise: thermal expansion (red) and added water, mostly due to glacier melt (blue). Added together (purple line), these separate estimates match the observed sea level very well. NOAA Climate.gov graphic, adapted from Figure 3.15a in *State of the Climate in 2018*.

Figure 16.36 Sea level changes as a result of thermal expansion and increased melting of land-based ice such as glaciers and ice sheets https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content.

Changes in global sea level since 1880 to present are shown in Figure 16.37, NOAA, https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level. The rate of sea level rise in May 2021 is estimated to be greater than 3.4 mm per year, https://climate.nasa.gov/vital-signs/sea-level/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter. They report that global sea levels are rising as a result of human-caused global warming, with recent rates greater than has been experienced for 2000 years. Local gravitational effects and postglacial rebound (land rising or sinking) will result in significant variations above and below the average.   Subsidence (land sinking) can also be a result of groundwater extraction.

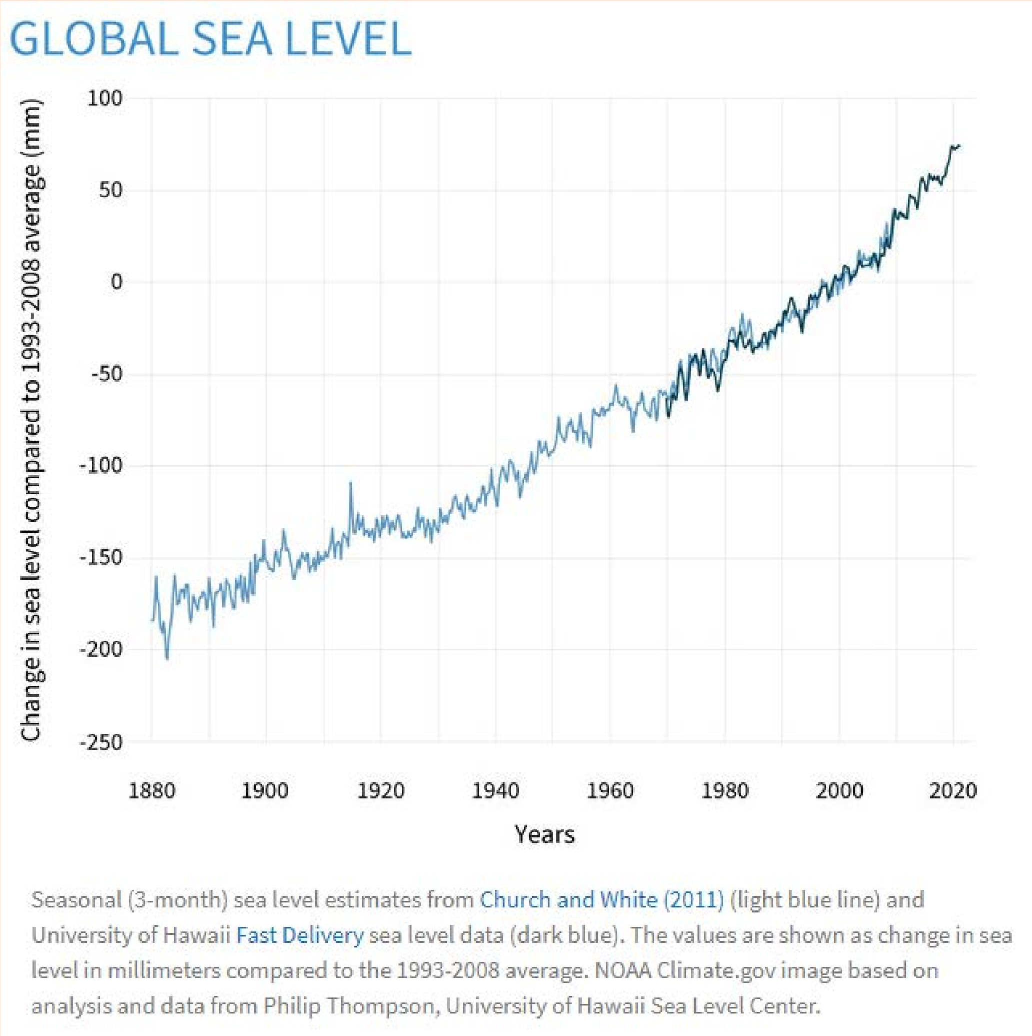


Figure 16.37 Changes in global sea level 1880 to present compared to average of 1993-2008 NOAA, https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

NASA has constructed an animation of global sea level change from 1992 to 2017, https://climate.nasa.gov/climate_resources/294/animation-global-sea-level-change-1992-2017/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter.

16.7.3 AMOC – Atlantic Meridional Overturning Current 2022

The Atlantic Meridional Overturning Current or AMOC as it is commonly known is a large system of ocean currents that carry warm water from the tropics northwards into the North Atlantic, https://www.metoffice.gov.uk/weather/learn-about/weather/oceans/amoc#:~:text=The%20Atlantic%20Meridional%20Overturning%20Circulation%20(AMOC)%20is%20a%20large%20system,northwards%20into%20the%20North%20Atlantic. It is part of the system of ocean currents known as the global conveyor belt as described in Chapter 8.

There is continuing discussion in 2022 regarding the collapse of the AMOC resulting from global warming and the collapse of the Greenland ice sheet and dire consequences resulting however this is not considered immenent. https://gizmodo.com/amoc-atlantic-current-collapse-1849028108 .

16.8 Coral reefs

The International Union for Conservation of Nature states:

- Coral reefs harbour the highest biodiversity of any ecosystem globally and directly support over 500 million people worldwide, mostly in poor countries.
- They are among the most threatened ecosystems on Earth, largely due to unprecedented global warming and climate changes, combined with growing local pressures on the fisheries they support.
- Over the last three years, reefs around the world have suffered from mass coral bleaching events as a result of the increase in global surface temperature caused by anthropogenic greenhouse gas emissions.
- According to UNESCO, the coral reefs in all 29 reef-containing World Heritage sites would cease to exist by the end of this century if we continue to emit greenhouse gases under a business-as-usual scenario.
- Limiting global average temperature to well below 2°C above pre-industrial levels in line with the Paris Agreement provides the only chance for the survival of coral reefs globally

Coral reefs are alive. They are vulnerable to human activities as illustrated in Figure 16.38.

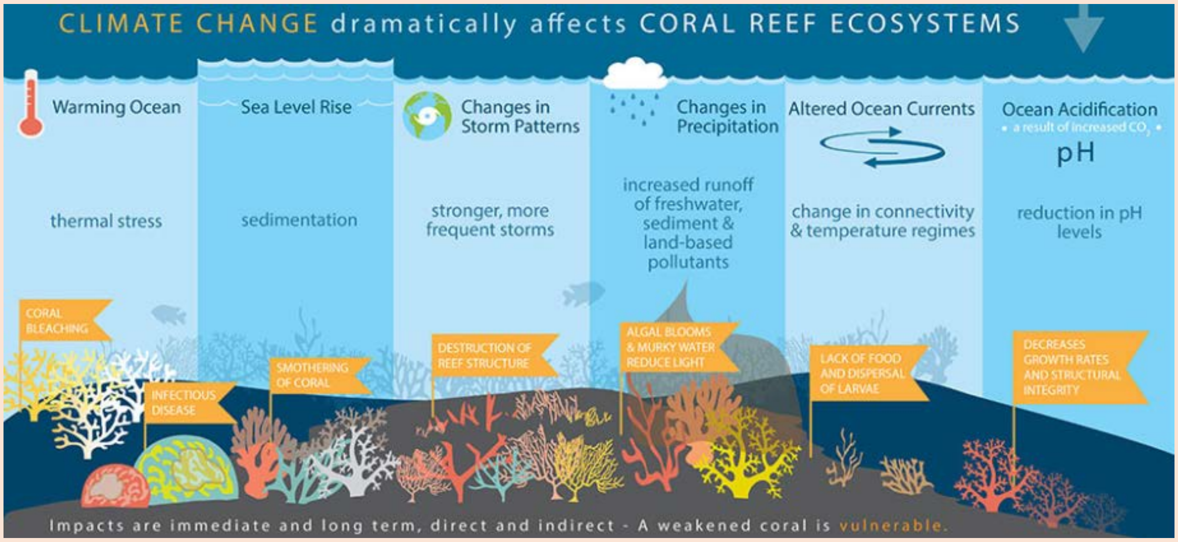


Figure 16.38 Impact of climate change on coral reef ecosystems.
https://oceanservice.noaa.gov/facts/coralreef-climate.html

When water is too warm, corals will expel the algae (zooxanthellae) living in their tissues causing the coral to turn completely white. This is called coral bleaching. When coral bleaches, it is not dead. Corals can survive a bleaching event, but they are under more stress and are subject to mortality. The web site: https://en.wikipedia.org/wiki/Coral_bleaching is particularly good at describing the process of coral bleaching and provides a very good survey of the state of coral health around the world.

March 25, 2022 it is reported that the Great Barrier Reef is experiencing what is being called 'unprecedented sixth mass coral bleaching event'
https://www.theguardian.com/environment/2022/mar/25/we-need-action-immediately-great-barrier-reef-authority-confirms-sixth-mass-coral-bleaching-event?utm_source=Nature+Briefing&utm_campaign=1cf0c44cbc-briefing-dy-20220325&utm_medium=email&utm_term=0_c9dfd39373-1cf0c44cbc-46124954

16.9 Thermal habitat of oceans and lakes

Extreme heat waves are considered the new normal since 2014, https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000007. The ocean is a habitat for all marine species and the terrestrial life that depends on them. The impact of extreme heat waves on tidal creatures, as it relates to the heat wave experienced in British Columbia, Canada in 2021 is discussed in https://www.nationalobserver.com/2021/07/08/news/billion-tidal-creatures-baked-to-death-bc-heat-wave. To quote the article; 'The ecological devastation of

B.C.'s recent heat wave is just starting to be understood ……', 'More than one billion marine intertidal animals may have perished ….'.

Warming oceans is changing the habitat for fish species. Warm water species are being found in northern waters that have gradually warmed. The consequences are significant from the perspective of changing commercial fisheries to miss-match of food for seabird breeding cycles and penguins (https://e360.yale.edu/features/feeling-the-heat-warming-oceans-drive-fish-into-cooler-waters, http://www.fao.org/3/a-i5707e.pdf, https://www.audubon.org/magazine/september-october-2014/how-climate-change-sinking-seabirds). Predatory species such as jelly fish are devastating fish populations https://www.fastcompany.com/90362601/jellyfish-are-booming-because-of-climate-change-and-human-activity.

Lakes are experiencing thermal habitat changes as reported in the journal, 'Nature Climate Change', https://www.nature.com/articles/s41558-021-01060-3?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210604&utm_medium=email&utm_source=Revue%20Daily. Lake surfaces are warming and lake organisms are responding resulting in changes in biodiversity.

A further effect is that lakes are not forming as much ice cover and losing their ice cover earlier resulting in changes in their water balance and ecology, https://theconversation.com/our-lakes-are-losing-their-ice-cover-faster-than-ever-heres-what-that-means-for-us-173471?utm_medium=email&utm_campaign=Latest%20from%20The%20Conversation%20for%20December%2021%202021&utm_content=Latest%20from%20The%20Conversation%20for%20December%2021%202021+CID_d207b906c6e2109dd8019e05af93db9a&utm_source=campaign_monitor_ca&utm_term=shed%20light%20on%20this%20disappearing%20lake%20ice%20and%20its%20impact.

16.10 Droughts

Drought is a prolonged dry period in the natural climate. It can occur anywhere in the world with serious negative impacts on health, agriculture, economies, energy and the environment. Attributing extreme drought to climate change is difficult because of the uncertainty in determining if the weather pattern fell beyond that which would be in the range of the naturally expected (statistically probable as determined using historic data) https://climate.nasa.gov/news/2175/nasa-study-finds-1934-had-worst-drought-of-last-thousand-years/.

Drought is expected to be more severe on the Canadian Prairies with expected very large increase in +30°C weather, http://prairieclimatecentre.ca/2016/05/climate-atlas-points-to-very-large-increase-in-30-c-weather-for-the-prairies/

The well documented extreme drought in California between 2012 and 2014 (Williams et al. 2015) is believed to been intensified by 5 to 18 per cent by GHG emissions. This drought continued until 2017. The drought experienced in 2020 is believed to have been intensified as a result of increased temperatures attributed to climate change caused by GHG emissions.   See Figure 16.39. A D0 weather pattern is an abnormally dry period. A D4 is an exceptional drought. Most of California experiences drought at the same time.

At the time writing no period of low rainfall in another region of the world has been attributed to global warming.
The drought in the western U.S. is persisting and expanding as shown in Figure 16.40. This drought is now considered the worst in 1200 years.

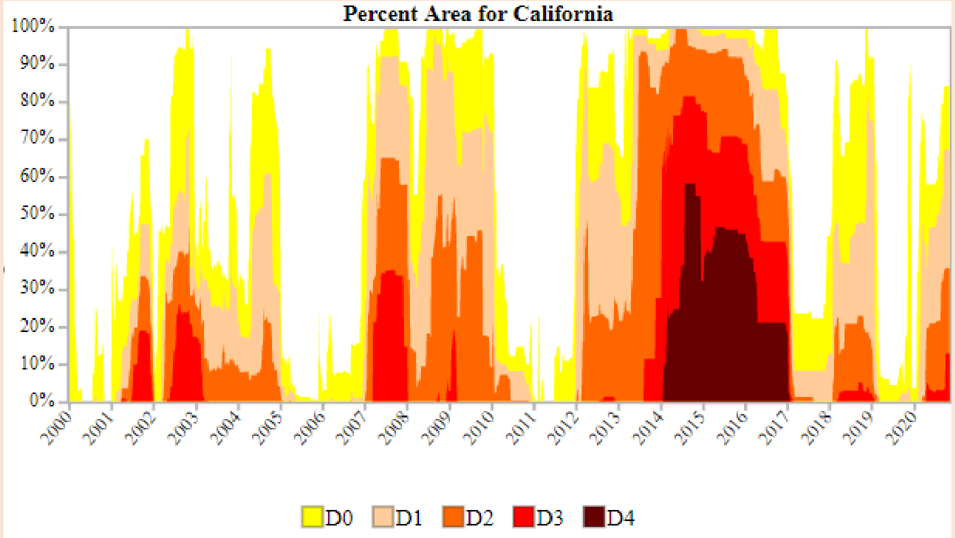


Figure 16.39 Droughts in California since 2000.
https://www.drought.gov/drought/states/california

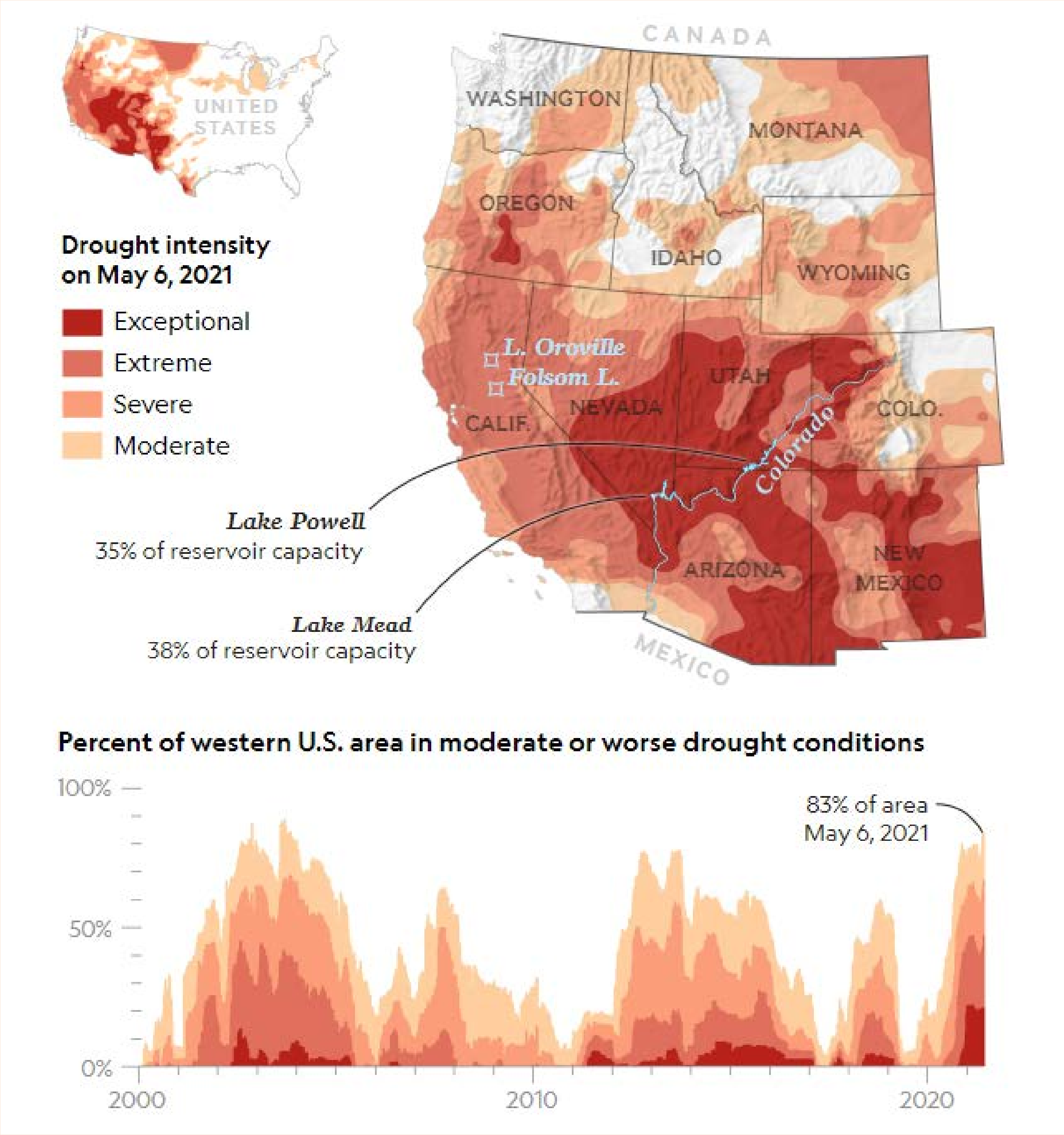


Figure 16.40 Drought affected areas in western U.S. 2021 https://www.nationalgeographic.com/environment/article/megadrought-persists-in-western-us-as-another-extremely-dry-year-develops?loggedin=true.

16.11 Desertification

Desertification is the process by which fertile land, dryland ecosystems, becomes desert as a result of drought, deforestation or inappropriate agriculture (tillage, poor irrigation practices and over grazing).

In recognition of the seriousness of problem (worldwide but the Sahel region of Africa in particular) the United Nations established the United Nations Convention to Combat Desertification (UNCCD) in 1994. In September 2017 they produced 'The future strategic framework for the Convention' to provide 'a more focused, targeted, effective and efficient implementation of the UNCCD'. https://www.unccd.int/sites/default/files/inline-files/ICCD_COP%2813%29_L.18-1716078E_0.pdf They say;

'Desertification/land degradation and drought (DLDD) are challenges of a global dimension. They contribute to and aggravate economic, social and environmental problems such as poverty, poor health, lack of food security, biodiversity loss, water scarcity, reduced resilience to climate change and forced migration.'

A very good discussion on desertification, its causes, scope and relationship to climate change, may be found in an article titled, 'Explainer: 'Desertification' and the role of climate change' published in Carbon Brief, https://www.carbonbrief.org/explainer-desertification-and-the-role-of-climate-change .

The regions of the world vulnerable to desertification (drylands) are shown in Figure 16.41. The United Nations Environment Program estimates that desertification has affected 36 million square kilometres of land affecting the lives of 250 million people of which 135 million people may be displaced by 2045. https://www.britannica.com/science/desertification

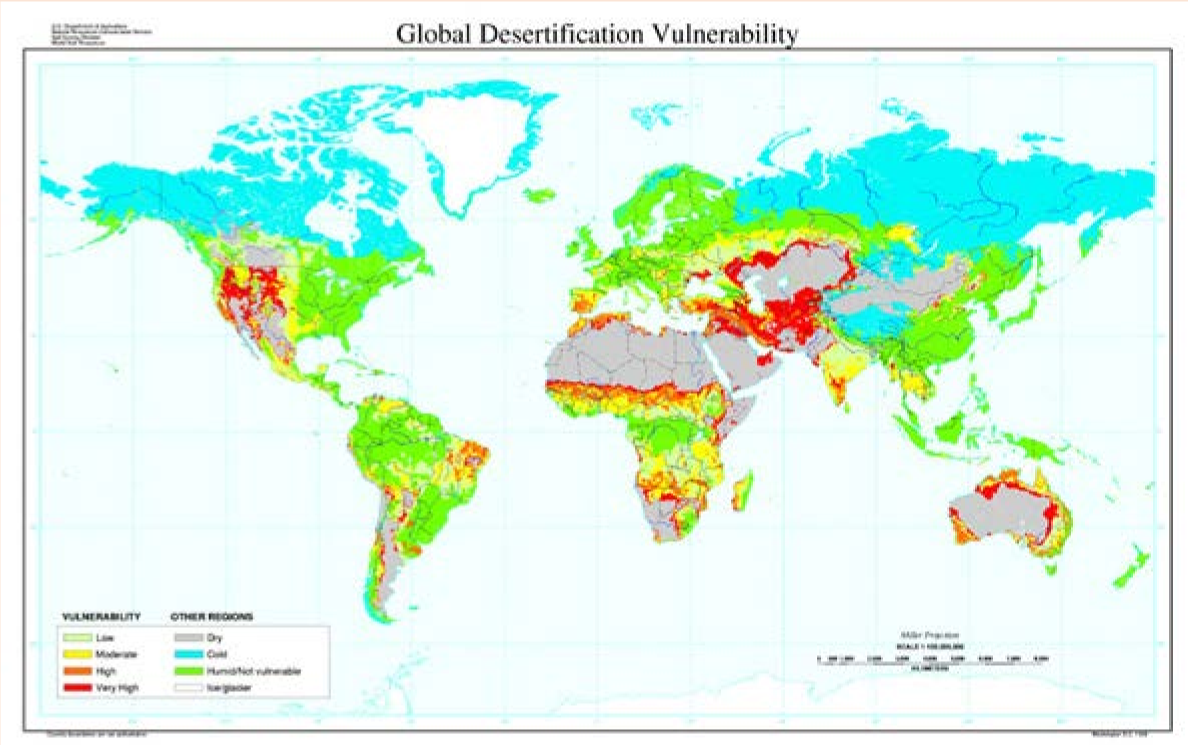


Figure 16.41 Regions of the world vulnerable to desertification.
https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/worldsoils/?cid=nrcs142p2_054003

16.12 Wildfires

A wildfire is an unplanned, unwanted, uncontrolled fire that burns in an area of combustible wildland vegetation. Recent wildfires of note are:

- Alberta, Canada wildfire 2016
  https://en.wikipedia.org/wiki/2016_Fort_McMurray_wildfire
- British Columbia, Canada wildfires 2017
  https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018EF001050
- Saskatchewan, Canada wildfires 2015.
  https://www.cbc.ca/news/canada/saskatchewan/climate-change-to-blame-for-so-many-sask-wildfires-says-expert-1.3136209 and
- Australian wildfire 2019-20
  https://en.wikipedia.org/wiki/2019%E2%80%9320_Australian_bushfire_season
- Australia wildfire, Fraser Island 2020
  https://modis.gsfc.nasa.gov/gallery/individual.php?db_date=2020-11-27

- California wildfire fall 2020 Wildfires Southern California Fall 2020. https://earthobservatory.nasa.gov/images/147625/new-fires-scorch-the-hills-of-southern-california
- California wildfire 2020 https://en.wikipedia.org/wiki/2020_California_wildfires
- Western United States 2021 – snapshot August 2020, National Interagency Fire Center, https://www.nifc.gov/fire-information/nfn.
- Siberian wildfire 2020 https://www.nature.com/articles/d41586-020-02568-y
- Amazon wildfires 2019-20 https://en.wikipedia.org/wiki/2019_Amazon_rainforest_wildfires
- Bolivia wildfires 2019 and 2020 https://earthobservatory.nasa.gov/images/147408/fierce-fires-in-bolivia
- Pantanal, Brazil 2020 https://earthobservatory.nasa.gov/images/147269/fires-char-the-pantanal
- British Colombia, Canada June and July, 2021 https://en.wikipedia.org/wiki/2021_British_Columbia_wildfires and estimates of mortality associated with the wildfires https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/data-management/news/estimates_mortality_rates_2021_wildfires_final.pdf

Very severe wildfires (2021) were also experienced in Turkey, Greece, Spain and Russian Siberia (2021). In 2022 extreme heat waves, drought and wildfires are being experienced around the world. This pattern has continued in 2023 with wildfires being experienced throughout Canada, United States, Europe and elsewhere.

Wildfires are a natural phenomenon. The wildfires listed are unusual because of their scale and the destruction they caused. Many thousands of wildfires occur throughout the world every year. Scientists are beginning to believe that increased temperatures and drought caused by climate change has resulted in increased frequency of the fires and their scale. NASA monitors wildfires using several satellite-based systems https://www.nasa.gov/mission_pages/fires/main/missions/index.html and has recently published an article describing climate connections to the record fire year in the U.S. west, https://climate.nasa.gov/blog/3066/the-climate-connections-of-a-record-fire-year-in-the-us-west/ .

The wildfires listed are believed to be caused by global warming and attendant drought. The positive feedback to increased global warming is the carbon dioxide and other GHG's that are released to the atmosphere.

16.13 Tropical cyclones

Tropical cyclones are described in Chapter 10. The hurricane season of 2020 is the most active on record. (See https://en.wikipedia.org/wiki/2020_Atlantic_hurricane_season)

It is not possible to say that climate change was definitely responsible for this record-breaking season, which has been very destructive throughout the Gulf Coast, the Caribbean Region, Mexico and Central America. The 2020 season was also a significant La Niña event (see Chapter 11) which sets the stage for exactly this type of hurricane season.

What is known about hurricanes, tropical cyclones in general, is that warming sea water will definitely provide ideal conditions for tropical storms to become hurricanes. The warmer sea water will strengthen and sustain them. The last hurricane, Iota, struck Central America and turned back into the Caribbean where it crossed Jamaica and Cuba as a subtropical storm, strengthening to hurricane force striking Florida. Though one of the most active hurricane seasons in history it is not possible to definitely attribute the severity of the 2020 hurricane season to the effects of climate change.

16.14 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), https://ipbes.net/, is an independent intergovernmental body established by countries to strengthen the science-policy interface for biodiversity and ecosystem services for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development. It was established in Panama City, on 21 April 2012 by 94 Governments. It is not a United Nations body. The United Nations Environment Programme, UNEP, provides secretariat services to IPBES.

At a meeting on biodiversity and ecosystem services in June 2010, membership of the United Nations adopted the Busan outcome document which stated that "an intergovernmental science-policy platform for biodiversity and ecosystem services should be established". By resolution 65/162 of 20 December 2010, the General Assembly "[took] note of the Busan outcome" and requested the United Nations Environment Programme (UNEP), "to convene a plenary meeting…to determine modalities and institutional arrangements for [IPBES]". According to the UN Office of Legal Affairs, the General Assembly by taking note of the Busan outcome did not establish IPBES as a United Nations body.

The 2019 global assessment report on Biodiversity and Ecosystem Services was produced by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) https://ipbes.net/global-assessment . It concludes nature and its vital contributions to people, which together embody biodiversity and ecosystem functions and services, are deteriorating worldwide and human actions threaten more species with global extinction now than ever before. Figure 16.42 is taken from their report. They report that around one million animal and plant species are now threatened with extinction with climate change as one the major causes.

A paper published January 12, 2021 in the Proceedings of the National Academy of Sciences of the United States of America, titled Insect decline in the Anthropocene: Death by a thousand cuts, provides an update on the decline of insect populations worldwide due to all causes including climate change https://www.pnas.org/content/118/2/e2023989118.full?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210113&utm_medium=email&utm_source=Revue%20Daily.

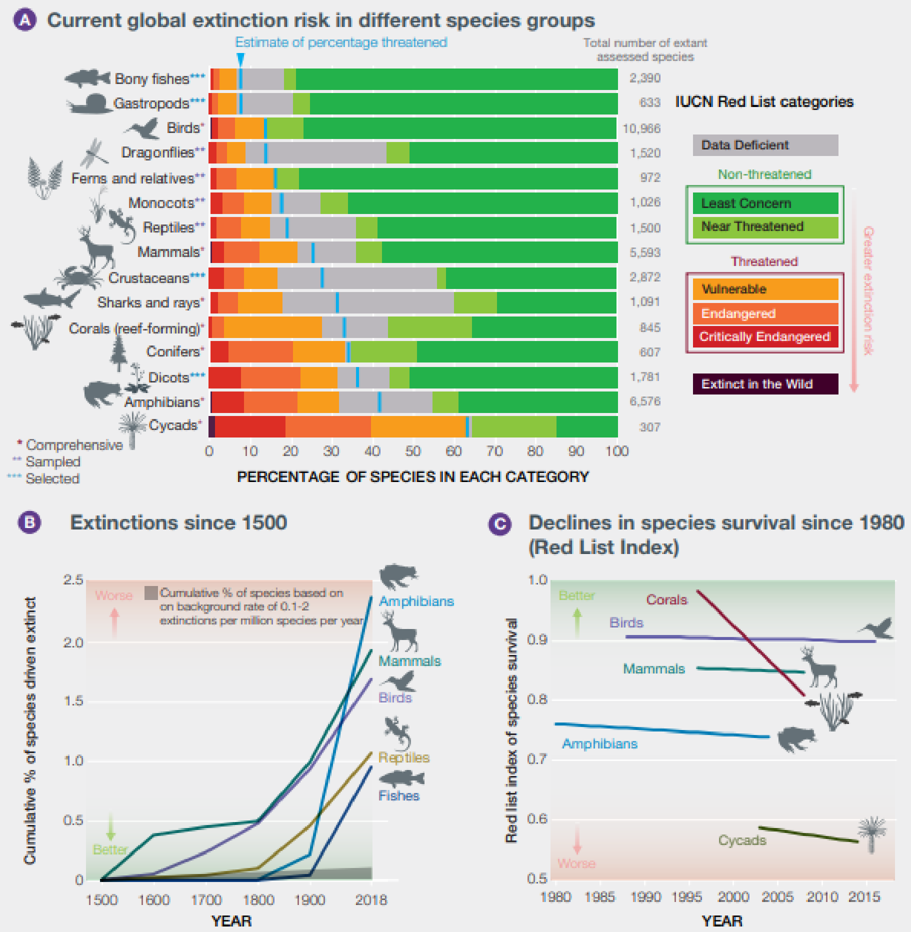


Figure SPM 3 **A substantial proportion of assessed species are threatened with extinction and overall trends are deteriorating, with extinction rates increasing sharply in the past century.**

A Percentage of species threatened with extinction in taxonomic groups that have been assessed comprehensively, or through a 'sampled' approach, or for which selected subsets have been assessed, by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. Groups are ordered according to the best estimate for the percentage of extant species considered threatened (shown by the vertical blue lines), assuming that data deficient species are as threatened as non-data deficient species. B Extinctions since 1500 for vertebrate groups. Rates for reptiles and fishes have not been assessed for all species. C Red List Index of species survival for taxonomic groups that have been assessed for the IUCN Red List at least twice. A value of 1 is equivalent to all species being categorized as Least Concern; a value of zero is equivalent to all species being classified as Extinct. Data for all panels derive from www.iucnredlist.org (see Chapter 3 Figure 3.4 and Chapter 2 Figure 2.7).

Figure 16.42 Current global extinction risk in different species groups. https://www.ipbes.net/sites/default/files/2020-02/ipbes_global_assessment_report_summary_for_policymakers_en.pdf

16.15 Biological diversity (biodiversity)

The reports prepared by the IUCN Section 16.15.2 and the WWF Section 16.15.3 are very important to understanding the challenges, including climate change, facing the preservation of biodiversity on Earth. Section 16.16 on habitat change elaborates on the specific effects of habitat change on various species.

16.15.1 Convention on Biological Diversity, CBD

The Convention on Biological Diversity, CBD, https://www.cbd.int/convention/, is part of the United Nations Environmental Program (UNEP). Signed by 150 government leaders at the 1992 Rio Earth Summit, the Convention on Biological Diversity is dedicated to promoting sustainable development. Conceived as a practical tool for translating the principles of Agenda 21 into reality, the Convention recognizes that biological diversity is about more than plants, animals and micro-organisms and their ecosystems. It is about people and our need for food security, medicines, fresh air and water, shelter, and a clean and healthy environment in which to live.
The mission of the CBD is:
"Take effective and urgent action to halt the loss of biodiversity in order to ensure that by 2050 ecosystems are resilient and continue to provide essential services, thereby securing the planet's variety of life, and contributing to human well-being, and poverty eradication. To ensure this, pressures on biodiversity are reduced, ecosystems are restored, biological resources are sustainably used and benefits arising out of utilization of genetic resources are shared in a fair and equitable manner; adequate financial resources are provided, capacities are enhanced, biodiversity issues and values mainstreamed, appropriate policies are effectively implemented, and decision-making is based on sound science and the precautionary approach."

The first United Nations Summit on Biodiversity held at the level of Heads of State and Government was held on 30 September 2020. A summary report was produced, https://www.cbd.int/events/unbiodiversitysummit/summary.pdf. The following two excerpts were taken from this report.
'As mandated in General Assembly resolution A/RES/74/269, the summary reflects the discussions of the summit held to highlight the urgency of action at the highest levels in support of a post-2020 global biodiversity framework that contributes to the 2030 Agenda for Sustainable Development and places the global community on a path towards realizing the 2050 Vision for Biodiversity, "Living in harmony with nature". '

'A majority of Member States recognized the intrinsic link between biodiversity and climate change. Climate change contributes to the loss of biodiversity, and the increasing and continuous challenges from climate change and natural disasters are connected to the loss of biodiversity and ecosystem services. Nature-based solutions anchored in biodiversity can help address climate change and achieve sustainable development, protect and generate livelihoods and ensure food security, combat desertification and recover biodiversity, and achieve land degradation neutrality. The majority of countries emphasized the need for urgent action toward ambitious goals and targets at COP-15, comparable to the goals of the Paris Agreement. The host country of the next COP of UNFCCC committed to deal with biodiversity loss and climate change as intrinsically linked crises.'

COP-15 Part 1 was held in October 2021 in Kunming, PRC
https://www.cbd.int/conferences/2021-2022 .

COP-15 Part 2 will be held in Montreal, Canada December 2022
https://www.cbd.int/meetings/COP-15 .

The World Biodiversity Summit was held in New York September 2022, Sharm el-Sheikh November 2022 and Montreal December 2022 https://www.worldbiodiversitysummit.org/new-york?gclid=EAIaIQobChMIqMjEtIvb-QIVTgytBh0oUQf_EAAYASAAEgJ5gfD_BwE .

A recent study published in the journal Nature and mentioned in the newsletter Carbon Brief highlights the impacts of climate change on endemic and other species world wide (https://www.carbonbrief.org/climate-change-will-hit-endemic-plants-and-animals-the-hardest-study-warns) and https://www.sciencedirect.com/science/article/abs/pii/S0006320721001221.

Many countries introduced clean energy and carbon-neutral initiatives and stressed the importance of nature-based solutions to tackle global warming and fulfill the Paris Agreement. One group of countries remarked that climate change and biodiversity loss reinforce each other, and emphasized that this vicious cycle must be broken.

The United Nations Convention on Biological Diversity (CBD) Conference of the Parties number 15 (COP15) or CBD COP15 Phase 1 was held between the 12 and 13 of October 2021 in Kunming, PRC http://sdg.iisd.org/events/2020-un-biodiversity-conference/, where the achievement and delivery of the CBD's Strategic Plan for Biodiversity 2011-2020 was reviewed and future activities decided. The second part of CBD COP15 will be held in Montreal December 2022 https://vitasapien.org/cbd-cop-15 . The world sees human caused climate change as a very serious threat to life on Earth and the nations of the world are again meeting to develop urgently needed strategies to mitigate and adapt to the threat.

16.15.2 International Union for Conservation of Nature (IUCN) https://www.iucnredlist.org/
The IUCN has recently updated its Red List of Threatened Species. One in four species are at risk of extinction. Species assessed are:

1. Amphibians 40% of the species are a risk.
2. Conifers 34%.
3. Reef corals 33%.
4. Sharks and rays 31%.
5. Selected crustaceans (lobsters and freshwater crabs, crayfishes and shrimps).

6. Mammals 25%.
7. Birds 14%.

The Birdlife International publication, State of the World's Birds 2022, https://www.birdlife.org/papers-reports/state-of-the-worlds-birds-2022/ provides insights from birds on the biodiversity crisis and solutions needed.

16.15.3 World Wildlife Fund (WWF) – Living Planet Report 2020 The WWF publishes the Living Planet Report https://f.hubspotusercontent20.net/hubfs/4783129/LPR/PDFs/ENGLISH-FULL.pdf which includes the 'Living Planet Index' which "measures trends in thousands of populations of mammals, birds, reptiles, amphibians and fish across the globe". A graph for the period 1970 to 2016 is shown in Figure 16.43 taken from the full 2020 report that may be found in https://livingplanetindex.org/home/index.

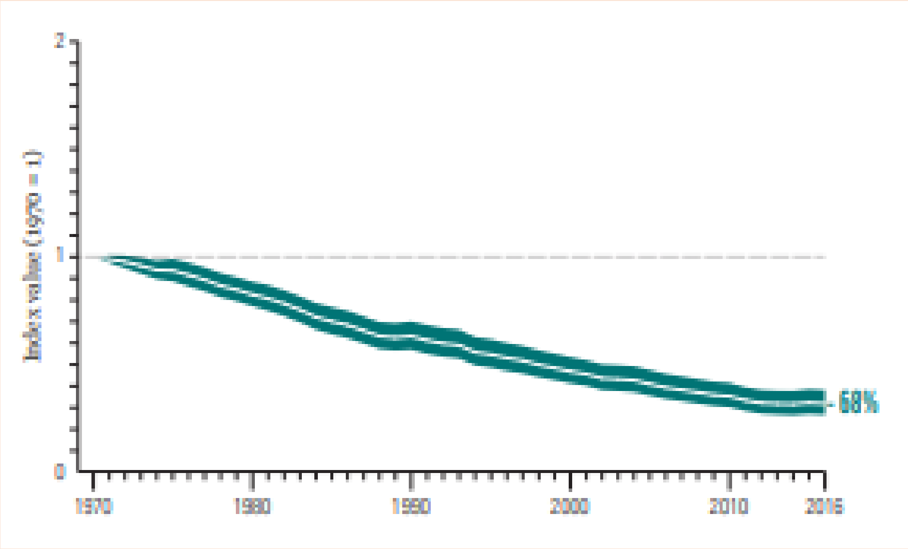


Figure 16.43 World Wildlife Fund, Living Planet Index for period 1970 to 2016 https://livingplanetindex.org/home/index.

The report details threats to biodiversity including; changes in land and sea use, including habitat loss and degradation, species overexploitation, invasive species and disease, pollution and climate change. Regions considered are North America, Europe and Central Asia, Latin America and Caribbean, Africa and the Asia Pacific.

The report states that 'Biodiversity as we know it today is fundamental to human life on Earth, and the evidence is unequivocal – it is being destroyed by us at a rate unprecedented in history.' The headline reads: 'Biodiversity on the brink: We know it is crashing.'

16.15.4 The World Wildlife Fund – Living Planet Index 2022

The World Wildlife Fund – Living Planet Index 2022 has been published https://livingplanet.panda.org/en-GB/. The rate of decline of global wildlife populations continues with outcome similar to Figure 16.43.

16.16 Habitat change – natural environment – general comments

Habitat is the natural environment that plants and animals live in. This is the environment in which they have evolved, over millions of years typically, to live and reproduce. Environment includes climate, geology, geography, water and all of the plants and animals around them, including predators. Environment defines the ecology within which the plants and animals live. If the habitat becomes unsatisfactory plants and animals will attempt to move to more suitable habitats. The pathways for this movement must be available. Human activities such as transportation corridors and urban development may block or remove these pathways in what is called habitat fragmentation and the affected plants and animals may go extinct.

Climate change is affecting each and every plant and animal species. The exact effects are not known since there are many millions of plant and animal species which interact in complex ways. So, despite the best efforts of scientists to try and identify and understand the numerous ecologies on planet Earth, it is an impossible task to discern what the impact of climate change might be. For example, how does climate change affect the food chain for various species? As just one example, reduced phytoplankton has a direct impact on killer whales. Disappearing sea ice is having a major impact on polar bear populations. There are countless other examples that remain to be clearly defined. What is known is that the effects are almost universally negative. It seems possible that some assessments can be made on the impacts of climate change such as on:

- advancing tree lines, (Mt. Fuji http://www.asahi.com/ajw/articles/14035103, https://esajournals.onlinelibrary.wiley.com/doi/10.1890/ES14-00111.1 , https://academic.oup.com/aob/article/90/4/537/185822),
- polar bears (https://www.wwf.org.uk/learn/wildlife/polar-bears#:~:text=The%20Arctic%20is%20warming%20about,ice%20to%20raise%20their%20young, http://assets.worldwildlife.org/publications/398/files/original/Effects_of_Climate_Change_on_Polar_Bears_fact_sheet.pdf?1345754206), and https://arcticwwf.org/work/climate/),
- penguins (https://www.biologicaldiversity.org/news/media-archive/Penguins_ActionBioscience_9-09.pdf, https://www.weforum.org/agenda/2020/02/penguin-colony-antarctic-islands-climate-change-environment) , and https://www.nature.com/articles/s43247-023-00927-x

- seals (https://climate.org/archive/topics/ecosystems/seals-battle-climatechange, https://www.humanesociety.org/sites/default/files/docs/seals-sea-ice.pdf, and https://www.iucn.org/sites/dev/files/import/downloads/fact_sheet_red_list_ringed_seal_v2.pdf),
- infestation of pine bark beetles (https://e360.yale.edu/features/small-pests-big-problems-the-global-spread-of-bark-beetles and https://www.unbc.ca/releases/2007/climate-change-and-mountain-pine-beetle),
- coral reefs (Section 16.8),
- seabirds (https://www.audubon.org/magazine/september-october-2014/how-climate-change-sinking-seabirds),
- jelly fish (https://www.fastcompany.com/90362601/jellyfish-are-booming-because-of-climate-change-and-human-activity),
- warm water fish species moving north (Section 16.9), and
- starfish die off, (https://www.nbcnews.com/science/environment/warming-oceans-may-be-choking-oxygen-starfish-causing-them-drown-n1253355 , https://news.cornell.edu/stories/2021/01/organic-matter-bacteria-doom-sea-stars-oxygen-depletion , https://www.frontiersin.org/articles/10.3389/fmicb.2020.610009/full);
- marsh migration, (https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL092420?utm_campaign=Carbon+Brief+Daily+Briefing&utm_content=20210702&utm_medium=email&utm_source=Revue+Daily)
- 30% of world’s trees are at risk of extinction, Botanic Gardens Conservation International, https://www.bgci.org/news-events/bgci-launches-the-state-of-the-worlds-trees-report/
- Plants in the UK flower a month earlier under recent warming, https://royalsocietypublishing.org/doi/10.1098/rspb.2021.2456

but it is apparent that resources available to make exhaustive assessments, if possible, remain insufficient.

Recently, the global loss of peatlands (https://www.iucn.org/resources/issues-briefs/peatlands-and-climate-change) and the disturbance of the ocean floor as a result of the practice of trawling for fish, (https://www.nature.com/articles/s41586-021-03371-z, https://www.sciencedaily.com/releases/2021/03/210317141645.htm, https://www.bluemarinefoundation.com/2021/03/18/trawling-discovered-to-have-massive-climate-change-impact/, https://www.theguardian.com/environment/2021/mar/17/trawling-for-fish-releases-as-much-carbon-as-air-travel-report-finds-climate-crisis) have been recognized as major contributors to the loss of biodiversity.

16.17 Glaciers

The United States Geological Survey, USGS, describes a glacier as a large, perennial accumulation of crystalline ice, snow, rock, sediment, and often liquid water that originates on land and moves down slope under the influence of its own weight and gravity. Figure 16.44 shows the locations of glaciers around the world.

The observable effect of global warming and climate change on glaciers is that they are disappearing from most of the world. The annual accumulation of snow is not replacing the annual melt. Consequently, glaciers are said to retreat – their leading edge is retreating. Some glaciers, like the one on Mount Kilimanjaro, Kenya will disappear by 2040, Figure 16.45.

Recent studies using the NASA Terra satellite have been able to assess 97% of the world's glacierized regions that established that melting glaciers drove 21% of sea level rise over the past two decades https://www.carbonbrief.org/melting-glaciers-drove-21-of-sea-level-rise-over-past-two-decades?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210429&utm_medium=email&utm_source=Revue%20Daily and https://www.theguardian.com/environment/2021/apr/28/speed-at-which-worlds-glaciers-are-melting-has-doubled-in-20-years?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210429&utm_medium=email&utm_source=Revue%20Daily .

Also see State of the Cryosphere 2022 – Growing losses, Global Impacts, https://iccinet.org/statecryo2022/ .

Many communities around the world depend on melt water from glaciers for their water supply twelve months of the year. If the glaciers disappear so does their water supply.
Rivers and streams that have their headwaters at the base of glacier receive most their water from the groundwater adjacent to the river or stream further downstream of the glacier. That water comes from snow melt or rain that enters the groundwater. As the river progresses more water drains into it from the groundwater and also from tributaries until the river may become quite large and the contribution from the glacier that originally fed it quite small or even insignificant by comparison.

Frequently the melt water from a glacier will form a glacial lake which will overflow as it fills https://nsidc.org/cryosphere/icelights/2013/05/ebb-and-flow-glacial-lakes . The outflow capacity from a glacial lake must match the inflow rate. If the inflow exceeds the outflow there is a danger of a glacial lake outburst which has the potential of damaging human activities downstream. The damage could include structures such as hydro-electric dams and their catastrophic failure. See videos, https://www.youtube.com/watch?v=ZN8a-pP60wk,

https://www.youtube.com/watch?v=z7GKW-u-Gg4, and
https://www.youtube.com/watch?v=Q0xq-fpo2c0.

The disappearance of glaciers is a clear, observable phenomenon providing indisputable evidence that global warming is occurring. It is a warning of the present danger and consequences of global warming – like the canary in the coal mine.

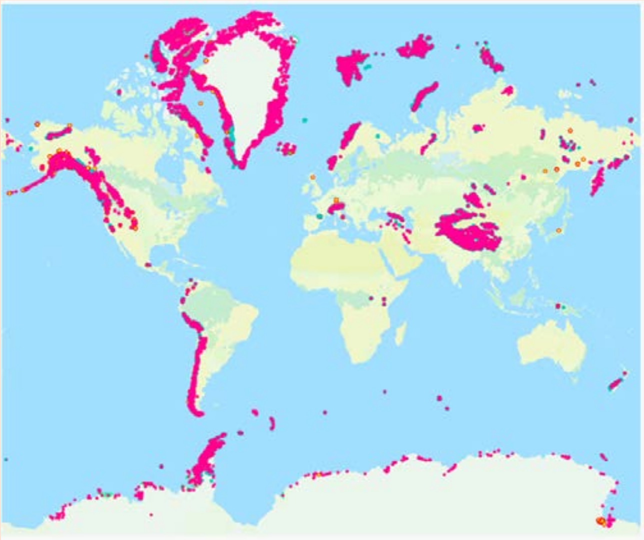


Figure 16.44 Location of glaciers (shown in red) around the world.
https://nsidc.org/cryosphere/glaciers/questions/located.html

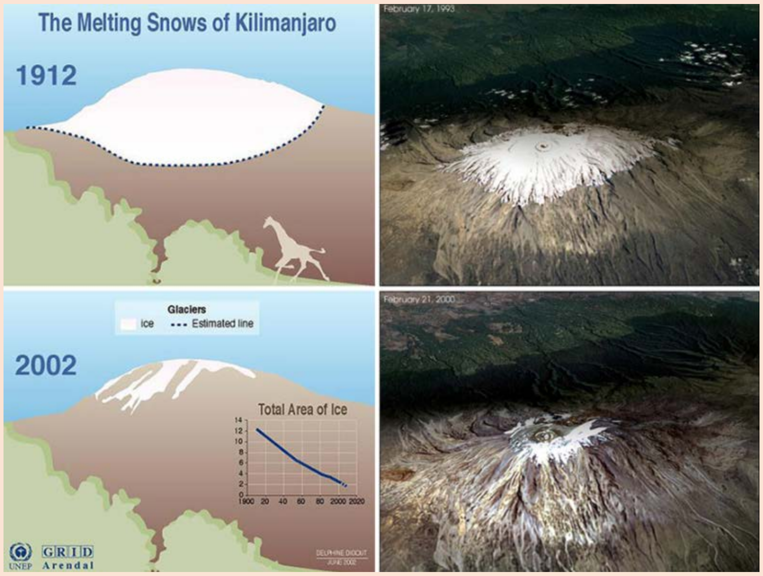


Figure 16.45 Melting glacier on Mount Kilimanjaro, Kenya.

The Himalayan glaciers are losing their glaciers at a rapid rate. A paper titled 'Accelerated mass loss of Himalayan glaciers since the Little Ice Age' by Lee, et al, in scientific reports published by nature briefing reports "The ten-fold acceleration in ice loss we have observed across the Himalaya far exceeds any centennial-scale rates of change that have been recorded elsewhere in the world." https://www.nature.com/articles/s41598-021-03805-8?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20211221&utm_medium=email&utm_source=Revue%20Daily. The water crisis for communities which depend on meltwater from the glaciers is described in a paper titled 'As Himalayan Glaciers Melt, a Water Crisis Looms in South Asia by Vaishnave Chandrashekhar in the Yale journal, Yale Environment 360 https://e360.yale.edu/features/himalayas-glaciers-climate-change?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20221004&utm_medium=email&utm_source=Revue%20Daily . Observations of melting glaciers in Chile and their impact on water supplies is described in the paper, https://phys.org/news/2022-02-glaciers-fast-disappering-gauge-climate.html

The Thwaites glacier in West Antarctica is showing signs of immanent collapse https://climate.to/antarcticas-doomsday-glacier-how-its-collapse-could-trigger-global-floods-and-swallow-islands/?utm_term=&utm_campaign=Climate+To+DSA&utm_source=adwords&utm_medium=ppc&hsa_acc=8742646434&hsa_cam=15307078284&hsa_grp=129385859225&hsa_ad=562837904855&hsa_src=g&hsa_tgt=dsa-19959388920&hsa_kw=&hsa_mt=&hsa_net=adwords&hsa_ver=3&gclid=EAIaIQobChMIhdHhuoOR9QIVQRx9Ch0h9Q7_EAAYASAAEgKMCvD_BwE. The stability of the glacier is being threatened by the break up of the ice shelf at its terminus. The ice shelf slows the glacier flow by blocking its movement and it is believed that if the ice shelf is lost the glacier flow will accelerate – possibly causing the flow of other adjacent glaciers to accelerate as well. A complete breakup of the Thwaites glacier would result in a 0.65 m increase in sea level.

16.18 Regional impacts of climate change, IPCC Climate Change 2014, Synthesis Report, Fifth Assessment Report

In 2014 the IPCC stated; 'Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.' Their conclusions are summarized in Figure 16.46.

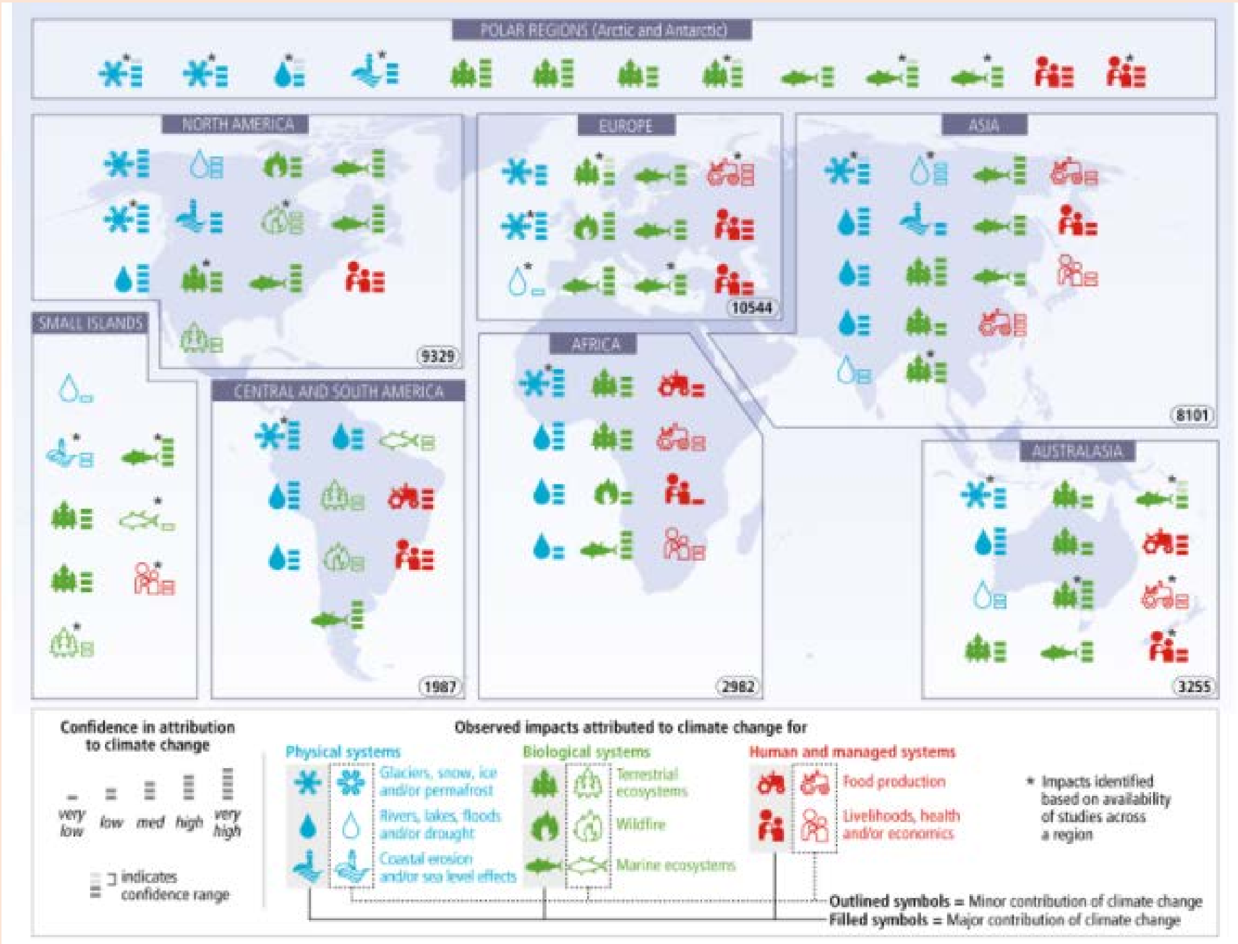


Figure 16.46 Widespread impacts attributed to climate change based on the available scientific literature since the AR4. https://ar5-syr.ipcc.ch/topic_observedchanges.php and https://ar5-syr.ipcc.ch/index.php

16.19 Extreme Weather

The frequency and severity of extreme weather is attributed to global warming and climate change.

Carbon Brief has published an updated map of the world showing locations where human influence has impacted, has not impacted or it is inconclusive if human impact had any effect. This may be found on https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/?utm_campaign=Daily%20Briefing&utm_content=20220805&utm_medium=email&utm_source=Revue%20newsletter or simply searching Carbon Brief extreme weather attribution. Each conclusion is referenced. The impacts reported are classified as follows; atmosphere, cold, snow and ice, coral bleaching, drought, ecosystem function, heat, oceans, rain and flooding, river flow, storm, sunshine, wildfire and compound.

The World Weather Attribution initiative, (https://www.worldweatherattribution.org/), a collaboration between climate scientists at Imperial College London in the UK, KNMI in the Netherlands, IPSL/LSCE in France, Princeton University and NCAR in the US, ETH Zurich in Switzerland, IIT Delhi in India and climate impact specialists at the Red Cross/ Red Crescent Climate Centre (RCCC) around the world was founded to provide robust assessments on the role of climate change in the aftermath of the event. The Carbon Brief publication, Guest post: Lessons learned from five years of extreme weather 'rapid attribution' describes how this study is performed, (https://www.carbonbrief.org/guest-post-lessons-learned-from-five-years-of-extreme-weather-rapid-attribution/). There is extensive use of historic observations and climate models. This approach is said to be 'scientific' and is only possible when needed information is available.

The American Meteorological Society has published a series of reports titled Explaining Extreme Events of 2019 (2018 and 2017 are also available) from a Climate Perspective, https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/ . Recently, The National Academies of Sciences, Engineering and Medicine published a paper supporting the claim that extreme weather can be linked to global warming. See https://www.nationalacademies.org/based-on-science/climate-change-global-warming-is-contributing-to-extreme-weather-events?utm_source=Division+on+Earth+and+Life+Studies&utm_campaign=e3c0b0b55a-EMAIL_CAMPAIGN_2021_06_24_01_47&utm_medium=email&utm_term=0_3c0b1ad5c8-e3c0b0b55a-278885679&mc_cid=e3c0b0b55a&mc_eid=b6391f6645 .

Clearly, most extreme events will not have the needed information to perform the scientific rapid (or otherwise) attribution assessment but 'unscientific' assessments will still be made on the basis of the present knowledge of the underlying science.

16.19.1 Heat dome - heatwave Pacific Northwest 2021

See Section 7.7 for discussion on heat domes.

Canada and NW United States experienced a significant heat wave (June and July 2021) that has resulted in several hundred heat related deaths. The heat wave extended from Southern California to the Arctic Circle and the Pacific Coast to Eastern Manitoba. It has lasted over one week. The unusual and extreme nature of the heat wave is believed to be a natural phenomenon, aggravated by global warming, known as a 'heat dome' a natural atmospheric circulation that traps very warm air. A description of the phenomenon is provided by the Royal Meteorological Society, https://www.rmets.org/metmatters/what-heat-dome.

Explanations of the heatwave experienced are just starting to be published. See https://www.carbonbrief.org/media-reaction-pacific-north-west-heat-dome-and-the-role-of-climate-change?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210701&utm_medium=email&utm_source=Revue%20Daily and https://en.wikipedia.org/wiki/2021_Western_North_America_heat_wave. In a paper titled 'Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021', Philip, S. Y. et al (https://www.worldweatherattribution.org/wp-content/uploads/NW-US-extreme-heat-2021-scientific-report-WWA.pdf?utm_source=north%20shore%20news&utm_campaign=north%20shore%20news&utm_medium=referral) published by World Weather Attribution (https://www.worldweatherattribution.org/) conclude that the extreme heat experienced was attributable to or at the very least aggravated by human caused global warming.

Extreme heat attributed to formation of heat domes continue to be experienced in 2022 and 2023.

16.19.2 Atmospheric river - extreme rainfall caused by multiple atmospheric rivers British Columbia, Canada 2021

See Section 7.5 for discussion on atmospheric rivers.

The southwest corner of the Province of British Columbia, Canada has experienced extreme rainfall resulting from four atmospheric rivers, November 2021. The amount of rainfall has exceeded all previous records and the damage from flowing water, flooding and mudslides to infrastructure (roads, bridges, drainage, water treatment plants, wastewater treatment plants and more) has been extensive. The flooding resulting from nearby rivers which overtopped their banks and dike systems resulted in tens of thousands of hectares for flooded farmland, hundreds of thousands of dead livestock, flooded homes and agriculture infrastructure and destroyed crops. Fifteen thousand people required evacuation. All highways were damaged to the point where they were impassable. Several highways will require several months and perhaps years to restore. Many communities were impacted, flooded and isolated. Mudslides resulted in the loss of several lives. It is estimated that there was several billion dollars in damage. A timely overview of the rainfall events and resulting impacts may be found in Wikipedia, https://en.wikipedia.org/wiki/November_2021_Pacific_Northwest_floods.

16.19.3 Increasing major snowstorms

Climate change scientists are finding a correlation between episodes of Arctic warming and colder East Asia (resulting from climate change) and severe winter weather events in the northern hemisphere and the eastern United States in particular, https://www.nature.com/articles/s41467-018-02992-9 . The exact mechanism is not understood. The basic idea may be found in a simpler discussion provided by https://www.washingtonpost.com/weather/2022/02/01/northeast-snow-storm-climate/ where it is hypothesized that warmer Arctic destabilizes the polar vortex resulting in the jet stream dropping south and drawing warm moist air from the south into the Arctic.

16.20 US EPA Report May 2021 https://www.epa.gov/climate-indicators

16.19.4 USEPA climate change indicators

The United States Environmental Protection Agency has issued a very important report on climate change indicators on a global perspective and specifically on the United States https://www.epa.gov/climate-indicators . It is acknowledged that nations do not exist is isolation from the rest of the world. Climate change is a global phenomenon. This report considers the best historical data available and is regularly updated. Historical and recent trends are identified.

The report considers:

- Greenhouse gases
- Weather and climate
- Oceans
- Snow and ice
- Health and society
- Ecosystems

References are provided to important information sources on global warming and climate change in the United States many of which have been extensively reported in this Guide.

16.19.5 Double jet streams – heatwaves over Europe 2022

Extreme heatwaves have been experienced over Europe 2022. These are attributed to the formation of double jet streams over Eurasia (https://www.bloomberg.com/news/articles/2022-08-10/temperatures-rise-in-europe-as-another-heat-wave-blankets-region , https://www.nature.com/articles/s41467-022-31432-y and https://www.weforum.org/agenda/2022/08/jet-stream-winds-fuelling-heatwaves/). They are considered the likely cause of heatwaves over the United States, China and elsewhere. The heatwaves have resulted in severe drought, wildfires, serious health impacts, damage to infrastructure and extraordinary power demand for cooling.

Jet streams are discussed in Section 7.4

16.19.6 Extreme weather 2022

Extreme weather in 2022 continues to be a worldwide concern. The issues are similar to what has already been discussed and won't be discussed further. The list is long and serious. In no particular order, it includes:

- Drought and wildfires Argentina 2022. https://earthobservatory.nasa.gov/images/149478/wildfires-ravage-corrientes-argentina
- Heatwave in Europe (Spain, Portugal, France and United Kingdom) https://www.bloomberg.com/news/articles/2022-08-10/temperatures-rise-in-europe-as-another-heat-wave-blankets-region , https://www.nature.com/articles/s41467-022-31432-y , https://www.weforum.org/agenda/2022/08/jet-stream-winds-fuelling-heatwaves/ , https://www.bbc.com/news/science-environment-62833937?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220909&utm_medium=email&utm_source=Revue%20Daily , https://www.bbc.com/news/world-europe-62648912?utm_campaign=Daily%20Briefing&utm_content=20220824&utm_medium=email&utm_source=Revue%20newsletter , https://www.bbc.com/news/uk-62758367?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220902&utm_medium=email&utm_source=Revue%20Daily and https://www.carbonbrief.org/guest-post-a-met-office-review-of-the-uks-record-breaking-summer-in-2022/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220929&utm_medium=email&utm_source=Revue%20Daily and https://climate.copernicus.eu/c3s-climate-bulletin-shows-summer-2022-was-europes-warmest-record?utm_source=C3S+Newsletter&utm_medium=email and https://climate.copernicus.eu/surface-air-temperature-august-2022 and https://www.ecmwf.int/en/about/media-centre/news/2022/ecmwf-directors-talk-about-european-heatwaves and https://www.ecmwf.int/en/about/media-centre/news/2022/ecmwf-directors-talk-about-european-heatwaves and https://www.worldweatherattribution.org/without-human-caused-climate-change-temperatures-of-40c-in-the-uk-would-have-been-extremely-unlikely/ and https://www.lemonde.fr/en/health/article/2022/11/07/at-least-15-000-killed-by-hot-weather-in-europe-in-2022-says-who_6003286_14.html?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20221108&utm_medium=email&utm_source=Revue%20Daily
- Drought in Europe https://edo.jrc.ec.europa.eu/documents/news/GDO-EDODroughtNews202208_Europe.pdf , https://www.nature.com/articles/s43247-022-00498-3 , https://www.reuters.com/world/europe/climate-activists-protest-dry-banks-danube-2022-08-11/?utm_campaign=Daily%20Briefing&utm_content=20220812&utm_medium=email&utm_source=Revue%20newsletter , https://www.reuters.com/world/europe/frances-

river-loire-sets-new-lows-drought-dries-up-its-tributaries-2022-08-17/?utm_campaign=Daily%20Briefing&utm_content=20220818&utm_medium=email&utm_source=Revue%20newsletter ,https://www.reuters.com/world/europe/frances-river-loire-sets-new-lows-drought-dries-up-its-tributaries-2022-08-17/?utm_campaign=Daily%20Briefing&utm_content=20220818&utm_medium=email&utm_source=Revue%20newsletter and https://www.bloomberg.com/news/features/2022-08-10/europe-s-low-water-levels-threaten-rhine-river-hit-80b-trade-lifeline?cmpid=BBD083022_GREENDAILY&utm_medium=email&utm_source=newsletter&utm_term=220830&utm_campaign=greendaily&leadSource=uverify%20wall and https://www.carbonbrief.org/guest-post-a-met-office-review-of-the-uks-record-breaking-summer-in-2022/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220929&utm_medium=email&utm_source=Revue%20Daily and https://climate.copernicus.eu/precipitation-relative-humidity-and-soil-moisture-august-2022

- Wildfires in Europe https://en.wikipedia.org/wiki/2022_European_and_Mediterranean_wildfires#:~:text=In%20June%20through%20August%202022,%2C%20Greece%2C%20Portugal%20and%20Spain , https://www.theguardian.com/world/2022/aug/15/wildfires-europe-burn-area-equivalent-one-fifth-belgium?utm_campaign=Daily%20Briefing&utm_content=20220816&utm_medium=email&utm_source=Revue%20newsletter and https://www.telegraph.co.uk/environment/2022/08/10/exceptional-risk-wildfires-could-sweep-across-britain-weekend/?utm_campaign=Daily%20Briefing&utm_content=20220811&utm_medium=email&utm_source=Revue%20newsletter
- Heat wave in the United States https://www.nytimes.com/interactive/2022/us/heat-wave-map-tracker.html , https://en.wikipedia.org/wiki/2022_North_American_heat_waves , and https://climate-xchange.org/2018/07/19/beyond-latest-heat-wave-pattern-extremes/
- Drought in the United States https://www.ers.usda.gov/newsroom/trending-topics/drought-in-the-western-united-states/ , https://www.theguardian.com/environment/2022/sep/12/us-west-megadrought-climate-disaster?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220913&utm_medium=email&utm_source=Revue%20Daily and https://apnews.com/article/science-arizona-lakes-california-b85a466248bd8ac8552636a892a8b690?utm_campaign=Daily%20Briefing&utm_content=20220816&utm_medium=email&utm_source=Revue%20newsletter
- Wildfires in the United States https://www.nifc.gov/fire-information/nfn
- Flooding in the United States https://www.theguardian.com/us-news/2022/aug/11/america-summer-floods-rainfall-climate-crisis
- Heat wave China https://www.cnn.com/2022/08/26/china/china-sichuan-power-crunch-climate-change-mic-intl-hnk/index.html and https://en.wikipedia.org/wiki/2022_China_heat_wave

- Drought in China https://www.theguardian.com/world/2022/aug/22/china-drought-causes-yangtze-river-to-dry-up-sparking-shortage-of-hydropower , https://www.bbc.com/news/world-asia-china-62644870 and https://www.reuters.com/world/china/china-issues-first-national-drought-alert-battles-save-crops-extreme-heatwave-2022-08-19/?utm_campaign=Daily%20Briefing&utm_content=20220819&utm_medium=email&utm_source=Revue%20newsletter
- Wildfires in China https://www.cnn.com/2022/08/23/china/china-heat-wave-chongqing-wildfires-intl-hnk/index.html
- Flooding in China https://www.nytimes.com/2022/06/23/world/asia/china-floods-heatwaves.html
- Drought Africa https://www.oxfam.ca/blog/climate-change-driving-drought-crisis-in-horn-of-africa/?gclid=EAIaIQobChMIsZSIhoXv-QIVosLCBB1fiQgDEAAYBCAAEgLEcfD_BwE , https://news.un.org/en/story/2022/07/1123132?gclid=EAIaIQobChMIsZSIhoXv-QIVosLCBB1fiQgDEAAYAiAAEgKQJfD_BwE and https://www.unicef.org/esa/reports/horn-africa-drought-crisis
- Drought in Africa explained ITCZ 2022. https://www.cpc.ncep.noaa.gov/products/international/africa/africa_hazard.pdf
- Heat wave India and Pakistan 2022 https://en.wikipedia.org/wiki/2022_heat_wave_in_India_and_Pakistan
- Drought in India and Pakistan 2022 https://www.nextias.com/current-affairs/19-05-2022/drought-in-numbers-2022-un-report
- Flooding in Pakistan 2022 https://en.wikipedia.org/wiki/2022_Pakistan_floods , https://www.carbonbrief.org/climate-change-likely-increased-extreme-rainfall-that-led-to-pakistan-flooding/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220916&utm_medium=email&utm_source=Revue%20Daily , https://www.carbonbrief.org/guest-post-how-the-south-asian-monsoon-is-changing-in-a-warming-climate/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220916&utm_medium=email&utm_source=Revue%20Daily and https://climate.copernicus.eu/pakistan-devastated-august-floods?utm_source=C3S+Newsletter&utm_medium=email and https://www.worldweatherattribution.org/climate-change-likely-increased-extreme-monsoon-rainfall-flooding-highly-vulnerable-communities-in-pakistan/ and https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(22)01874-8/fulltext?dgcid=raven_jbs_etoc_email
- Flooding in Brazil 2022 https://en.wikipedia.org/wiki/2022_Northeastern_Brazil_floods_and_mudslides
- Flooding in India and Bangladesh 2022 https://en.wikipedia.org/wiki/2022_Northeastern_Brazil_floods_and_mudslides , https://en.wikipedia.org/wiki/2022_India%E2%80%93Bangladesh_floods and

https://www.reuters.com/world/india/indias-august-monsoon-rains-34-above-average-weather-department-2022-08-31/?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220901&utm_medium=email&utm_source=Revue%20Daily

- Flooding in South Korea 2022 https://www.theguardian.com/environment/2022/aug/12/weather-tracker-deadly-floods-in-south-korea-and-drought-in-china and https://foreignpolicy.com/2022/08/12/south-korea-flood-parasite-banjiha/
- Flooding in Australia 2022 https://disasterphilanthropy.org/disasters/2022-australian-flooding/?gclid=EAIaIQobChMImN31_Ivv-QIVFR6tBh0LtwChEAAYASAAEgLaXvD_BwE and https://en.wikipedia.org/wiki/2022_eastern_Australia_floods
- Drought in Chile 2022 https://www.theguardian.com/world/2022/jun/01/chiles-water-crisis-megadrought-reaching-breaking-point
- Heatwave Japan 2022 https://en.wikipedia.org/wiki/2022_Japan_heatwave
- Atlantic Canada and Puerto Rico 2022 – hurricane Fiona https://www.accuweather.com/en/hurricane/fiona-becomes-most-intense-storm-on-record-to-slam-into-atlantic-canada/1251355
- Cuba, Florida, South Carolina and North Carolina – hurricane Ian https://en.wikipedia.org/wiki/Hurricane_Ian
- Philippines and Japan – super typhoon Nanmadol (Josie) https://en.wikipedia.org/wiki/Typhoon_Nanmadol_(2022)
- Philippines and Viet Nam – super typhoon Noru https://en.wikipedia.org/wiki/Typhoon_Noru
- Nigeria – West Africa flooding 2022 https://earthobservatory.nasa.gov/images/150463/flooding-inundates-southern-nigeria and https://www.carbonbrief.org/west-africas-deadly-rainfall-in-2022-made-80-times-more-likely-by-climate-change/?utm_campaign=Cropped&utm_content=20221124&utm_medium=email&utm_source=Revue%20Land
- Arctic warming 2022. https://www.arctictoday.com/summer-2022-was-warmest-on-record-for-svalbard/?wallit_nosession=1 and https://www.sciencedaily.com/releases/2022/07/220705162148.htm
- Antarctic warming 2022. https://www.google.com/search?q=arctic+temperatures+2022+severgarden&sxsrf=ALiCzsZ05yt0oqOa0WB82lZPin3L7snHPQ%3A1667744867208&ei=Y8RnY4CzDJat0PEPgb-f-AM&oq=arctic+temperatures+2022+severgar&gs_lcp=Cgxnd3Mtd2l6LXNlcnAQARgAMgUIIRCgATIFCCEQoAEyBQghEKABOgoIABBHENYEELADOgYIABAWEB46BQgAEIYDOggIIRAWEB4QHToHCCEQoAEQCjoECCEQFUoECE0YAUoECEEYAEoECEYYAFDYFFi8xgFgleoBaAFwAXgAgAGOAYgBnAiSAQMxLjiYAQCgAQHIAQjAAQE&sclient=gws-wiz-serp

- Wildfires Canada 2023. Four times previous maximum https://www.cbc.ca/news/politics/canada-wildfire-season-worst-ever-more-to-come-1.6934284 .

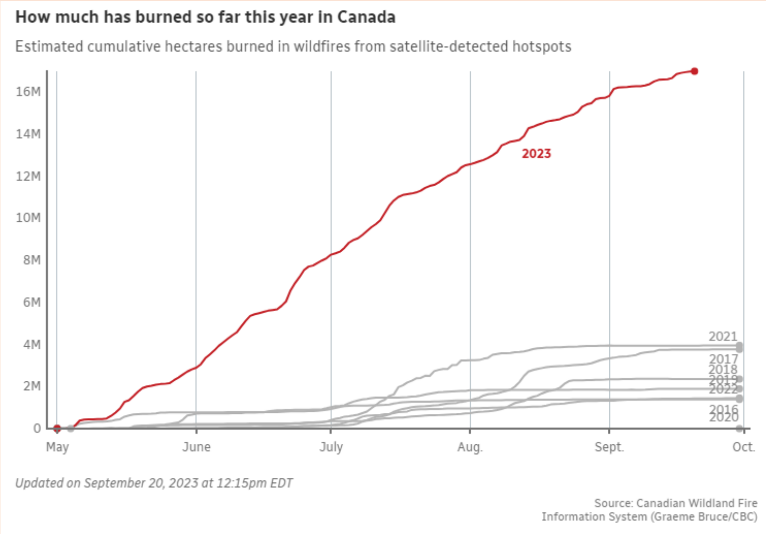


Figure 16.47 Wildfires Canada 2023, https://www.cbc.ca/news/politics/canada-wildfire-season-worst-ever-more-to-come-1.6934284 .

Extreme climate events, of all types, continue to be reported in 2023.

16.20 U.S. EPA Report Climate Change Indicators in the United States May 2021

The United States Environmental Protection Agency published a web site, https://www.epa.gov/climate-indicators , which describes climate change indicators as they pertain to the United States in particular and global environment under the following general headings:

- Greenhouse Gases
  - U.S. Greenhouse Gas Emissions
  - Global Greenhouse Gas Emissions
  - Atmospheric Concentrations of Greenhouse Gases
  - Climate Forcing
- Weather and Climate
  - U.S. and Global Temperature
  - Seasonal Temperature
  - High and Low Temperatures
  - Heat Waves
  - U.S. and Global Precipitation
  - Heavy Precipitation

- Tropical Cyclone Activity
    - River Flooding
    - Drought
    - A Closer Look: Temperature and Drought in the Southwest
- Oceans
    - Ocean Heat
    - Sea Surface Temperature
    - Sea Level
    - A Closer Look: Land Loss Along the Atlantic Coast
    - Coastal Flooding
    - Ocean Acidity
- Snow and Ice
    - Arctic Sea Ice
    - Antarctic Sea Ice
    - Ice Sheets
    - Glaciers
    - Arctic Glaciers
    - A Closer Look: The Glaciers of Glacier National Park
    - Lake Ice
    - Great Lakes Ice Cover
    - Community Connection: Ice Breakup in Three Alaskan Rivers
    - Snowfall
    - Snow Cover
    - Snowpack
    - Permafrost
    - Freeze-Thaw Conditions
- Health and Society
    - Climate Connection: Climate Change and Human Health
    - Heat-Related Deaths
    - Heat-Related Illnesses
    - Cold-Related Deaths
    - Heating and Cooling Degree Days
    - Residential Energy Use
    - Lyme Disease
    - West Nile Virus
    - Length of Growing Season
    - Growing Degree Days
    - Ragweed Pollen Season
- Ecosystems
    - Wildfires
    - Streamflow
    - Stream Temperature
    - Tribal Connection: Trends in Stream Temperature in the Snake River
    - Lake Temperature

- Great Lakes Water Levels and Temperatures
- Bird Wintering Ranges
- A Closer Look: The Black Guillemots of Cooper Island
- Marine Species Distribution
- Leaf and Bloom Dates
- Community Connection: Cherry Blossom Bloom Dates in Washington, D.C

The scope and thoroughness of this report provide a standard which is difficult to meet in most other regions of the world.

The web site provides referrals to other EPA web sites:

- USEPA Climate Change Homepage: https://www.epa.gov/climate-change .
- USEPA Climate Change Science: https://www.epa.gov/climatechange-science .
- USEPA Climate Change Research: https://www.epa.gov/climate-research .
- USEPA Climate Change Indicator Platform: https://www.globalchange.gov/browse/indicators .

16.21 Health

16.21.1 Heat and hot weather

The World Health Organization has recognized that "heat waves, or heat and hot weather that can last for several days" can result in significant health impacts including deaths https://www.who.int/health-topics/heatwaves#tab=tab_1 . This has been observed in the US EPA Report discussed in Section 16.20 and in a study recently published in the journal Nature of Climate Change titled 'The burden of heat-related mortality attributable to recent human-induced climate change' https://www.nature.com/articles/s41558-021-01058-x.epdf?sharing_token=WUEzuKQw9CqhUDFoBdIcjtRgN0jAjWel9jnR3ZoTv0N74knunZjp4k1Ncyycvvs4s-boSk4oaOLQNv21uGPfVoY9_A5EcLOzWQqs1rG12YxR_sIsdMQ0QeguVqZaPOLtBLd9-mF4Ko5eQywxAWRteYSRPA01GIAZj3Zf6Eks5kL8yuR4hOTLhwLGMNXtNuMk4WXwcRA4e1Zd1L9_rLBW8_n_MS19PBwPRTXsBUTjwsMYwhWnKBfKnVi8IN5mZVhpKBo3rRgi3Anx2SP7X8c6p8AXAtfDfX_PIytawT0SnDoijffVmXcGMJN66D1madSEL27-3jl1g5wxVnP_hnf-Dg%3D%3D&tracking_referrer=www.theguardian.com .

A paper titled, 'Global risk of deadly heat' was published in the letters of the journal, Nature Climate Change, online June 19, 2017, in which they report documented circumstances of heat-related mortality and what the impact of global warming will have https://www.nature.com/articles/nclimate3322.epdf?sharing_token=PtWlyHIFXVZ9RNTZ29by3dRgN0jAjWel9jnR3ZoTv0P1ZmqVLxKfxqQX-KqJzVRLBBVboAWW8gu7iH3qRbNOymP_5r6TsScQ_dWlqQpQZoWdM23_F7SgAw7eQrB_j5PSMqrvuhGlVoP6jfsRq11tstHI1SXCrYGZeyCGdBvjmrBf1vKZQcILFIjPx12ljVs14nOhYS0G7c2npZTnrW5nMJE5HT6kBO7oWKKgR5xsMA%3D&tracking_referrer=www.technologyreview.com .

In 2018 Europe recorded one hundred thousand heat related deaths, https://www.preventionweb.net/news/view/75857#:~:text=In%202018%2C%20the%20EU%20recorded,than%20the%201981%2D2010%20average.

Canada and NW United States experienced a significant heat wave (June and July 2021) that has resulted in several hundred heat related deaths. (See https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/forest-analysis-inventory/data-management/news/estimates_mortality_rates_2021_wildfires_final.pdf .) The heat wave extended from Southern California to the Arctic Circle and the Pacific Coast to Eastern Manitoba. It has lasted over one week. The unusual and extreme nature of the heat wave is believed to be a natural phenomenon known as a heat dome that has been aggravated by global warming. Explanations of the heat wave are just starting to be published. See https://www.carbonbrief.org/media-reaction-pacific-north-west-heat-dome-and-the-role-of-climate-change?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210701&utm_medium=email&utm_source=Revue%20Daily .

NASA published an article March 9, 2022 titled ‘Too Hot to Handle: How Climate Change May Make Some Places Too Hot to Live” https://climate.nasa.gov/ask-nasa-climate/3151/too-hot-to-handle-how-climate-change-may-make-some-places-too-hot-to-live/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter .

An article titled, ‘How hot is too hot for the human body?’ describes, in a quantitative manner, the impact of extreme heat and humidity on the human body and associated mortality risk https://www.technologyreview.com/2021/07/10/1028172/climate-change-human-body-extreme-heat-survival/?truid=&utm_source=the_download&utm_medium=email&utm_campaign=the_download.unpaid.engagement&utm_term=&utm_content=09-21-2022&mc_cid=92b47c9970&mc_eid=89ad5f9312 .

Article in Copernicus 24 August 2022 titled, Record-breaking European heatwaves: the role climate change and weather patterns, https://climate.copernicus.eu/record-breaking-european-heatwaves-role-climate-change-and-weather-patterns?utm_source=C3S+Newsletter&utm_medium=email discusses the heat-waves experienced in Europe in 2022 considering the role of climate change and differing weather patterns. The original paper discusses different types of heatwaves https://www.ecmwf.int/en/about/media-centre/news/2022/ecmwf-directors-talk-about-european-heatwaves .

Up-to-date information and networking opportunities on health impacts of heat may be found on the web site of the Global Heat Health Information Network, https://ghhin.org/ .

16.21.2 Present and potential health impacts of climate change

Four reports are particularly significant in light of COP26 and COP27. These are:

1. World Health Organization COP26 Special Report on Climate Change and Health, https://www.who.int/publications/i/item/cop26-special-report .
2. The Lancet 2021 report, Countdown on health and climate change: code red for a healthy future published October 20, 2021, https://www.thelancet.com/action/showPdf?pii=S0140-6736%2821%2901787-6 .
3. The Lancet 2022 report, Countdown on health and climate change: health at the mercy of fossil fuels. Published October 25, 2022, https://www.thelancet.com/action/showPdf?pii=S0140-6736%2822%2901540-9 .
4. The Lancet 2023 report, Countdown on health and climate change: health at the mercy of fossil fuels. Published November 15, 2023, https://www.thelancet.com/countdown-health-climate .

These reports make it very clear that virtually all of the current and future impacts of climate change effect all aspects of human health and quality of life in general including:

- Immediate impacts of extreme weather such as excessive heat, drought, storms, flooding and destruction of human environment (dwellings and infrastructure).
- Disease (aggravated, spread and new).
- Health.
- Agriculture.
- Food.
- Wealth.
- Mobility.
- Education.
- Traditional community structure and values.
- Security (crime, war and urgency to migrate).

Essentially, climate change means change in all aspects of the human environment.

A recent paper titled, 'Over half of known human pathogenic diseases can be aggravated by climate change' published in the journal Nature Climate Change which describes the impacts of ten climatic hazards sensitive to greenhouse gas emissions on each known human pathogenic disease. See https://www.nature.com/articles/s41558-022-01426-1?utm_campaign=Daily%20Briefing&utm_content=20220809&utm_medium=email&utm_source=Revue%20newsletter

16.21.3 Stress and anxiety among our children and youth and everyone else
The expanding awareness of climate change and its present and potential impacts is causing significant stress and anxiety in our youth. This is documented in the journal Nature https://www.nature.com/articles/d41586-021-02582-8?utm_source=Nature+Briefing&utm_campaign=5c3ff9eef1-briefing-dy-20210923&utm_medium=email&utm_term=0_c9dfd39373-5c3ff9eef1-46124954 and reported in the newsletter, The Conversation, https://theconversation.com/climate-change-is-harming-childrens-mental-health-and-this-is-just-the-start-168070?utm_medium=email&utm_campaign=Latest%20from%20The%20Conversation%20for%20September%2023%202021&utm_content=Latest%20from%20The%20Conversation%20for%20September%2023%202021+CID_28dab82048765185a8b3dce2cbc9bae9&utm_source=campaign_monitor_ca&utm_term=how%20climate%20change%20is%20affecting%20kids%20psychological%20development%20around%20the%20world.
Youth recognize the need to address the challenges climate change represents. They understand the need to mitigate and adapt. Most important youth need to see that the responsible elements of society are actually taking action to ensure they will have a hospitable future.

A recent poll (November 2021) conducted by the Global Future thinktank in conjunction with the University of York found that overall, 78% of people reported some level of eco-anxiety. This includes all age groups, social classes and income level https://www.theguardian.com/environment/2021/oct/31/eco-anxiety-over-climate-crisis-suffered-by-all-ages-and-classes?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20211101&utm_medium=email&utm_source=Revue%20Daily. This view is supported by the new UN climate science chief, Jim Skea, who also cautions against being overly optimistic (false hope and inaction), https://news.sky.com/story/apocalyptic-climate-change-language-can-make-people-feel-hopeless-warns-new-un-climate-science-chief-jim-skea-12974965?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-10-03&utm_campaign=Daily+Briefing+03+10+2023 .

16.22 Forecasting

16.22.1 Overview
Forecasting is the process of predicting the occurrence and magnitude of events that will occur in the future. Forecasting may be deterministic or stochastic.

Deterministic forecasting implies the use of physically correct (complete) models of the phenomena of interest. The model is able to determine (calculate) the outcome of interest such as flow in a river when the only input is historical weather and rainfall information. Information provided the model may real-time such as that used by models used to forecast the weather or flood forecasting. Or, the input of interest may be of a future scenario that might occur (Examples are the use of deterministic models to predict the outcome from changes in the energy budget due to emission of greenhouse gases or the result of a severe rainfall event or change in land use.) The future scenario itself may be the result of stochastic analytics.

Stochastic forecasting uses a probabilistic or statistical approach that relies on the availability of a history of parameters of interest. (Examples include maximum yearly flow in a stream at a given location, maximum or minimum temperature, wind speed, rainfall (daily, monthly, yearly.) Stochastic forecasting allows prediction of extreme events, that is events with low probability of occurrence (This type of forecasting is used in the design of buildings, dams, water supplies, and water management strategies.) Stochastic forecasting relies on the fact that the observed parameters of interest are the result of a physical environment that has not changed over the period of interest, that is, a stable environment responsible for generating a stable population of parameters. Forecasts made using stochastic techniques are only valid if the physical environment remains similar to the period over which the historical parameters were collected.

16.22.2 Climate change models

Climate change models as discussed in Chapter 17 are deterministic models. They are used to predict changes in climate resulting from changes in greenhouse gas concentration in the atmosphere and the human response to these changes. The results of these studies are intended to provide guidance for adaptation to expected climate change and what is necessary to mitigate changes in climate change by reducing emission of greenhouse gases to the atmosphere.

It is believed that there is value in short-term climate change projections. This is one of the World Climate Research Programme, WCRP 'Grand Objectives' https://www.wcrp-climate.org/about-wcrp/wcrp-overview and https://www.wcrp-climate.org/gc-near-term-climate-prediction . A recent application from Copernicus, titled European hydrology and climate data explorer, https://cds.climate.copernicus.eu/cdsapp#!/software/app-hydrology-climate-explorer?tab=overview was recently developed to provide short-term change projections.

Attribution of climate change to current events is still largely intuitive though significant progress is being made to at least provide insights into extreme events as discussed in the Introduction. That said, attribution remains a discussion about something that has already happened. It is really a warning regarding what climate change does actually mean.

16.22.3 Stochastic models

Stochastic models are very important in that they allow prediction of events (parameters of interest) based on the actual observation of the events over a period of time. The use of actual observations provides confidence that the analyses are relevant. As stated in Section 16.22.1 stochastic analyses depend on the existence of a stable population of observed parameters with which the analyses depend. That is the observation of parameters of interest are made when the environment responsible for characterizing the parameters has remained unchanged.

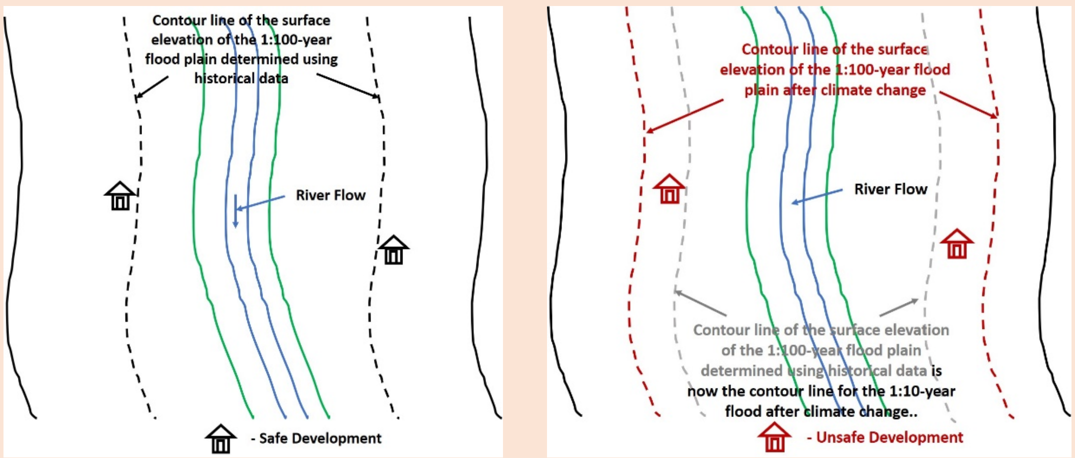
Stability does not mean constant value. It means unchanging environment responsible for determining the value of the parameter of interest. Stability means that the values of individual parameters will exhibit a range of values, low to high, with a distribution of values that remains constant over time. The distribution of values is known as the probability distribution.

Every parameter identified in Chapters 3 and 6 will vary over a range of values in a fashion that can be statistically described and used for forecasting provided the population from which the parameters are taken is stable. That is, the values of the parameter are not influenced by new, different or fewer factors over the sampling period.

Climate change is inserting uncertainty into seasonal routines, confidence in ability to prepare for daily changes, confidence in stochastically determined parameters used in the design of all elements of our infrastructure, all elements of societal management strategies, and all elements of the biological community. Climate change affects every aspect of existence. Unfortunately, many of the useful predictions need to be daily or at least for shorter periods of time than associated with predicted climate variations – very different from the information that can be confidently gleaned from current climate change modelling. In the opinion of the author the utility of climate change predictions is limited to generalities and seasonal considerations without any hint of the potential variability of the weather. It should be clear from discussions of forecasting in Chapters 3 and 6 that the ability to provide statistically meaningful meteorological and hydrological forecasts, and therefore the ability to develop rational strategies for future human activities, depends on the availability of sufficient, quality weather and hydrologic data collected during periods of stable climate. One of the most significant impacts of climate change is the loss of confidence in the ability to use historical knowledge of climate to predict future weather or hydrologic events.

Climate models predict a changing environment. The distribution of daily values will change in a way that is not known except in an intuitive fashion. If climate change predictions can be used to confidently predict a revised distribution of daily values it may be discovered that averages and median values have increased or decreased and historical extremes might be more or less common in the future. The fact that the impact of climate change on the distribution of daily values is unknown is very important because it limits the utility of analyses based on historical data.

The potential impact of climate change on flood plain delineation provides an important example. The delineation of the 1:100-year flood plain using pre-climate change data (historical data) is shown in Figure 16.48 (a) and post-climate change in Figure 16.48 (b). The flow in a river that might have been equaled or exceeded once every 100 years based on analyses of historical data might be equaled or exceeded once every 10 years with climate change. Previous safe development is at risk of being flooded after climate change.



(a) (b)

Figures 16.48(a) Contour lines of surface elevation of the extent of a flood plain resulting from a river flow determined to be a 1:100-year flood from the analyses of historical data and (b) the contour lines of the surface elevation of the extent of a flood plain that may result from a river flow determined to be a 1:100-year flood after climate change.

The explanation is that the frequency analysis that might be developed after climate change indicates a greater 1:100-year flow as shown in Figure 16.49.

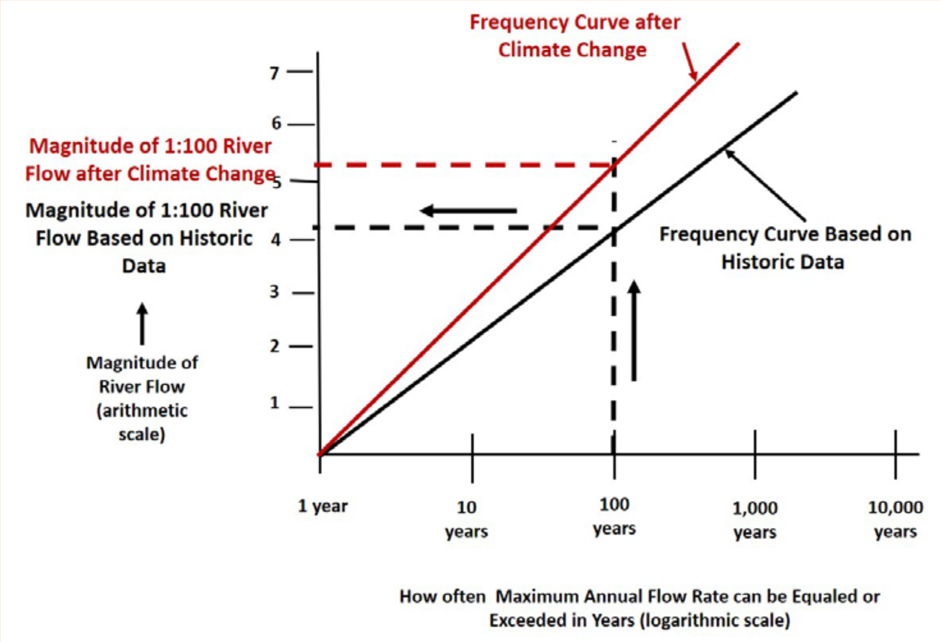


Figure 16.49 Frequency analysis based on historical data and after climate change.

The surface elevation for the flow after climate change as shown in Figure 16.50 is greater than that using historical data. The contours in Figure 16.48 are based on this result. (Note that it is assumed that the hydraulics of river flow remain the same before and after climate change which might not necessarily be true.)

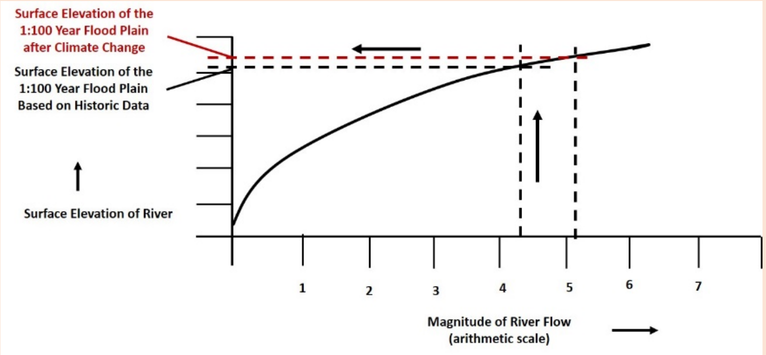


Figure 16.50 Surface elevation predicted using historical data and after climate change.

This example suggests that infrastructure and development designed using historic analysis might now be under-designed or simply wrong. See Section 6.13. Structures will fail, development guidelines are no longer useful for new projects and existing development based on old guidelines is at risk of being damaged by flooding. There are many, many other scenarios of interest. The once in every 500-year events as determined using analysis that uses historical data might increase in frequency with the impact of climate change and become a once in every 50-year event. Implementation of pro-active adaptation measures requires reliable quantitative forecasts.

Climate models, by themselves, do not (cannot at this time) provide information on the changes to the distribution of day-to-day parameter values. The World Climate Research Program has made this problem one of its Grand Challenges, https://www.wcrp-climate.org/gc-extreme-events and https://www.wcrp-climate.org/gc-extremes-themes/614-gc-extremes-theme-attribute . Users of statistical analysis of climate data – weather, including the energy budget actually – are not completely lost because they are at least provided a general quantitative direction as to how their parameter of interest is changing over time.

Hydrological parameters change in response to weather. The need is for quantitative information that has the same utility as historical data and can be used with the same confidence.

It is important that methodologies be developed, such as those being undertaken by the World Climate Research Programme, which can predict how probability distributions of daily weather and hydrological parameters are changed due to climate change. With this information it would be possible to predict changes of extreme events and of relatively low frequency events such as once every five years or ten years which are frequently used in design. The ability to determine how climate change is impacting frequency analyses derived using historical data would be very useful – particularly for the implementation of resilient adaptation measures.

Confident quantitative attribution of the impact of climate change on current weather and hydrologic events remains a significant and important challenge.

16.22.4 Insurance and insurability

See Section 19.5, Insurance and the impact of climate change.

Note that the very existence of the insurance industry depends on the ability to forecast the potential impacts of climate change.

16.23 Social Impacts

The social impacts of climate change are numerous and typically negative. The saying 'that any change is a bad change' appears to be true because of the resulting disruption that must be accommodated. A few of the more impactful changes are economic, increase in poverty, increase in mass migration and possibility of war. Climate justice is discussed in Section 19.6.

16.23.1 Economic impacts

Economic impacts will challenge the resilience of all commercial, industrial, financial, individual and political aspects of society. Governance can be expected to become more complex, perhaps with fewer resources to manage a less affluent, impatient constituency and the risk of becoming dysfunctional.

Economic impacts are discussed in Sections 19.4 and 19.5 in the references provided.

16.23.2 Poverty

The common perspective of poverty is that it exists in communities living under subsistence conditions, living on the edge of life and death, which might have some truth. Negative changes to the factors which affect their condition will likely result in high mortality and social/political unrest. Fringe and possibly violent factions may evolve simply as a survival strategy. Rule of law will be impaired. Haiti is a good example https://www.hrw.org/world-report/2022/country-chapters/haiti .

Creation of poverty is different. Economic changes resulting from the effects of climate change will likely drive a large fraction of the middle and upper classes into poverty though they are more likely to survive. This group will be the source of considerable social and political upheaval as they will not be tolerant of the 'new normal'. If they perceive that there will be no foreseeable political resolution (and civil war is not an option) there will be attempts to migrate to regions where they may continue to live, to some degree, in the manner with which they are accustomed. The question is 'migration to where?' See recent reporting on internal migration in Zimbabwe and the difficulties arising https://www.climatechangenews.com/2022/09/12/displaced-drought-climate-migrants-clash-zimbabwes-timber-industry-migration/?utm_source=Climate+Weekly&utm_campaign=70880e1286-CW-22-Jul_COPY_01&utm_medium=email&utm_term=0_bf939f9418-70880e1286-408118282

16.23.3 Migration

Loss of economic opportunities, loss of livelihood, poverty, insecurity, internal migration, and political instability. caused directly or indirectly by the effects of climate change, will result in the desire to move to places which provide security, livelihood and opportunities. The migration may be internal to the country, to adjacent countries perceived as stable or as is often seen, to perceived places of opportunity such as Europe, United States, and parts of Asia. The tales of crossings of the Mediterranean from North Africa and Turkey into Greece, Italy and Spain, treks from Turkey through Bulgaria and into member countries of the European Union, boat and vehicle crossings from France into the United Kingdom, migrants travelling to South Africa, migrants travelling to South America and northward joining migrants from all over South and Central America to the United States, Cambodia to Thailand, Myanmar to Thailand, Malaysia and Australia are common tales. There are many more. The migrants come from

Afghanistan, Iraq, Iran, all of Africa, all of South and Central America and disadvantaged communities from troubled countries in Asia. They are typically not welcome at their destination as they are considered an unwelcome economic burden. They are often taken advantage of. Many do not survive the journey. As the impacts of climate change worsen the resulting attempts at migration will increase and so will the problems of trying to accommodate them.

It is inevitable that the migrant phenomena will eventually be commonplace in all countries including those temporarily unaffected throughout the southern and northern hemisphere. There is a global migration crisis that may already be unmanageable. The United Nations International Organization on Migration promotes orderly and humane migration for the benefit of all, https://www.iom.int/who-we-are . Their work in South Africa which is experiencing significant influx of migrants from other parts of Africa is described in the following web site, https://www.iom.int/countries/south-africa . See the perspective of Doctors Without Borders at https://www.doctorswithoutborders.org/what-we-do/focus/migration-and-refugee-crisis .

The only solution to the global migration crisis appears to be preventing and resolving the problems in the migrant countries of origin. Social and economic conditions must be improved. Funding and implementing adaptation projects to limit the impacts of climate change are critical. Mitigation of climate change is critically important to limit impacts to manageable proportions.

An optimistic assessment is provided in the article, 'Migrant cities of the future-the climate crisis will require mass movement, we can do it well' https://inews.co.uk/inews-lifestyle/climate-change-mass-migration-cities-future-adapt-transform-1816377?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20220830&utm_medium=email&utm_source=Revue%20Daily

16.23.4 War

Economic hardship, insecurity and competition for limited resources that appear unresolvable through discussion will ultimately result in armed conflict, destruction of limited economic potential, loss of lives, internal migration and international migration.

Migration to adjacent countries from a country viewed as responsible for the exodus may also result in armed conflict between country of origin and destination country.

Access to water resources is already resulting in internal conflict between competing users and between neighbouring countries. The drought in southwestern United States also affects Mexico. It is uncertain how water resource sharing within the United States will be resolved (https://www.cnn.com/interactive/2021/08/us/colorado-river-water-shortage/)and definitely unclear how conflicts between the United States and Mexico will be resolved (https://www.e-education.psu.edu/earth111/node/991 and https://theconversation.com/megadrought-along-border-strains-us-mexico-water-relations-160338).

Recent completion of the Renaissance Dam on the Blue Nile in Ethiopia has raised the spectre of conflict between Ethiopia, Egypt and the Sudan https://www.brookings.edu/blog/africa-in-focus/2020/08/05/the-controversy-over-the-grand-ethiopian-renaissance-dam/ .

Similar conflicts regarding Mekong River Basin development between Viet Nam, Laos, Cambodia, Thailand and China appear to be resolved https://asean.org/wp-content/uploads/images/2013/economic/mbdc/basic%20framework%20of%20ambdc.pdf ; however there is concern regarding the instream and riparian ecosystems https://www.oecd-ilibrary.org/sites/b3463307-en/index.html?itemId=/content/component/b3463307-en .

There may be conflicts between China, India and Bangladesh regarding Indian plans to develop water management structures on the Brahmaputra River upstream of Bangladesh https://warontherocks.com/2020/12/a-conflict-prone-river-takes-a-step-backwards/ .

The effects of major droughts attributed to climate change and other social disruptions such as terrorist groups in Somalia, Nigeria, Mali, Chad, Senegal, Somalia and elsewhere destabilize governance already weakened by the effects of climate change.

A book titled, Climate Wars by Gwynne Dyer published by Random House 2008 discusses the relationship between international conflict and climate change.

16.24 Tipping points, domino effects, knock-on effects, runaway global warming and hothouse Earth

See Section 18.5 for discussion on tipping points, domino effects, knock-on effects runaway global warming and hothouse Earth.

16.25 Climate activism and climate action

The impacts of climate change that are being experienced, and the forecasts of the impacts of future climate change, are dire. Significant portions of the global community, not just those that are presently being affected (such as the island countries experiencing sea level increase and loss of country); but also, the affluent and informed portions of the global population, to pressure governments and industry to take action (climate action) to accept climate science and demonstrating their social responsibility by implementing adaptation and mitigation strategies that are needed to avoid the worst outcomes.

While all age groups are part of the climate concerned communities it is the younger population in particular who are willing to publicly and aggressively express their views in important forums such as the United Nations COPS (both formally and informally), social media and demonstrations - wherever they are able to bring attention to their concerns. The many organized groups promoting climate activism do not seem to include the real 'shaker and mover' elements which are the ones that will actually get things done. (Shaker and mover elements include financial institutions, leaders in industry, leaders in education, government and leadership in politics.) This is gradually changing as established political organizations, those that run the country, adopt strategies to address the imminent impacts brought on by climate change. Climate activism is very important and is being heard even if it appears ad hoc. It is inevitable that political success will depend on how well and equitable the apparently different political entities address the climate change crisis.

Note: There are many web sites that discuss climate activism and climate action. The number increases daily.

16.26 Comments

The ability to document the effects of climate change requires substantial resources to observe and study the natural environment and communicate the results of these studies to policy makers, politicians and the global community in general.

Three books worth reading are 'The Ends of World' which describes the evolution, extinction and redevelopment of life on Earth and current human impacts, 'The Ferocious Summer' which describes the plight of penguins in the Antarctic which are coping with a mismatch of food availability and feeding their young as a result of climate change and 'The Sixth Extinction' whose title is self-explanatory. The references for these books may be found in section 16.21.

Recent investigations into the Atlantic Meridional Overturning Circulation, AMOC, has determined how this circulation has changed over the past 1500 years. (The Gulf Stream is the warm surface element of this circulation discussed in Section 8.3.) This is discussed in a paper by Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N. and Rahmstorf, S. published in Nature Geoscience, https://www.nature.com/articles/s41561-021-00699-z?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210226&utm_medium=email&utm_source=Revue%20Daily and described in the Independent https://www.independent.co.uk/climate-change/news/atlantic-ocean-current-weakening-amoc-b1807337.html?utm_campaign=Carbon%20Brief%20Daily%20Briefing&utm_content=20210226&utm_medium=email&utm_source=Revue%20Daily . The most significant weakening has occurred in the twentieth century and the authors surmise that climate change be the cause. This has yet to be established.

16.27 Future updates

December 12, 2020 – Fifth Anniversary of the Paris Agreement
August 9, 2021 – Publication of IPCC AR6 WG1, Climate Change, The Physical Science Basis, February 28, 2022 IPCC AR6 WGII, Climate Change: Impacts, Adaptability and Vulnerability and April 4, 2022 IPCC AR6 WGIII, Climate Change: Mitigation

Every year and often during the year the World Meteorological Organization (WMO) publishes a report titled 'United in Science 2022' https://public.wmo.int/en/resources/united_in_science co-authored by the United Nations Environment Program (UNEP) https://www.unep.org/ , Global Carbon Project (GCP), https://www.globalcarbonproject.org/ ,Urban Climate Change Research Network, (UCCRN) https://uccrn.ei.columbia.edu/ , United Kingdom Met Office https://www.metoffice.gov.uk/ , the Intergovernmental Panel on Climate Change (IPCC) https://www.ipcc.ch/ and the United Nations Office for Disaster Risk Reduction (UNDRR) https://www.undrr.org/ .

The WMO also publishes reports titled, 'State of the Global Climate 2021, State of the Climate in Latin America and the Caribbean 2021, State of the Climate in Africa 2021 and State of the Climate in Europe 2021, and the Provisional State of the Global Climate in 2022, https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate .

The WMO reports are quite comprehensive in topics and global coverage. Their work will not be repeated unless there is more science which has not already been covered in this document.

Many other important organizations produce annual updates on their area(s) of interest. These include:

- The Global Carbon Project
- The World Wildlife Fund
- NASA
- NOAA
- International Cryosphere Climate Initiative
- USEPA
- Copernicus Institute of Sustainable Development
- U.S. Global Change Research Program (USGCRP), Fourth National Climate Assessment, Volume I, Climate Science Special Report and Volume II, Impacts, Risks and Adaptation in the United States. See https://science2017.globalchange.gov/ and https://nca2018.globalchange.gov/ .

There are more that will be added in time.

16.28 Information support

Key web sites:

1. Polar amplification. http://www.realclimate.org/index.php/archives/2006/01/polar-amplification/ .

2. Global emissions. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

3. Mauna Loa carbon dioxide forecast for 2021. https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long-range/forecasts/co2-forecast

4. Earth observatory, NASA – all maps. https://earthobservatory.nasa.gov/global-maps/MYD28M

5. Ocean carbon dioxide uptake. https://www.ncei.noaa.gov/news/global-ocean-absorbing-more-carbon

6. Ocean acidification. https://www.pacioos.hawaii.edu/projects/acid/

7. Ocean acidification. https://en.unesco.org/ocean-acidification

8. Ocean acidification in the Arctic. https://www.npolar.no/en/themes/ocean-acidification-in-the-arctic/

9. UK Ocean Acidification Research Program. https://www.oceanacidification.org.uk/

10. Global Ocean Acidification Observing Network. http://goa-on.org/home.php

11. Capacity of ocean to absorb carbon dioxide. https://cmns.umd.edu/news-events/features/4527

12. ICESat-2. https://icesat-2.gsfc.nasa.gov/

13. Gravity recovery and climate experiment, GRACE. https://www.nasa.gov/mission_pages/Grace/index.html, https://gracefo.jpl.nasa.gov/resources/33/greenland-ice-loss-2002-2016/ , and https://grace.jpl.nasa.gov/resources/31/antarctic-ice-loss-2002-2020/.

14. Global Ecosystem Dynamics Investigation, GEDI. Ecosystem lidar. https://gedi.umd.edu/

15. Larsen C ice shelf, Antarctica. https://cmns.umd.edu/news-events/features/4391

16. Global ice viewer. https://climate.nasa.gov/interactives/global-ice-viewer/#/

17. Glacial lakes. https://nsidc.org/cryosphere/icelights/2013/05/ebb-and-flow-glacial-lakes

18. Glacial lakes, most dangerous lake in Nepal. https://www.youtube.com/watch?v=ZN8a-pP60wk

19. Glacial lakes, Imja Lake. https://www.youtube.com/watch?v=z7GKW-u-Gg4

20. IPCC climate change 2014 synthesis report AR5. https://ar5-syr.ipcc.ch/index.php

21. Arctic sea (and other) maps. https://www.arcticcentre.org/EN/arcticregion/Maps

22. Snow, water, ice, permafrost in the Arctic, SWIPA 2017. https://swipa.amap.no/

23. European Space Agency, cryosat, ESA's ice mission. http://www.esa.int/Applications/Observing_the_Earth/CryoSat

24. True North: Adapting infrastructure to climate change in northern Canada. http://nrt-trn.ca/climate/true-north

25. ArcticNet, University of Laval. https://arcticnet.ulaval.ca/

26. Permafrost. http://www.global-greenhouse-warming.com/permafrost.html

27. Arctic sea ice minimum 2020. https://climate.nasa.gov/news/3023/2020-arctic-sea-ice-minimum-at-second-lowest-on-record/

28. Arctic ice roads. https://www.cbc.ca/news/technology/climate-change-to-ravage-arctic-ice-roads-1.1117369

29. Arctic News, Covid19 did not cut emissions. http://arctic-news.blogspot.com/

30. Permafrost thawing. https://skepticalscience.com/The-speed-of-coastal-erosion-in-Eastern-Siberia_AWI.html

31. Permafrost map, northern hemisphere. https://www.sciencedirect.com/science/article/pii/S0012825218305907

32. Polar bears, effect of climate change. https://www.wwf.org.uk/learn/wildlife/polar-bears#:~:text=The%20Arctic%20is%20warming%20about,ice%20to%20raise%20their%20young and http://assets.worldwildlife.org/publications/398/files/original/Effects_of_Climate_Change_on_Polar_Bears_fact_sheet.pdf?1345754206

33. Sea ice, State of the Cryosphere. https://nsidc.org/cryosphere/sotc/sea_ice.html

34. Tree species distribution in high latitudes changing with climate. https://esajournals.onlinelibrary.wiley.com/doi/10.1890/ES14-00111.1

35. Impacts of Climate change on the Tree Line, Grace, Berninger and Nagy, 2002. https://academic.oup.com/aob/article/90/4/537/185822

36. Tree line on Mt. Fuji, Sugiyama,2021. http://www.asahi.com/ajw/articles/14035103

37. Polar bears, Polar Bears International, https://www.fastcompany.com/90362601/jellyfish-are-booming-because-of-climate-change-and-human-activity.

38. Polar bears, NASA. https://earthobservatory.nasa.gov/images/146023/polar-bears-struggle-as-sea-ice-declines

39. Polar bears, WWF. https://www.wwf.org.uk/learn/wildlife/polar-bears#:~:text=The%20Arctic%20is%20warming%20about,ice%20to%20raise%20their%20young.

40. Penguins, Action Bioscience. https://www.biologicaldiversity.org/news/media-archive/Penguins_ActionBioscience_9-09.pdf

41. Penguins, World Economic Forum. https://www.weforum.org/agenda/2020/02/penguin-colony-antarctic-islands-climate-change-environment

42. Seals, Climate Institute. https://climate.org/archive/topics/ecosystems/seals-battle-climatechange.html

43. Seals, humane society. https://www.humanesociety.org/sites/default/files/docs/seals-sea-ice.pdf

44. Ringed seals and climate change, IUCN. https://www.iucn.org/sites/dev/files/import/downloads/fact_sheet_red_list_ringed_seal_v2.pdf

45. Starfish die off due to global warming. 2021. https://www.nbcnews.com/science/environment/warming-oceans-may-be-choking-oxygen-starfish-causing-them-drown-n1253355 , https://news.cornell.edu/stories/2021/01/organic-matter-bacteria-doom-sea-stars-oxygen-depletion , https://www.frontiersin.org/articles/10.3389/fmicb.2020.610009/full

46. Mountain Pine bark beetles. https://e360.yale.edu/features/small-pests-big-problems-the-global-spread-of-bark-beetles and https://www.unbc.ca/releases/2007/climate-change-and-mountain-pine-beetle

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