

Provisional State of the Global Climate 2023



Key messages

- The global mean near-surface temperature in 2023 (to October) was around 1.40 ± 0.12 °C above the 1850–1900 average. Based on the data to October, it is virtually certain that 2023 will be the warmest year in the 174-year observational record, surpassing the previous joint warmest years, 2016 at 1.29 ± 0.12 °C above the 1850–1900 average and 2020 at 1.27 ± 0.13 °C.
- The past nine years, 2015–2023, will be the nine warmest years on record.
- Record monthly global temperatures have been observed for the ocean – from April through to September – and, starting slightly later, the land – from July through to September.
- The ten-year average 2014–2023 (to October) global temperature is 1.19 ± 0.12 °C above the 1850–1900 average, the warmest 10-year period on record.
- Observed concentrations of the three main greenhouse gases – carbon dioxide, methane, and nitrous oxide – reached record high levels in 2022, the latest year for which consolidated global values are available (1984–2022). Real-time data from specific locations show that levels of the three greenhouse gases continued to increase in 2023.
- Ocean heat content reached its highest level in 2022, the latest available full year of data in the 65-year observational record.
- In 2023, global mean sea level reached a record high in the satellite record (1993 to present), reflecting continued ocean warming as well as the melting of glaciers and ice sheets. The rate of global mean sea level rise in the past ten years (2013–2022) is more than twice the rate of sea level rise in the first decade of the satellite record (1993–2002).
- Antarctic sea-ice extent reached an absolute record low for the satellite era (1979 to present) in February. Ice extent was at a record low from June onwards, and the annual maximum in September was far below the previous record low maximum.
- Glaciers in western North America and the European Alps experienced an extreme melt season. In Switzerland, glaciers lost around 10% of their remaining volume in the past two years.
- Extreme weather continues to lead to severe socio-economic impacts. Extreme heat affected many parts of the world. Wildfires in Hawaii, Canada and Europe led to loss of life, the destruction of homes and large-scale air pollution. Flooding associated with extreme rainfall from Mediterranean Cyclone Daniel affected Greece, Bulgaria, Türkiye, and Libya with particularly heavy loss of life in Libya.
- Food security, population displacements and impacts on vulnerable populations continue to be of concern in 2023, with weather and climate hazards exacerbating the situation in many parts of the world.
- Extreme weather and climate conditions continued to trigger new, prolonged, and secondary displacement in 2023 and increased the vulnerability of many who were already uprooted by complex multi-causal situations of conflict and violence.

Global climate indicators

The global climate indicators provide an overview of changes in the climate system¹. The set of interlinked physical indicators presented here connect the changing composition of the atmosphere with changes in energy in the climate system and the response of land, ocean, and ice.

The global indicators are based on a wide range of data sets which comprise data from multiple observing systems including satellites and in situ networks (for details on data sets used in the report, see [Data sets and methods](#)).

Changes to the physical climate, measured here by key indicators, can have cascading impacts on national development and progress toward the Sustainable Development Goals (SDGs)². For example, changes in the acidity or temperature of the ocean can affect marine life, potentially impacting coastal communities that may depend on the local catch for their livelihood or food security. On the other hand, climate science has a critical role to play in facilitating sustainable development. As demonstrated by the 2023 United in Science report, weather, climate, and water-related sciences support the achievement of many of the SDGs³. Recognizing the interconnections between climate and development can therefore lead to synergistic action—an increasing necessity as the world gets further off-track from achieving both the SDGs and Paris Agreement⁴.

Baselines

Baselines are periods of time, usually spanning three decades or more, that are used as a fixed benchmark against which current conditions can be compared. For scientific, policy and practical reasons, several different baselines are used in this report, and these are specified in the text and figures. Where possible, the most recent WMO climatological standard normal, 1991–2020, is used for consistent reporting.

For some indicators, however, it is not possible to use the standard normal owing to a lack of measurements during the early part of the period. There are also two specific exceptions. First, for the global mean temperature time series – and only for the global mean series – a reference period of 1850–1900 is used. This is the baseline used in IPCC AR6 WG I as a reference period for pre-industrial conditions and is relevant for understanding progress in the context of the Paris Agreement. Second, greenhouse gas concentrations can be estimated much further back in time using gas bubbles trapped in ice cores. Therefore, the year 1750 is used in this report to represent pre-industrial greenhouse gas concentrations.

Greenhouse gases

Key message:

- Observed concentrations of the three main greenhouse gases – carbon dioxide, methane, and nitrous oxide – reached record high levels in 2022, the latest year for which consolidated global values are available (1984–2022). Real-time data from specific locations show that levels of the three greenhouse gases continued to increase in 2023.

Atmospheric concentrations of greenhouse gases reflect a balance between emissions from human activities, natural sources, and sinks. Increasing levels of greenhouse gases in the atmosphere due to human activities have been the major driver of climate change since the industrial revolution. Global

¹ <https://journals.ametsoc.org/view/journals/bams/102/1/BAMS-D-19-0196.1.xml>

² Climate Indicators and Sustainable Development: Demonstrating the Interconnections (wmo.int)

<https://library.wmo.int/records/item/56276-climate-indicators-and-sustainable-development-demonstrating-the-interconnections>

³ United In Science 2023 (wmo.int) <https://library.wmo.int/records/item/68235-united-in-science-2023>

⁴ https://sdgs.un.org/sites/default/files/2023-09/UN%20Climate%20SDG%20Synergies%20Report-091223B_1.pdf

average mole fractions of greenhouse gases – referred to here for simplicity as the “concentration” in the atmosphere – are calculated from in situ observations made at multiple sites through the Global Atmosphere Watch (GAW) Programme of WMO and partner networks.

In 2022 – the latest year for which consolidated global figures are available – atmospheric levels of greenhouse gases reached new highs (Figure 1), with globally averaged concentrations for carbon dioxide (CO₂) at 417.9 ± 0.2 parts per million (ppm), methane (CH₄) at 1923 ± 2 parts per billion (ppb) and nitrous oxide (N₂O) at 335.8 ± 0.1 ppb, respectively 150%, 266% and 124% of pre-industrial (1750) levels. The rate of increase of CH₄ was the second highest on record, after 2021 and the rate of increase of N₂O was the highest on record. The rate of increase of CO₂ at 2.2 ppm was slightly below the 10-year average of 2.46 ppm·yr⁻¹. CO₂ growth rate is typically lower in years which start with La Niña as 2022 did, and higher in years which start with El Niño as 2016 did⁵. Real-time data from specific locations, including Mauna Loa⁶ (Hawaii, United States of America) and Kennaook/Cape Grim⁷ (Tasmania, Australia) indicate that levels of CO₂, CH₄ and N₂O continued to increase in 2023.

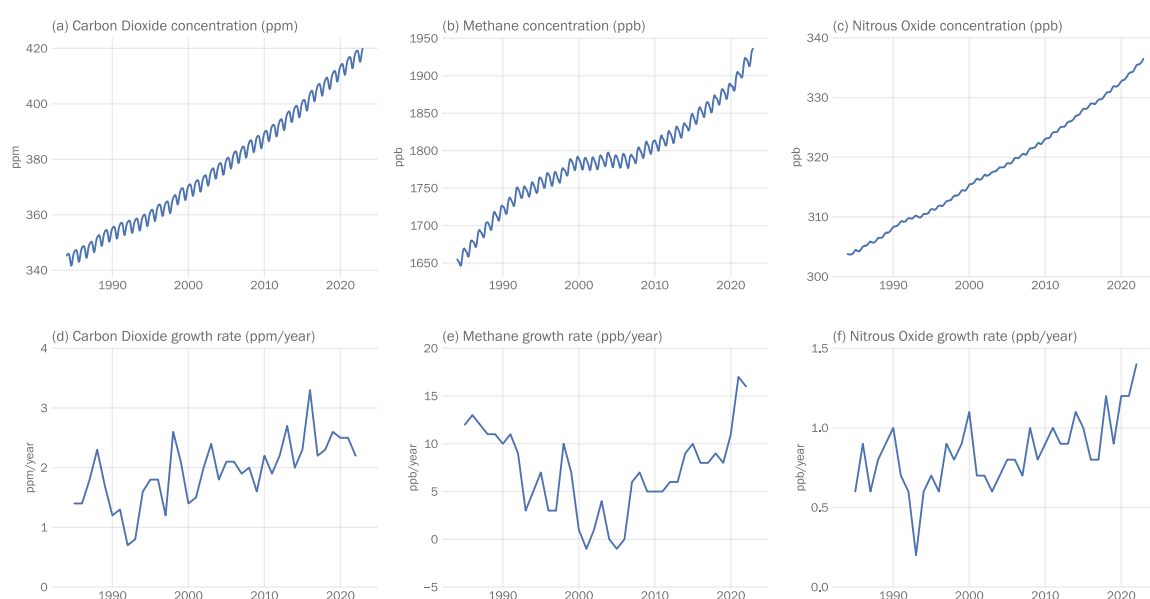


Figure 1: Top row: Monthly globally averaged mole fraction (measure of atmospheric concentration), from 1984 to 2022, of (a) CO₂ in parts per million, (b) CH₄ in parts per billion and (c) N₂O in parts per billion. Bottom row: the growth rates representing increases in successive annual means of mole fractions for (d) CO₂ in parts per million per year, (e) CH₄ in parts per billion per year and (f) N₂O in parts per billion per year.

Temperature

Key messages:

- The global mean near-surface temperature in 2023 (to October) was around 1.40 ± 0.12 °C above the 1850–1900 average. Based on the data to October, it is virtually certain that 2023 will be the warmest year in the 174-year observational record, surpassing the previous joint warmest years, 2016 at 1.29 ± 0.12 °C above the 1850–1900 average and 2020 at 1.27 ± 0.13 °C.
- The past nine years, 2015–2023, will be the nine warmest years on record.

⁵ Betts, R., Jones, C., Knight, J. et al. El Niño and a record CO₂ rise. *Nature Climate Change* 6, 806–810 (2016).

<https://doi.org/10.1038/nclimate3063>

⁶ <https://gml.noaa.gov/ccgg/trends/mlo.html> Measurements at Mauna Loa were interrupted by a volcanic eruption and the measurement site was temporarily relocated to Maunakea observatories 21 miles to the north.

⁷ <https://www.csiro.au/greenhouse-gases/>

- Record monthly global temperatures have been observed for the ocean – from April through to September – and, starting slightly later, the land – from July through to September.
- The ten-year average 2014–2023 (to October) global temperature is $1.19 \pm 0.12^\circ\text{C}$ above the 1850–1900 average, the warmest 10-year period on record.

Global mean near-surface temperature in 2023 (data to October) was $1.40 \pm 0.12^\circ\text{C}$ above the 1850–1900 average⁸ (Figure 2). The analysis is based on a synthesis of five global temperature datasets (see [Data sets and methods](#)). Based on the data to October, it is virtually certain that 2023 will be the warmest year in the 174-year instrumental record in each of the five data sets. The most recent nine years – 2015 to 2023 – will be the nine warmest years on record. The two previous joint warmest years were 2016 with an anomaly of $1.29 \pm 0.12^\circ\text{C}$, and 2020 with an anomaly of $1.27 \pm 0.13^\circ\text{C}$.

There were some noteworthy individual months, with June, July, August, and September 2023 each surpassing the previous record for the respective month by a wide margin in all datasets. The margin increased from between 0.14 and 0.20°C in June to between 0.46 and 0.51°C in September. The second-highest margin by which a September record was broken in the past 60 years (the period covered by all datasets) was 0.02 to 0.17°C in 1983. October was also record warm. July is typically the warmest month of the year globally, and thus July 2023 became the all-time warmest month on record.

The long-term increase in global temperature is due to increased concentrations of greenhouse gases in the atmosphere. The shift from La Niña, which lasted from mid-2020 to early 2023, to fully developed El Niño conditions by September 2023 (see [Short-term Climate Drivers](#)) likely explains some of the rise in temperature from 2022 to 2023. However, some areas of unusual warming such as the Northeast Atlantic (Figure 3) do not correspond to typical patterns of warming or cooling associated with El Niño. Other factors, which are still being investigated, may also have contributed to the exceptional warming from 2022 to 2023.

The average global temperature over the past ten years, 2014 to 2023 (data to October), was $1.19 \pm 0.12^\circ\text{C}$ above the 1850–1900 average, making the past ten years the warmest among all ten-year periods on record in all five datasets. The 2014 to 2023 average is slightly higher than the total observed warming (1.15 [1.00 to 1.25] $^\circ\text{C}$) for the period 2013 to 2022 estimated by Forster et al. (2023)⁹, consistent with continued warming.

Global average sea-surface temperatures (SSTs) were at a record observed high for the time of year, starting in the late Northern Hemisphere spring. April through to September (the latest month for which we have data) were all at a record warm high, and the records for July, August and September were each broken by a large margin (around 0.21 to 0.27°C). Exceptional warmth relative to the 1991–2020 baseline, was recorded in the eastern North Atlantic, the Gulf of Mexico and the Caribbean, and large areas of the Southern Ocean (Figure 3, see also [Marine heatwaves and cold-spells](#)).

Global land temperature anomalies reached record observed levels in July and August, somewhat later than for the SSTs, and the September average was a record by a large margin of 0.53 to 0.72°C . The second highest margin in the past 60 years was 0.21 to 0.27°C in 2002. For the year 2023 to date, most land areas were warmer than the 1991–2020 average (Figure 3). Unusual warmth was reported across large areas of the eastern U.S., Mexico, and Central America, as well as western and

⁸ For anomalies relative to other baselines see [Global mean temperature anomalies for 2023 relative to other periods](#).

⁹ Forster et al. used an update of the IPCC methodology based on four datasets, two of which are used in the current report. Forster et al. (2023) Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence, Earth Syst. Sci. Data, 15, 2295–2327, <https://doi.org/10.5194/essd-15-2295-2023>.

southern areas of South America. Western Europe and western parts of North Africa, western Eurasia, areas of Central and southeast Asia, and Japan, were also unusually warm.

Global Mean Temperature Difference (°C) Compared to 1850-1900 average

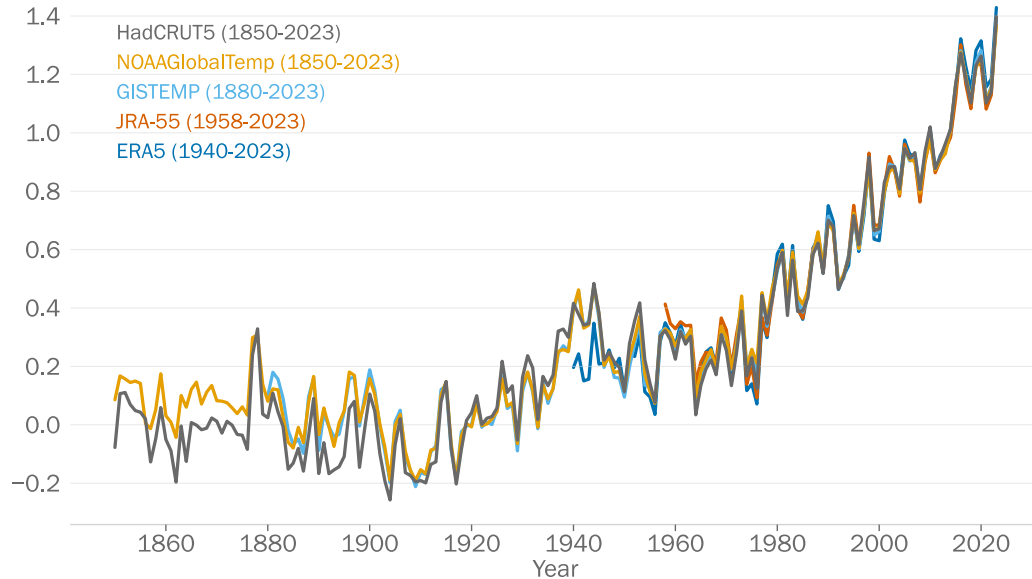


Figure 2: Annual global mean temperature anomalies (relative to 1850–1900) from 1850 to 2023. The 2023 average is based on data to October. Data are from five data sets, see Data sets and methods for details.

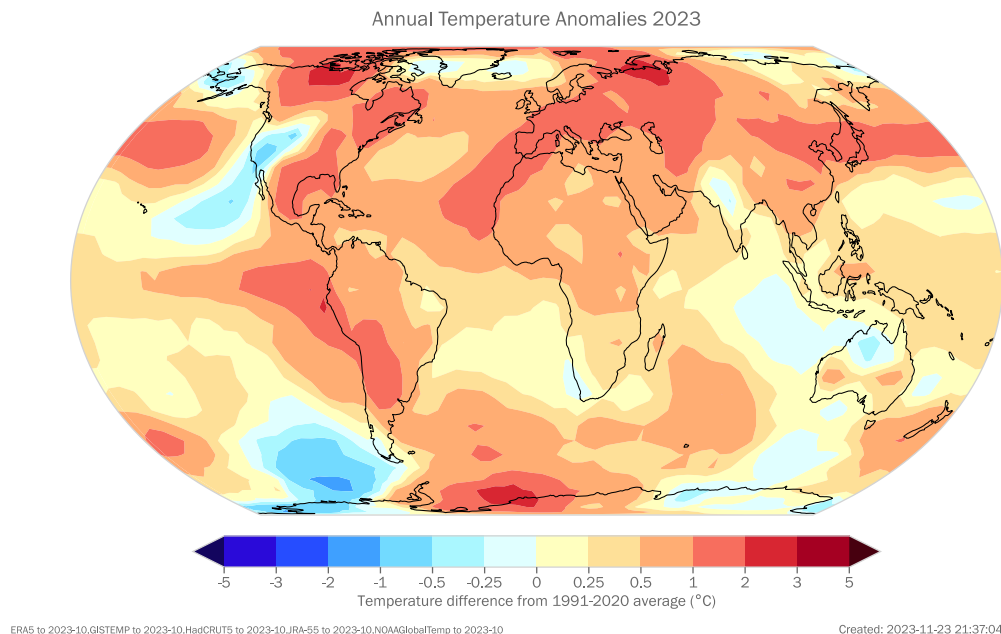


Figure 3: Mean near-surface temperature anomalies (difference from the 1991–2020 average) for 2023 to October. Data are the median of five data sets as indicated in the legend, see Data sets and methods for details.

Ocean

Increasing human emissions of CO₂ and other greenhouse gases cause a positive radiative imbalance at the top of the atmosphere, meaning energy is being trapped within the climate system. The imbalance leads to an accumulation of energy in the Earth system in the form of heat that is driving

global warming^{10,11}. The ocean, which covers around 70% of the Earth's surface, absorbs heat and CO₂, which can act to slow the rate of warming in the atmosphere. However, the heat absorbed by the ocean leads to ocean warming which, together with the melting of ice on land, raises sea levels. The ocean also absorbs CO₂ leading to ocean acidification¹². Warming waters, sea level rise and ocean acidification all have significant effects on the ocean, as well as the plants and animals that live in it and the people who rely upon it for their livelihoods.

Ocean heat content

Key message:

- Ocean heat content reached its highest level in 2022, the latest available full year of data in the 65-year observational record.

Around 90% of the energy that accumulated in the Earth system since 1971 was stored in the ocean. As energy has accumulated in the ocean, it has warmed and the heat content of the ocean (Ocean Heat Content, Figure 4) has increased.

According to a consolidated analysis based on seven individual datasets, the upper 2000 m of the ocean continued to warm in 2022 (the latest full year for which we have data)¹³. It is expected that warming will continue – a change which is irreversible on centennial to millennial timescales^{14,15}. Ocean heat content in 2022 was the highest on record, exceeding the 2021 value by 17 ± 9 ZJ (Figure 4). All data sets agree that ocean warming rates show a particularly strong increase in the past two decades. The rate of ocean warming for the 0–2000 m layer was $0.7 \pm 0.1 \text{ W}\cdot\text{m}^{-2}$ from 1971–2022, but $1.2 \pm 0.2 \text{ W}\cdot\text{m}^{-2}$ from 2006–2022 (the period covered by the Argo programme). Deep-ocean global warming below 2000 m depth is estimated to be $0.07 \pm 0.1 \text{ W}\cdot\text{m}^{-2}$ from 1992–2022¹⁶.

Although ocean heat content (OHC) has increased strongly through the entire water column, the rate of warming has not been the same everywhere¹⁷. The strongest warming in the upper 2000 m occurred in the Southern Ocean (60°S–35°S), North Atlantic (20°N–50°N) and South Atlantic (60°S–0°S) (Figure 5). The Southern Ocean domain is the largest reservoir of heat, accounting for around 36% of the global OHC increase in the upper 2000 m since 1958. The Atlantic Ocean accounts for approximately 33% of the global 0–2000 m OHC increase; the Pacific Ocean around 20%.

Some relatively small regions are cooling, including the subpolar North Atlantic Ocean extending from near the surface down to a depth of over 800 m (also the only area to show centennial cooling at the surface). The contrasting pattern of cooling (50°N–70° N) and warming (20°N–50°N) in the North Atlantic has been associated with a slowing of the Atlantic Meridional Overturning Circulation

¹⁰Hansen, J. et al. (2011). Earth's energy imbalance and implications. *Atmospheric Chemistry and Physics* <https://doi.org/10.5194/acp-11-13421-2011>

¹¹ von Schuckmann, K. et al. (2016). An imperative to monitor Earth's energy imbalance. In *Nature Climate Change*. <https://doi.org/10.1038/nclimate2876>

¹² State of the Ocean Report 2022 | UNESCO <https://www.unesco.org/en/articles/state-ocean-report-2022>

¹³ von Schuckmann et al. (2020). Heat stored in the Earth system: where does the energy go? *Earth Syst. Sci. Data*, 12(3), 2013–2041. <https://doi.org/10.5194/essd-12-2013-2020>

¹⁴ Cheng, L.; Trenberth, K. E.; Fasullo, J. et al. Improved estimates of ocean heat content from 1960 to 2015, *Science Advances* 2017, 3 (3), e1601545. <https://doi.org/10.1126/sciadv.1601545>.

¹⁵ IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press <https://doi.org/10.1175/2010JCLI3682.1>.

¹⁶ Purkey, S. G., & Johnson, G. C. (2010). Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise Budgets. *Journal of Climate*, 23(23), 6336–6351. <https://doi.org/10.1175/2010JCLI3682.1>

¹⁷ Cheng, L., Abraham, J., Trenberth, K.E. et al. Another Year of Record Heat for the Oceans. *Adv. Atmos. Sci.* (2023).

<https://doi.org/10.1007/s00376-023-2385-2> and Cheng, L., von Schuckmann, K., Abraham, J.P. et al. Past and future ocean warming. *Nat Rev Earth Environ* 3, 776–794 (2022). <https://doi.org/10.1038/s43017-022-00345-1>.

and local interactions between the air and sea¹⁸. Other cooling regions include the northwest Pacific, southwest Pacific and southwest Indian Oceans.

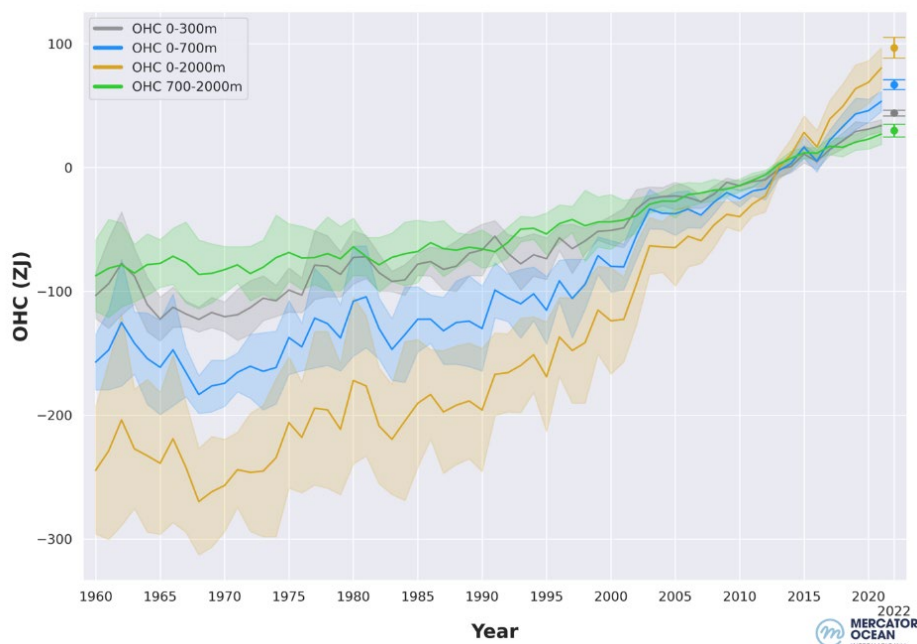


Figure 4: 1960–2021 ensemble mean time series and ensemble standard deviation (2-standard deviations, shaded) of global ocean heat content (OHC) anomalies relative to the 2005–2021 average for the 0–300 m (grey), 0–700 m (blue), 0–2000 m (yellow) and 700–2000 m depth layer (green). The ensemble means OHC anomalies for the year 2022 has been added as separate points, together with their ensemble spread, and is based on a subset of 7 datasets. Source: Mercator Ocean international. Updated from von Schuckmann et al. (2020)¹⁹

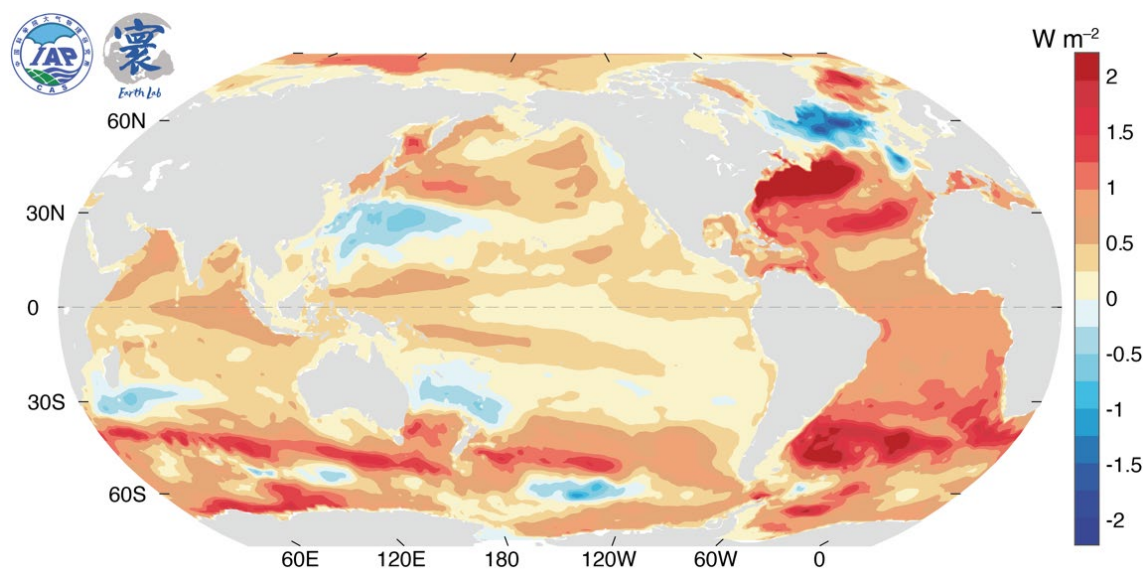


Figure 5: Observed upper 2000 m OHC trend from 1958 to 2022. Units: $W \cdot m^{-2}$. Data updated from Cheng et al. (2017)²⁰.

¹⁸ Cheng, L., von Schuckmann, K., Abraham, J. P. et al: Past and future ocean warming. Nature Reviews Earth & Environment. 2022, <https://doi.org/10.1038/s43017-022-00345-1>.

¹⁹ von Schuckmann et al. (2020). Heat stored in the Earth system: where does the energy go? Earth Syst. Sci. Data, 12(3), 2013–2041. <https://doi.org/10.5194/essd-12-2013-2020>

²⁰ Cheng, L.; Trenberth, K. E.; Fasullo, J. et al. Improved estimates of ocean heat content from 1960 to 2015, Science Advances 2017, 3 (3), e1601545. <https://doi.org/10.1126/sciadv.1601545>

Sea level

Key message:

- In 2023, global mean sea level reached a record high in the satellite record (1993 to present), reflecting continued ocean warming as well as the melting of glaciers and ice sheets.
- The rate of global mean sea level rise in the past ten years (2013–2022) is more than twice the rate of sea level rise in the first decade of the satellite record (1993–2002).

In 2023, global mean sea level (GMSL) has continued to rise (Figure 6). The La Niña conditions between mid-2020 and early 2023 had only a small apparent effect on GMSL, unlike the 2011 La Niña that led to a temporary decrease in the GMSL of several millimetres. The rapid rise observed in 2023 is likely due in part to the nascent El Niño and is likely to increase further as the 2023 El Niño develops. The long-term rate of sea level rise has more than doubled since the start of the satellite record, increasing from $2.14 \text{ mm}\cdot\text{yr}^{-1}$ between 1993 and 2002 to $4.72 \text{ mm}\cdot\text{yr}^{-1}$ between 2013 and 2022.

From January to March 2023, sea levels (Figure 7) were higher than the long-term average (1993–2012) in the western tropical Pacific. This is characteristic of warm seawater in the region associated with ENSO-neutral conditions. Sea levels in the North Atlantic and eastern tropical Pacific were lower than the long-term average. Warming of the surface waters in the eastern Tropical Pacific during the early stages of the 2023 El Niño (see [Short-term Climate Drivers](#)) led to an increase in sea level relative to the long-term mean in the most eastern part of the Tropical Pacific between April and June. By July to September, the El Niño signature was clearly visible, with sea level being above average from the mid-tropical Pacific to the coasts of central and South America. Above average sea levels were also observed in the tropical and north-east Atlantic, associated with the anomalous warming in these areas during Northern Hemisphere summer.

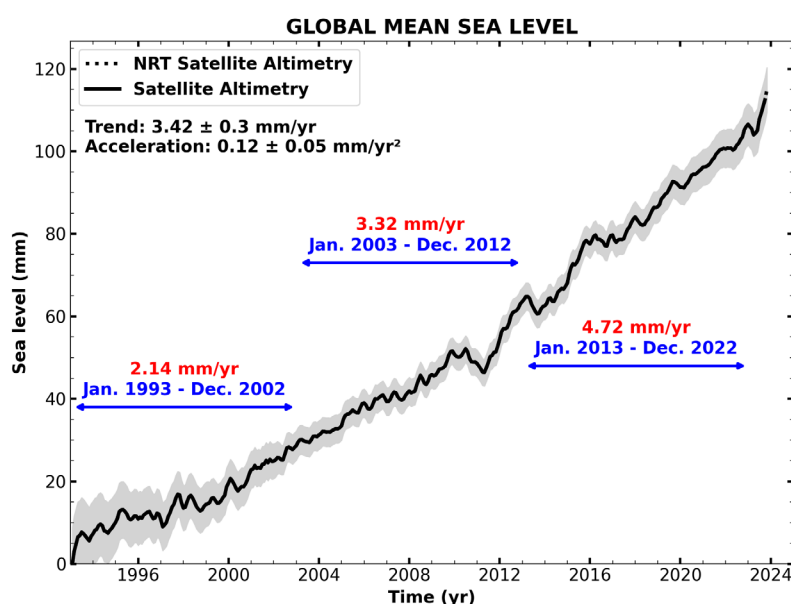


Figure 6: GMSL evolution between January 1993 and October 2023 based on satellite altimetry. The black line is the best estimate, and the grey shaded area indicates the uncertainty. Near-real-time updates are indicated by a dotted line. Red and blue annotations indicate the average rate of sea level rise during three decades of the record as indicated. (Source AVISO)

Intraseasonal sea level anomalies

E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). DOI: 10.48670/moi-00149

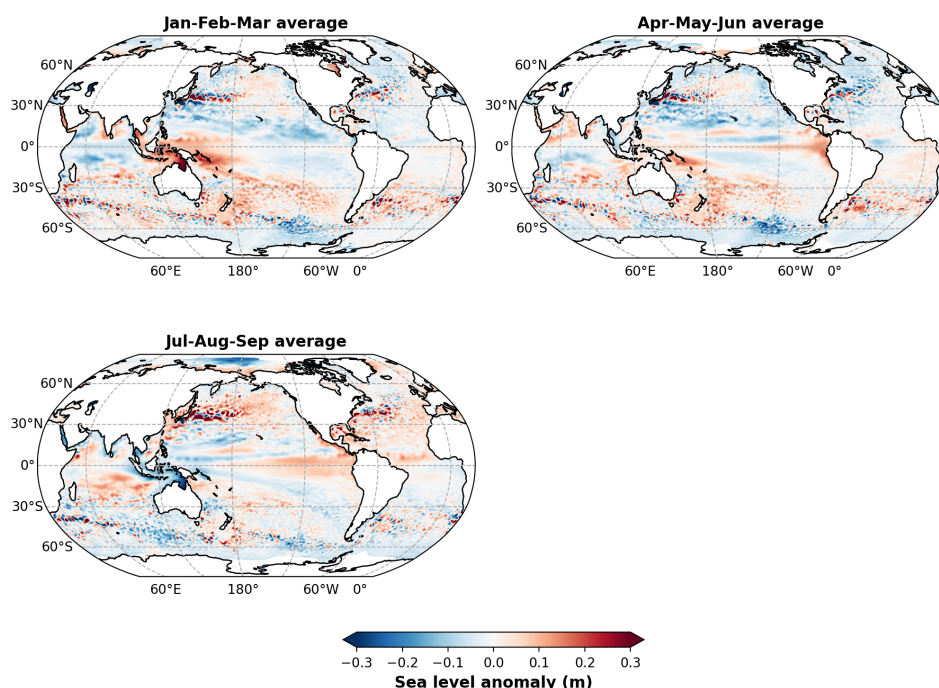


Figure 7: 3-month averages of altimetry-based sea level anomalies (relative to the 1993–2012 average, which is the product climatology) for (top left) January to March, (top right) April to June, and (bottom left) July to September. Data downloaded from the Copernicus Marine Service (CMEMS, <https://marine.copernicus.eu>).

Marine heatwaves and cold spells

As with heatwaves and cold-spells on land, marine heatwaves (MHW) and marine cold-spells (MCS) are prolonged periods of extreme high or low temperatures in the seas and ocean that can have a range of consequences for marine life and dependent communities²¹. MHWs have become more frequent, intense, and longer lasting since the late 20th century, while MCSs have been decreasing by those same measures. Satellite retrievals of sea-surface temperature are used to monitor MHWs and MCSs globally, categorized here as moderate, strong, severe, extreme, or ice (for definitions, see [Data sets and methods](#)).

El Niño events tend to cause wide-spread MHWs in the eastern Tropical Pacific. This region did experience 'strong' MHWs in 2023 (Figure 8a, to late August), but yet, they have covered a smaller area than during previous El Niño events. The area is likely to increase as the El Niño continues to develop. Of particular concern, in 2023 were the persistent and wide-spread MHWs in the North Atlantic throughout Northern Hemisphere summer and early autumn. The Mediterranean Sea was also unusually warm relative to the baseline period and experienced near complete coverage of 'strong' and 'severe' MHWs for the twelfth consecutive year. In the southern hemisphere, the waters surrounding New Zealand remained 1 to 2°C above the long-term average through January to September (~270 days).

In contrast, there were almost no occurrences of MCSs within 60° North or South of the equator in 2023 to date (Figure 9a). The global ocean experienced an average daily MHW coverage of 20% (to

²¹ Smale, D.A., Wernberg, T., Oliver, E.C.J. et al. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Chang.* 9, 306–312 (2019). <https://doi.org/10.1038/s41558-019-0412-1>

date, Figure 8b), well above the previous record of 17% in 2016. In contrast, the average daily coverage of MCS (Figure 9b) was only 2%, far below 2022 (5%).

Ref.: 24971/2023-1.5 S/CNP
Approved by Petteri Taalas, Thu Nov 16 14:21:44 UTC 2023

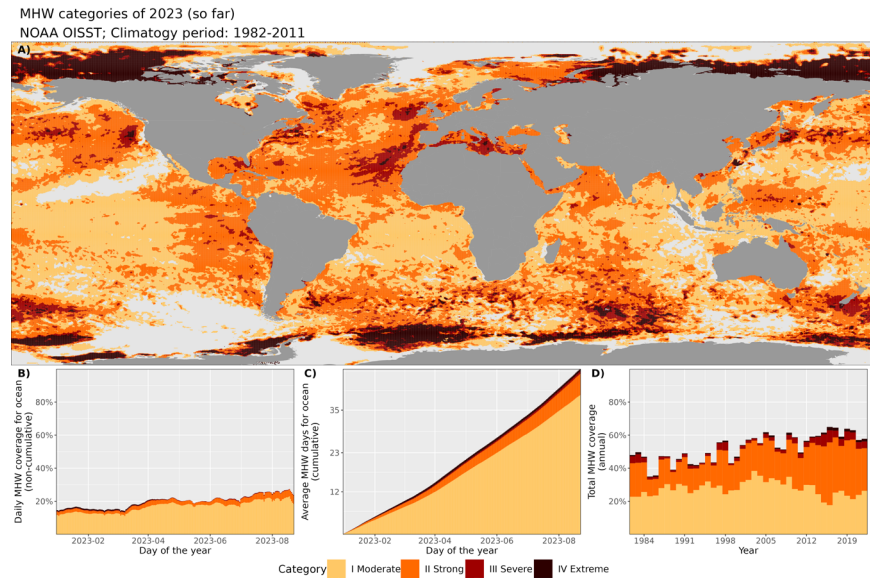


Figure 8: (a) Global map showing the highest MHW category (for definitions, see Data sets and methods) experienced at each pixel over 2023 (through September; reference period 1982–2011). Light grey indicates that no MHW occurred in a pixel over the entire year; (b) Stacked bar plot showing the percentage of the surface of the ocean experiencing an MHW on any given day of the year; (c) Stacked bar plot showing the cumulative sum of MHW days per pixel weighted by the surface area of those pixels. Note: This average is calculated by dividing the cumulative sum of MHW days per pixel weighted by the surface area of those pixels. (d) Stacked bar plot showing the total percentage of the surface of the ocean that experienced an MHW from 1982 to present. Data are from National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea-Surface Temperature (OISST). Source: Robert Schlegel

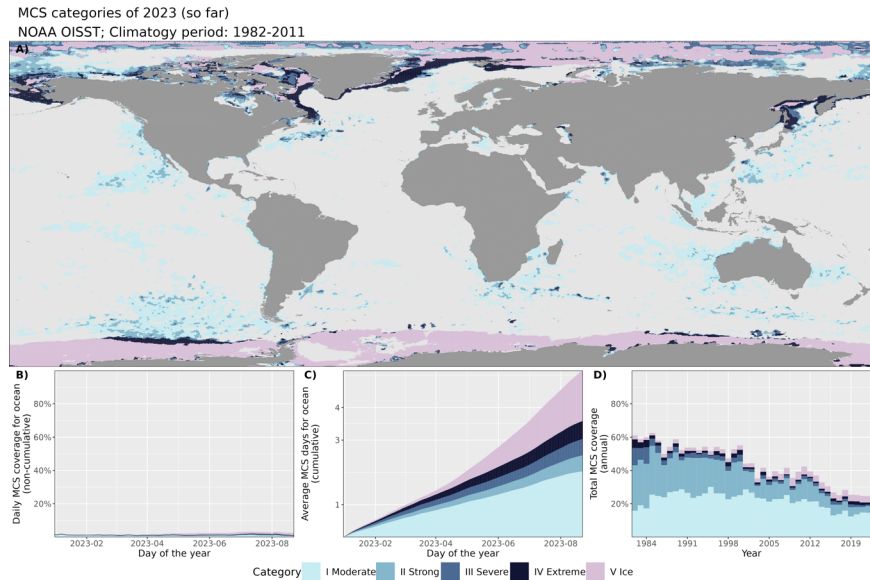


Figure 9: As for Figure 8 but showing marine cold-spells rather than marine heatwaves. Data are from NOAA OISST. Source: Robert Schlegel.

Ocean acidification

The ocean absorbs around one quarter of the annual emissions of anthropogenic CO₂ to the atmosphere^{22,23}. CO₂ reacts with seawater and alters the carbonate chemistry, resulting in a decrease in pH referred to as ‘ocean acidification’ (Figure 10). Ocean acidification affects organisms and ecosystem services, including food security, by reducing biodiversity, degrading habitats, and endangering fisheries and aquaculture²⁴. The IPCC AR6 concluded that *“There is very high confidence that open ocean surface pH is now the lowest it has been for at least 26 [thousand years] and current rates of pH change are unprecedented since at least that time”*.²⁵

Although global efforts, many supported by IOC-UNESCO and led by the Global Ocean Acidification Observing Network and its UN Ocean Decade Programme – Ocean Acidification Research for Sustainability, have resulted in an increase in the number of ocean acidification observations, many regions remain under-sampled. Data collected for the Sustainable Development Goal 14.3.1 Indicator (“Average marine acidity (pH) measured at agreed suite of representative sampling stations”) show that the current coverage is inadequate, with time series not long enough to determine trends and gaps in observations in all areas. The rate of change in ocean acidification, its pattern and scale, shows great regional variability, highlighting the need for global efforts to increase high-frequency and long-term monitoring.

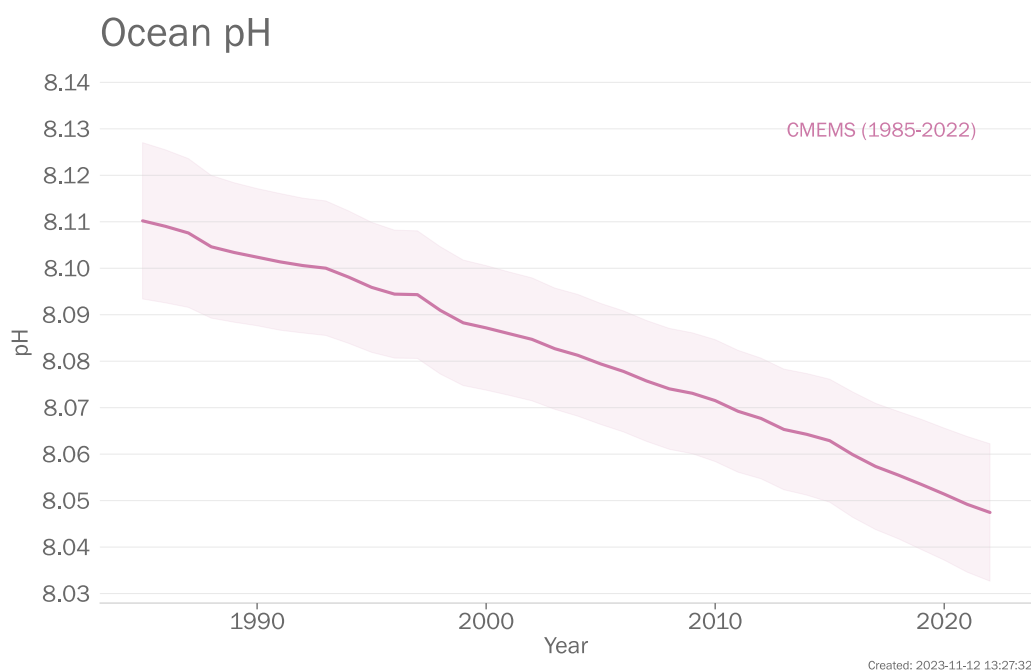


Figure 10: Global annual mean ocean surface pH (purple) covering the period 1985–2022. The shaded area indicates the estimated uncertainty in the values. Data from Copernicus Marine Environment Monitoring Service.

²² WMO. 2022. WMO Greenhouse Gas Bulletin (GHG Bulletin) – No.18: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2021. <https://library.wmo.int/idurl/4/58743>

²³ Friedlingstein, P., O’Sullivan, M., Jones, M. W., Andrew, R. M., et al. 2020. Global Carbon Budget 2020. *Earth System Science Data*, Vol. 12, pp. 3269–3340. <https://doi.org/10.5194/essd-12-3269-2020>

²⁴ IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: [10.59327/IPCC/AR6-9789291691647](https://doi.org/10.59327/IPCC/AR6-9789291691647)

²⁵ Intergovernmental Panel on Climate Change (IPCC), 2021: Climate Change 2021: The Physical Science Basis, Chapter 2, section 2.3.3.5 Ocean pH, <https://www.ipcc.ch/report/ar6/wg1/>.

Cryosphere

The cryosphere comprises the frozen parts of Earth – glaciers and ice sheets, sea-ice, snow, and permafrost. The inhospitable and often remote environments in which ice forms mean that it has sometimes been challenging to undertake long-term measurements of the cryosphere.

Sea-ice

Key messages:

- Arctic sea-ice extent remained well below normal in 2023, with the annual maximum and annual minimum extents being respectively the fifth and sixth lowest in the 45-year satellite record.
- Antarctic sea-ice extent reached an absolute record low for the satellite era (1979 to present) in February. Ice extent was at a record low from June onwards, and the annual maximum in September was far below the previous record low maximum.

Arctic sea-ice extent reached its annual maximum of 14.62 million km² on 6 March, the fifth lowest in the satellite record²⁶. The annual minimum Arctic sea-ice extent was reached on 19 September²⁷ (Figure 11), with a minimum extent of 4.23 million km², well below the long-term average (1991–2020) of ~5.5 million km². This was the sixth lowest minimum Arctic sea-ice extent in the satellite record (1979–2023), not as extreme as 2012 or 2020 but only slightly higher than 2007, 2016 and 2019, and continuing the long-term trend of reduced late-summer and early autumn Arctic ice cover. Major negative anomalies were observed in the Beaufort, Chukchi, and East Siberian Seas (Figure 11 right).

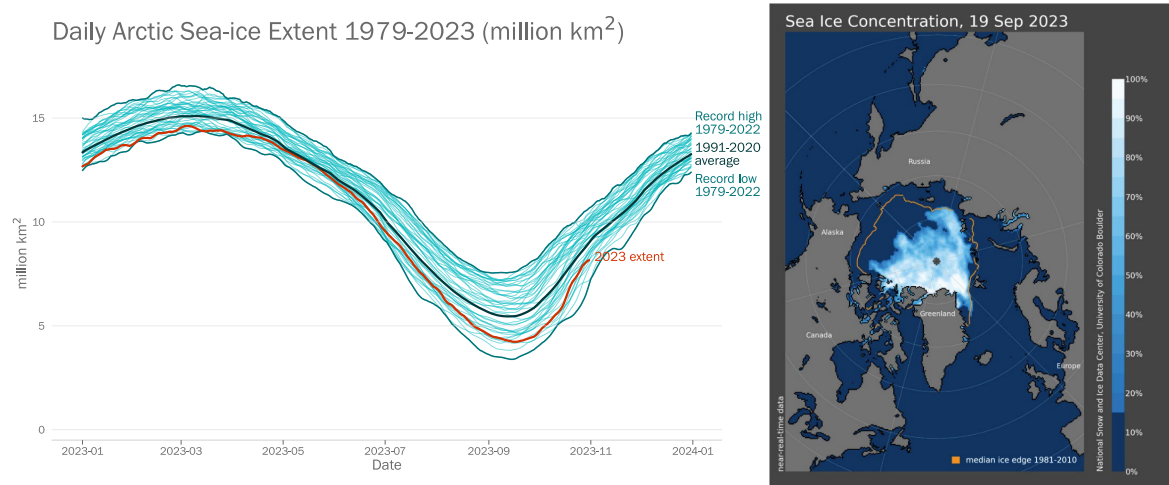


Figure 11: (left) Daily Arctic sea-ice extent from January through December, showing 2023 to date (red line) against the climate normal (1991–2020, dark blue) and the record highest and lowest extents for each day (mid blue). Individual years are shown in light blue. (right) Ice concentration on September 19, 2023, at the annual minimum Arctic ice extent. The orange line indicates the median ice edge for the 1981–2010 period²⁸. Data and map from the U.S. National Snow and Ice Data Center.

Antarctic sea-ice extent declined to 1.79 million km² on February 21, 2023 (Figure 12), an all-time minimum for the satellite era (1979 to present), slightly less than the previous record low that was

²⁶ Numbers in main text are from NSIDC. OSI SAF figures are provided in [Data sets and methods](https://nsidc.org/arcticseaicenews/2023/03/arctic-sea-ice-maximum-at-fifth-lowest-on-satellite-record/)
<https://nsidc.org/arcticseaicenews/2023/03/arctic-sea-ice-maximum-at-fifth-lowest-on-satellite-record/>,
<https://nsidc.org/arcticseaicenews/2023/04/polar-dawn-to-dusk/>

²⁷ <https://nsidc.org/arcticseaicenews/2023/09/arctic-sea-ice-minimum-at-sixth/>

²⁸ 1981–2010 is the period used by NSIDC for their monitoring.

set in 2022²⁹. Sea-ice extent remained below the average as the growth season commenced, becoming record low in May. Slow growth continued with exceptionally low extents between July and October, likely in association with warming of the Southern Ocean³⁰. The maximum Antarctic sea-ice extent for 2023 (Figure 12) was 16.96 million km² on 10 September, roughly 1.5 million km² below the 1991–2020 average and 1 million km² below the previous record low maximum, from 1986³¹.

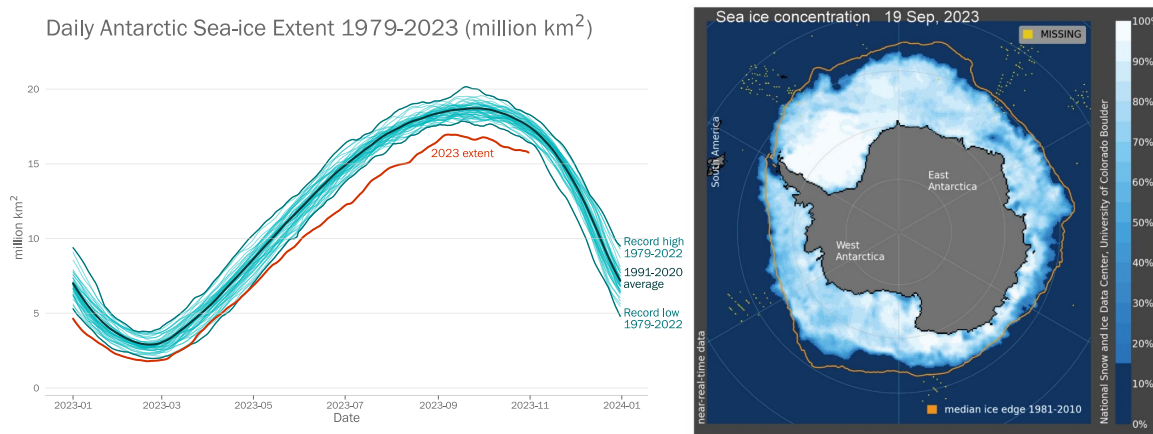


Figure 12: (left) Daily Antarctic sea-ice extent from January through December, showing 2023 (red) conditions against the 1991–2020 climate normal (dark blue) and the record highest and lowest extents for each day (mid blue). Individual years are shown in light blue. (right) Ice concentration on September 19, 2023, representative of the 2023 annual maximum extent. The orange line shows the median ice edge for the 1981–2010 climatology period³². Data and map from the U.S. National Snow and Ice Data Center.

Ice sheets

An ice sheet is³³ an expanse of ice that covers an area of more than 50 000 km². There are two ice sheets in the present-day climate system, in Greenland and Antarctica. The total mass balance (TMB) of an ice sheet is the sum of three components: the surface mass balance (SMB), the marine mass balance (MMB), and the basal mass balance (BMB). The SMB is the difference between snow accumulation and meltwater runoff from the ice sheet. The MMB is the mass loss at the edge of the ice sheet from the calving of icebergs and the melting of ice that is in contact with the ocean. BMB consists of melting at the ice sheet bed due to geothermal heat and friction as the ice slides over the ground beneath. A negative mass balance indicates a loss of ice mass; a positive mass balance indicates a gain.

Final numbers for the Greenland Ice Sheet mass balance for the hydrological year 2022–2023 (September 2022 to August 2023) are not yet available, but preliminary estimates from the regional climate model ensemble method³⁴ give an estimated 2022–2023 SMB of 330 Gt, below the long-term average but well above the extreme melt years of 2011–2012 and 2018–2019. Combined with BMB (–27 Gt) and MMB (–490 Gt), the estimate of the 2022–2023 ice sheet TMB is about –190 Gt. The summer 2023 melt season was relatively intense, punctuated by major heat waves in July and

²⁹ Liu, J., Z. Zhu and D. Chen, 2023. Lowest Antarctic Sea-Ice Record Broken for the Second Year in a Row. Ocean-Land-Atmos Res. 2023:2:0007. <https://doi.org/10.34133/olar.0007>

³⁰ Purich, A., Doddridge, E.W. Record low Antarctic Sea-ice coverage indicates a new sea-ice state. Commun Earth Environ 4, 314 (2023). <https://doi.org/10.1038/s43247-023-00961-9>.

³¹ <https://nsidc.org/arcticseaicenews/2023/09/antarctic-sets-a-record-low-maximum-by-wide-margin/>

³² The period 1981–2010 is used by NSIDC for their monitoring.

³³ <https://www.ipcc.ch/srocc/chapter/glossary/>

³⁴ Mankoff, K.D. et al. (2021). Greenland ice sheet mass balance from 1840 through next week, Earth Syst. Sci. Data, 13, 5001–5025, <https://doi.org/10.5194/essd-13-5001-2021>.

August³⁵. It was the warmest summer on record at the Summit station, 3.4 °C warmer than the 1991–2020 average and 1.0 °C warmer than the previous record³⁶. Satellite melt-extent data indicate that the ice sheet is on track for the second highest cumulative melt-day area³⁷ on record (1978–2023), after the extreme melt season of 2012 (Figure 13).

The Ice Sheet Mass Balance Intercomparison Exercise (IMBIE) has documented the acceleration in combined mass loss from the Greenland and Antarctic Ice Sheets over the period of the satellite record, 1992–2020³⁸. The average Greenland and Antarctic Ice Sheet TMBs over this period were –169 and –92 Gigatonnes per year (Gt·yr⁻¹), respectively, and –261 Gt·yr⁻¹ combined. Combining the two ice sheets, the seven highest melt years on record are all since 2010, and average rates of mass loss increased from 105 Gt·yr⁻¹ from 1992–1996 to 372 Gt·yr⁻¹ from 2016–2020. This is equivalent to ~1 mm·yr⁻¹ of global sea level rise attributed to the polar ice sheets in the latter period. Preliminary data from 2023 are consistent with these recent rates of mass loss in Greenland, but the Antarctic ice sheet gained mass due to higher-than-normal snow accumulation in the last year and a half.

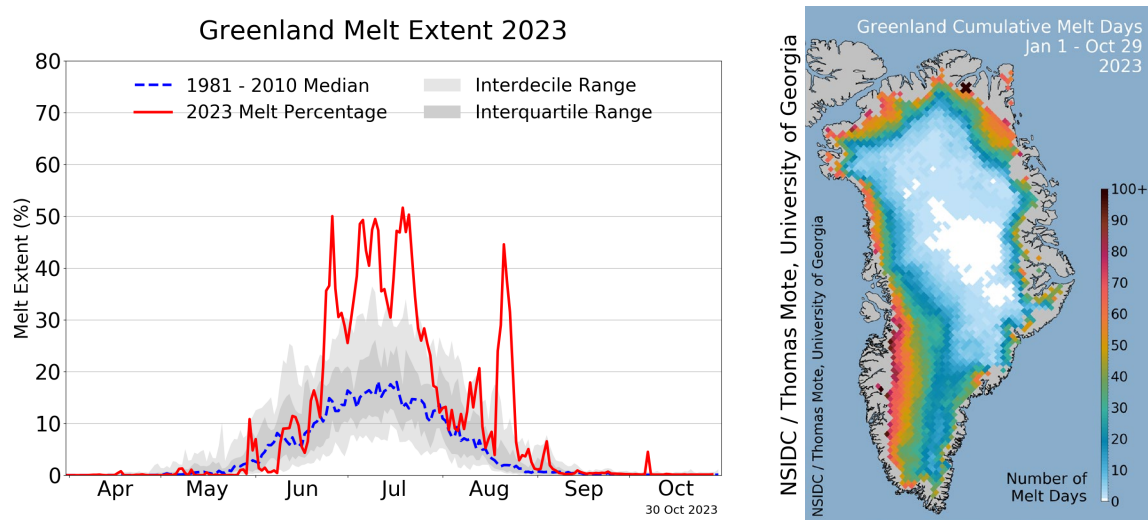


Figure 13: (left) Greenland Ice Sheet melt extent through the 2023 melt season, courtesy of the U.S. National Snow and Ice Data Center. (right) Cumulative melt days for Greenland between 1 January and 29 October. White areas indicate no melting occurred. Images and analysis courtesy of Thomas Mote, University of Georgia.

Glaciers

Key message:

- Glaciers in western North America and the European Alps experienced an extreme melt season. In Switzerland, glaciers lost around 10% of their remaining volume in the past two years.

Glaciers are formed from snow that has compacted to form ice, which then deforms and flows downhill. Glaciers comprise two zones: an accumulation zone where accumulation of mass from snowfall exceeds ice loss, and an ablation zone where ice loss (ablation) from melting and other mechanisms exceeds accumulation. Where glaciers end in a lake or the ocean, ice loss can occur through melting where the ice meets the water, and via calving when chunks of the glacier break off.

³⁵ Greenland Today – Late-season melt spike <https://nsidc.org/greenland-today/2023/09/late-season-melt-spike/>, Sudden shift to southern heat <https://nsidc.org/greenland-today/2023/07/sudden-shift-to-southern-heat/>

³⁶ <https://www.dmi.dk/nyheder/2023/varmerekorder-pa-indlandsisen/>

³⁷ Cumulative melt-day area is the area of the ice sheet that experienced melting conditions each day (diagnosed by the presence of liquid water at the surface), summed over the number of days in the melt season.

³⁸ Otosaka, I. N., et al. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, Earth Syst. Sci. Data, 15, 1597–1616, <https://doi.org/10.5194/essd-15-1597-2023>.

Glacier mass balance – the amount of mass gained or lost by the glacier – is commonly expressed as the annual thickness change averaged over the glacier area, expressed in metres of water equivalent (m w.e.)³⁹. Melt rates are strongly affected by the glacier albedo, the fraction of sunlight that is reflected by the glacier surface. Exposed glacier ice is darker and therefore has a lower albedo than the seasonal snowpack and is sensitive to darkening from mineral dust, black carbon, algal activity, and fallout from forest fires. Reduced snow cover, long melt seasons, and wildfire activity all serve to concentrate darker material on the glacier surface, decreasing its albedo and thereby increasing the melt.

Glacier mass balance data for the 2022–2023 hydrological year are not yet available, but preliminary observations indicate extremely negative mass balance in both western North America and the European Alps.

The annual mass loss for Swiss glaciers in 2022–2023 was the second largest on record (1950 to present, Figure 14) at 4.4% of the remaining ice volume. Together with the record mass loss in 2021–2022 of 5.9%, Swiss glaciers have lost around 10% of their remaining volume in just two years. This has been driven by low snowpacks and warm summers each year with potential cumulative impacts from glacier darkening associated with longer-than-normal periods of exposed glacier ice and loss of the high-elevation firn⁴⁰.

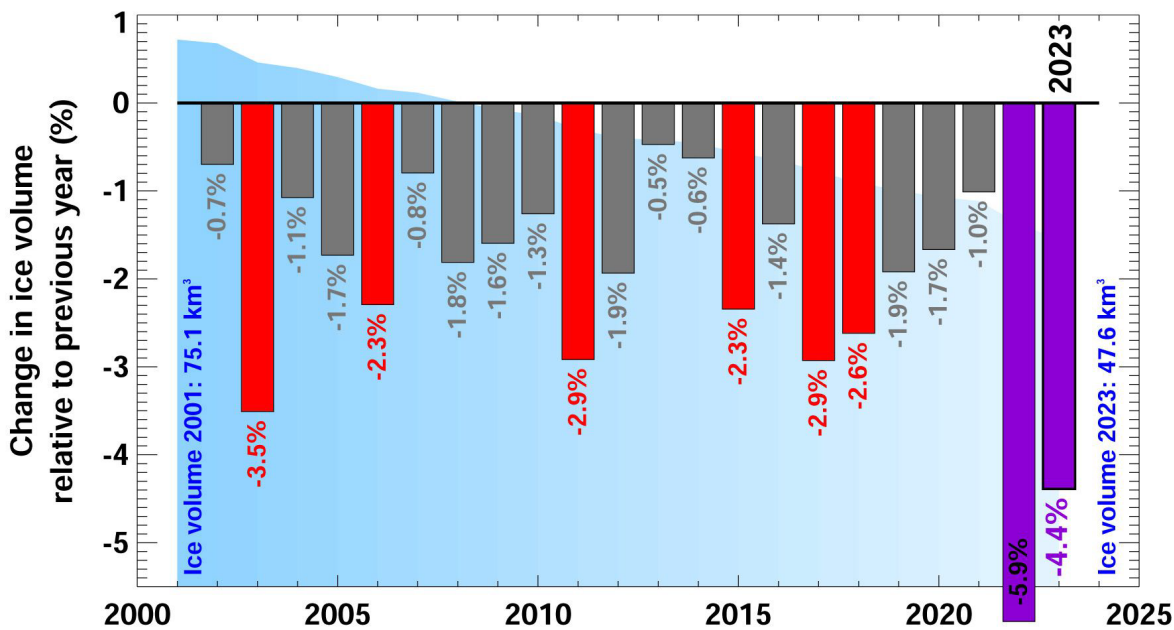


Figure 14: Total annual loss of Swiss glaciers related to the current ice volume. The vertical bars indicate the percentage change in ice volume relative to the previous year. Red and purple bars are the 8 largest relative mass losses on record. The purple bars are the relative mass losses for 2022 and 2023. The blue shaded area in the background represents the overall ice volume. Source: Matthias Huss based on Glacier Monitoring Switzerland, 2022: Swiss Glacier Mass Balance (Release 2023), <https://doi.org/10.18750/massbalance.2022.r2022>.

Western North America experienced record (1965 to present) glacier mass loss in 2023, with glacier-averaged annual thinning of more than 3.5 m at LiDAR-monitored⁴¹ glacier sites in the Canadian Rockies and southern Coast Mountains. This compares with an average glacier thinning rate of

³⁹ m w.e. is the depth of water equivalent to the change in ice thickness. Glacier ice is less dense than water, so the equivalent depth of water is slightly less than the thickness of ice lost.
⁴⁰ Firn is multi-year snow, which has a higher albedo than glacier ice.
⁴¹ LiDAR stands for Light Detection and Ranging, which uses a laser to determine the height of the glacier surface.

0.90 ± 0.13 m w.e./year in western Canada over the period 2010–2019⁴². Adjusting the LiDAR altimetry data for snow and ice density, preliminary estimates of mass balance at two sites with long-term measurements, Place and Haig Glaciers, are respectively, -3.1 ± 0.5 and -3.8 ± 0.6 m w.e. The large negative mass balances are due to the combination of a low winter snowpack, an intense spring heatwave that led to early exposure of bare ice across most glaciers and icefields, above-average summer temperatures, and record wildfire activity in western Canada⁴³ (see [Extreme weather and climate events](#)), with smoke from the wildfires darkening the glacier surface and contributing to the extreme melt. Seasonal snow had melted away by early July on many glaciers, exposing darker firn or ice over an extended melt season (Figure 15). High rates of cumulative melting over the past several years may also be a factor, as impurities are increasingly concentrated on the glacier surfaces and the firn zone has been lost on many mountain glaciers in western North America.

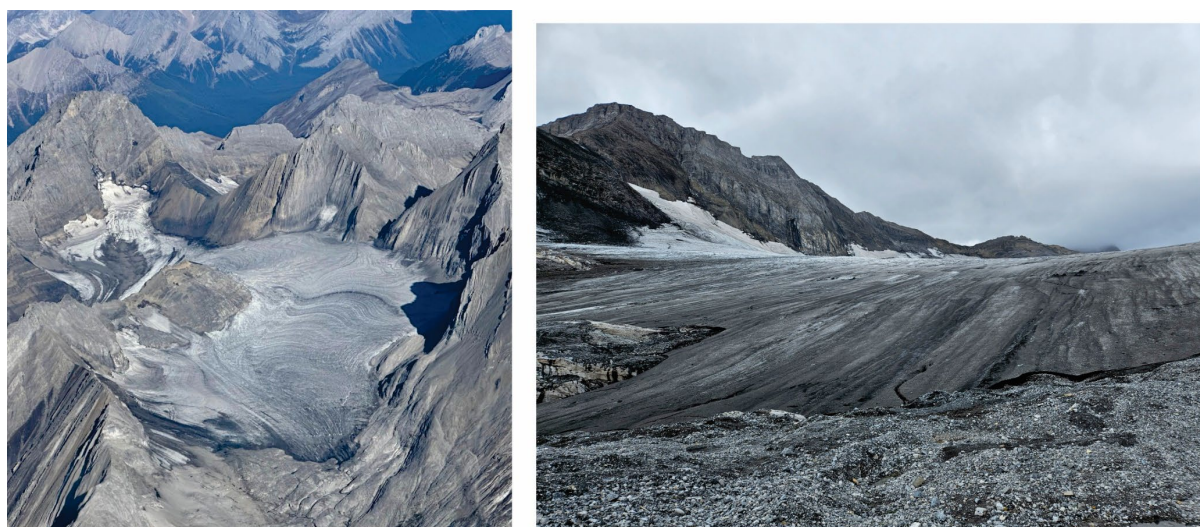


Figure 15: Aerial and ground views of Haig Glacier in the Canadian Rocky Mountains, September 15, 2023. No seasonal snow or firn remains on the glacier and the surface albedo was anomalously low, including values of 0.07 measured in the terminus region (albedo is between zero – very dark – and one – very light). Credit Brian Menounos and Shawn Marshall.

Snow cover

Key message:

- Seasonal snow cover in the Northern Hemisphere has been experiencing a long-term decline in the late spring and summer. Northern Hemisphere snow cover extent for May was the eighth lowest on record (1967–2023). North American snow cover extent for May 2023 was the lowest on record (1967–2023).

Seasonal snow cover in the Northern Hemisphere has been experiencing a long-term decline in the late spring and summer, which continued in 2023. Northern hemisphere snow-cover extent from January through April 2023 was close to the long-term average (1991–2020), but the spring heat wave in north-western North America drove widespread snowmelt. North American snow cover extent for May 2023 was the lowest on record (1967–2023) at 7.47 million km², about 1.57 million km² (17%) below the long-term average, while overall Northern Hemisphere snow cover extent was 16.74 million km², the eighth lowest since 1967, and 1.47 million km² below the long-term average (Figure 16).

⁴² Hugonnet, R., McNabb, R., Berthier, E. et al. Accelerated global glacier mass loss in the early twenty-first century. *Nature* 592, 726–731 (2021). <https://doi.org/10.1038/s41586-021-03436-z>

⁴³ Parisien, M.-A., Barber, Q. E., Flannigan, M. D., & Jain, P. (2023). Broadleaf tree phenology and springtime wildfire occurrence in boreal Canada. *Global Change Biology*, 00, 1–14. <https://doi.org/10.1111/gcb.16820>

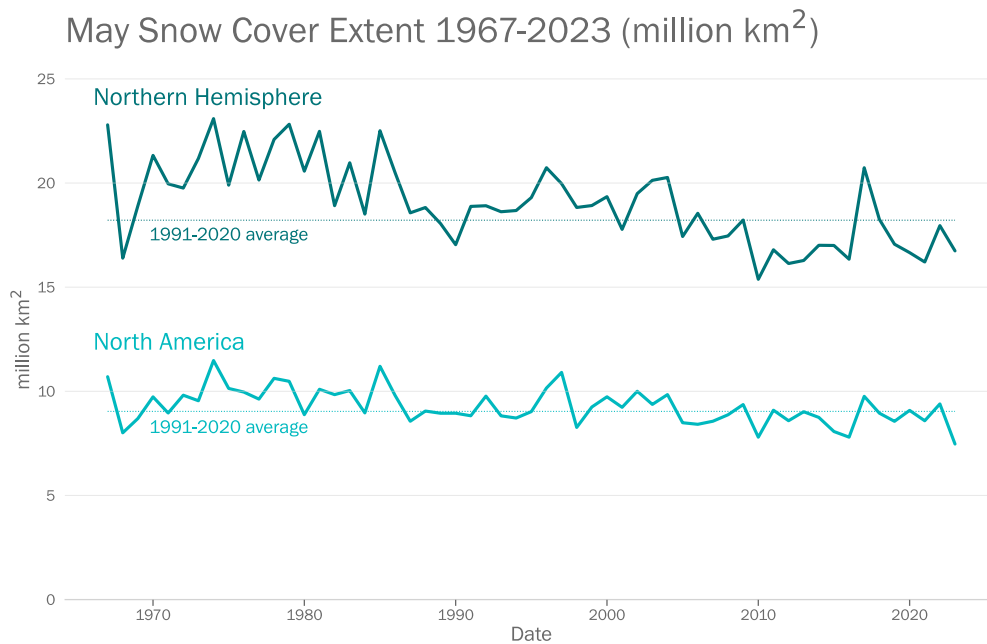


Figure 16: May snow-cover extent (SCE) for the Northern Hemisphere (dark blue) and North America (light blue), 1967–2023. The 1991–2020 average for each region is shown as a horizontal dotted line. Data from the Rutgers University Global Snow Lab⁴⁴ (<https://climate.rutgers.edu/snowcover/>).

Short-term Climate Drivers

Key message:

- A prolonged period of La Niña from mid-2020 to early 2023 gave way to El Niño conditions which were well established by September 2023, contributing to the observed rise in global sea-surface temperatures during 2023.

There are many different natural phenomena, often referred to as climate patterns or climate modes, that affect weather and climate at timescales ranging from days to several months or even years. In 2023, the El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation, highlighted here, contributed to major weather and climate events across large areas of the world.

ENSO – El Niño Southern Oscillation

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

A multi-year La Niña event began in mid-2020 and ended in early 2023. Subsequently, sea-surface temperatures in the eastern tropical Pacific increased, crossing typical El Niño thresholds by June

⁴⁴ Robinson, David A., Estilow, Thomas W., and NOAA CDR Program (2012): NOAA Climate Data Record (CDR) of Northern Hemisphere (NH) Snow Cover Extent (SCE), Version 1. NOAA National Centers for Environmental Information. doi: 10.7289/V5N014G9 [accessed September 19, 2023].

(Figure 17). However, the atmosphere was slower to respond, and it was not until early September that El Niño conditions were well established in both the atmosphere and ocean.

The latest forecasts⁴⁵ from the WMO Global Producing Centres for Long-Range Forecasts indicate a high probability (90%) of El Niño continuing throughout the upcoming Northern Hemisphere winter, with conditions at the peak of the event corresponding to a strong El Niño. Chances of a transition to ENSO-neutral are very low (10%).

Oceanic Niño Index (°C)

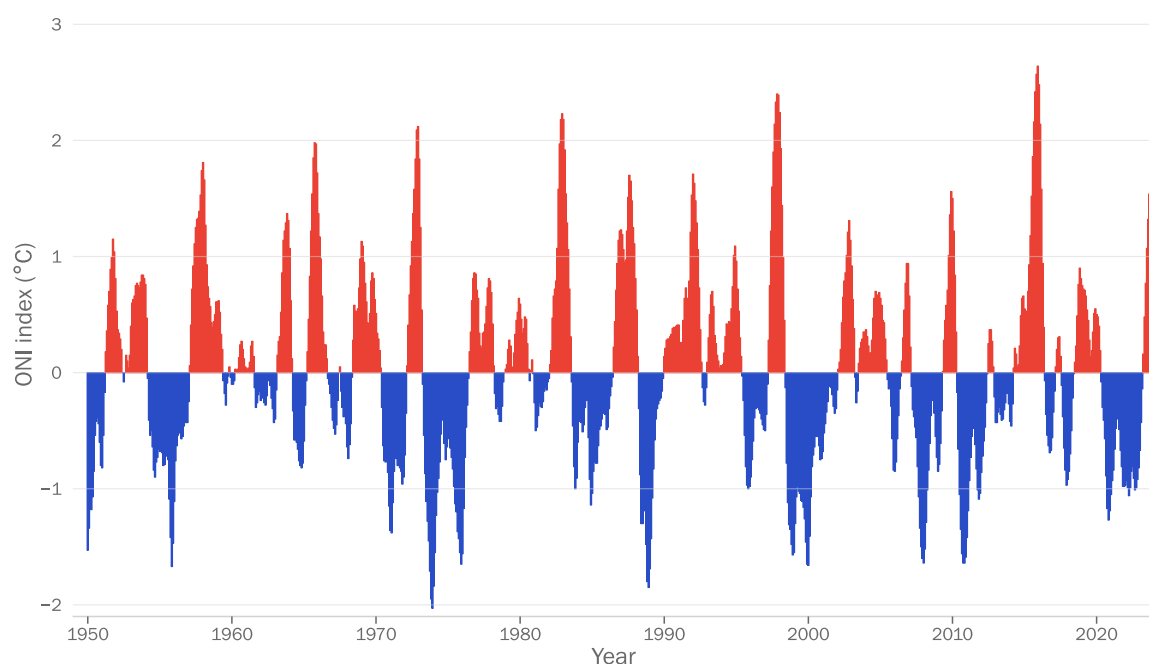


Figure 17: Time series of NOAA's Oceanic Niño index from January 1950 to September 2023 showing the presence of below-average conditions (blue) and above average conditions (red) during 3-month average time periods. Anomalies are with respect to the 1991–2020 average sea-surface temperature. (Data: NOAA NCEI)

El Niño has an influence on regional rainfall patterns. Precipitation anomalies were typical of El Niño in some regions (by September): drier than usual conditions in maritime Southeast Asia and from southern Mexico to northern South America and wetter than normal conditions in parts of Chile (Figure 18).

Decreased monsoon rainfall in southeast Asia is associated with El Niño. Onset of the monsoon over Kerala, India, occurred on 8 June, 7 days later than normal. By the end of September, India received 94% of its typical monsoon rainfall⁴⁶. Higher than normal rainfall totals were observed along the lower course of the Indus River and in central India.

In Australia, La Niña is associated with wetter-than-normal conditions and El Niño with drier-than-normal conditions. In January, rainfall for the country was 35% above normal as La Niña wound down, but in August it was 50% below normal with a strengthening El Niño. The dryness was also accompanied by the highest July-to-September national mean temperatures in Australia's 114-year record. September was the driest month on record in Australia for any month.

⁴⁵ <https://public.wmo.int/en/our-mandate/climate/el-ni%C3%B1o-la-ni%C3%B1a-update>

⁴⁶ <https://mausam.imd.gov.in/responsive/monsooninformation.php>

As average global temperature anomalies increased during the transition from La Niña to El Niño, the Earth experienced its hottest June-September period and hottest month on record (July). Many regions also experienced heatwaves, including parts of the United States, Mexico, Europe, the Mediterranean, North Africa and the Middle East, China, Siberia, and South America. The UNEP Frontiers report⁴⁷ highlighted that variability associated with El Niño has implications for biomass and fire weather⁴⁸ which increases the risk of large and intense wildfires in some places. Please refer to the section on [Extreme weather and climate events](#) for more details on extreme events.

NAO – North Atlantic Oscillation

Average sea level pressure in the North Atlantic is characterized by an area of lower pressure close to Iceland known as the Icelandic Low and an area of higher pressure centred over the Azores known as the Azores High. The North Atlantic Oscillation (NAO) is based on the sea-level pressure difference between the Icelandic Low and the Azores high. It is mainly associated with driving weather conditions in the North Atlantic basin, Europe, and the Mediterranean. The positive phase is characterized by below-normal pressure over the North Atlantic high latitudes and above-normal pressure over the central Atlantic, the eastern United States, and western Europe. The negative phase has the opposite pattern. Because the phases are determined by pressure changes in the atmosphere, they can fluctuate more rapidly, on the order of days to weeks, compared with other climate drivers such as ENSO, which are driven by slower changes in ocean temperature and fluctuate on the order of months to years.

High pressure associated with the negative NAO in late June and July 2023 contributed to a heatwave that caused significant snow and ice melt across southern Greenland. Several widespread melting events covering 800 000 km², up to 50% of the ice sheet, occurred during this period. Ireland reported its warmest June on record (124 years), as did Belgium (since 1833). In eastern Canada, many locations reported record warmth for July.

Precipitation

Accumulated precipitation totals for the first nine months in 2023 were above the long-term average (Figure 18) in east Asia, parts of northern Asia, the western Indian summer monsoon region, parts of the Maritime Continent, northern New Zealand, northern inland Australia, parts of West, Central and East Africa, Southeast Europe and the eastern Mediterranean region, southern Scandinavia, northwest, southwest and southeast North America, Greater Antilles, and parts of southwest South America.

⁴⁷ United Nations Environment Programme (2022 a). Frontiers 2022: Noise, Blazes and Mismatches-Emerging Issues of Environmental Concern. Nairobi. <https://www.unep.org/resources/frontiers-2022-noise-blazes-and-mismatches>

⁴⁸ Fire weather is weather conducive to wildfires, including high temperatures, low humidity, and high winds.

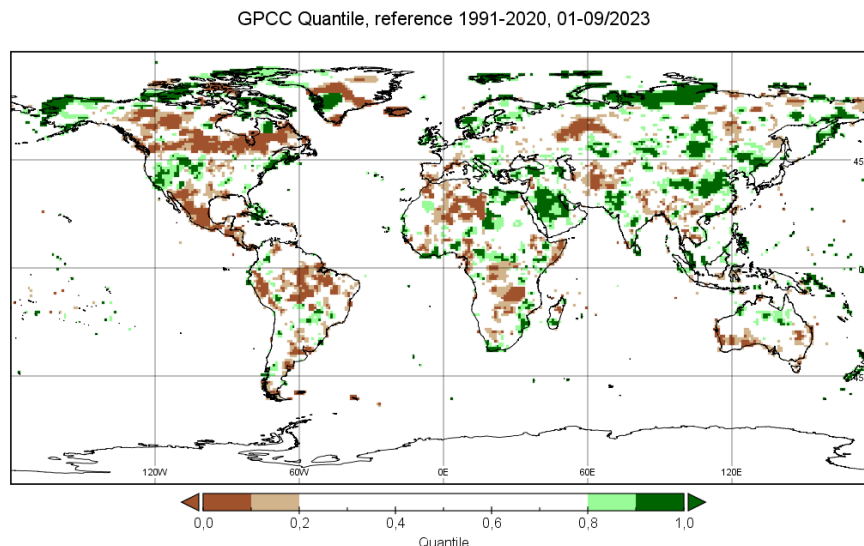


Figure 18: Total precipitation in 2023 (January to September), expressed as a quantile of the 1991–2020 reference period, for areas that would have been in the driest 20% (brown) and wettest 20% (green) of years during the reference period, with darker shades of brown and green indicating the driest and wettest 10%, respectively (Source: Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst, Germany). For more details see [Data sets and methods](#).

Regions with a marked rainfall deficit included: southeast South America, the Amazon Basin, much of Central America, southern Canada, the western Mediterranean region and Southwest Europe, parts of west, central, east, and southern Africa, central Asia, the eastern Indian Monsoon region, parts of southeast Asia and the Maritime Continent, southwest, southeast and coastal north Australia, and many of the Pacific Islands.

The onset of the West African Monsoon was around normal. The start of the Gu rain season (April to June) in the Greater Horn of Africa brought unusually large rainfalls amounts in some areas.

Extreme weather and climate events

Key messages:

- Extreme weather continues to lead to severe socio-economic impacts.
- Extreme heat affected many parts of the world.
- Wildfires in Hawaii, Canada and Europe led to loss of life, the destruction of homes and large-scale air pollution.
- Flooding associated with extreme rainfall from Mediterranean Cyclone Daniel affected Greece, Bulgaria, Türkiye, and Libya with particularly heavy loss of life in Libya.

Extreme weather and climate events had major impacts on all inhabited continents in 2023. These included major floods (some of them associated with tropical cyclones), extreme heat and drought, and associated wildfires which presented challenges to water and food security as well as human welfare^{49,50}. Some of the most significant events are described below, with a broader range of events described in the online supplement.

In terms of loss of life, the most significant event was the Mediterranean Cyclone (or *medicane*, referred to locally as ‘Storm Daniel’) in September. In its initial stages the storm produced extreme

⁴⁹ The United Nations (2022). The Sustainable Development Goals Report 2022. New York. <https://unstats.un.org/sdgs/report/2022/>

⁵⁰ The United Nations [UN] (2023). The Sustainable Development Goals Report 2023: Special edition. Towards a Rescue Plan for People and Planet. New York. <https://unstats.un.org/sdgs/report/2023/>

rainfall in Greece, southern Bulgaria, and parts of Türkiye, while at the same time another storm system produced significant flash flooding in Spain with adverse effects on cereal production⁵¹. The heaviest falls were in the Thessaly region of Greece north of Athens, where Zagora Pelion received 759.6 mm on 5 September and a 5-day total of 1096.2 mm from 4 to 8 September, while in Bulgaria, 329 mm fell in 16 hours at Kosti on 4–5 September. The storm then remained slow-moving in the eastern Mediterranean for several days before its major rainbands impacted north-eastern Libya on 10 and 11 September. Extreme rainfalls affected the coast and nearby mountains, with 414.1 mm falling in 24 hours at Al-Bayda on 10–11 September. The intense rainfalls resulted in extreme flooding in the region. The most extreme impacts were in the city of Derna (about 50 km east of Al-Bayda), where much of the central city was destroyed by flooding, exacerbated by the failure of two dams. At least 4 345 confirmed deaths in Libya⁵² have been attributed to the flooding, with 8 500 people still missing (as of 11 October). There were 19 additional deaths in Greece⁵³ and Bulgaria. Estimates for Storm Daniel indicate that approximately an additional 43 000 individuals were displaced in northeastern Libya⁵⁴.

Tropical Cyclone Freddy in February and March was one of the world's longest-lived tropical cyclones. It formed on 6 February off the western coast of Australia and, after earlier landfalls in Madagascar and Mozambique, made its final landfall in Mozambique on 11 March before moving inland as a remnant low. The major impacts of Freddy came because of flooding during the final landfall, both in Mozambique and Malawi, as extremely heavy rain fell (up to 672 mm in Mozambique). Parts of Mozambique and Malawi had not yet recovered from storms in 2022. Malawi was especially hard hit with at least 679 deaths reported and over 659 000 internal displacements⁵⁵, with a further 165 deaths in Mozambique. Casualties were also reported in Madagascar and Zimbabwe.

Tropical Cyclone Mocha, in May, was one of the most intense cyclones ever observed in the Bay of Bengal, reaching peak 10-minute sustained winds of 115 kt. It formed on 11 May and made landfall near the Bangladesh-Myanmar border on 14 May. Cyclone Mocha triggered 1.7 million displacements across the sub-region from Sri Lanka to Myanmar and through India and Bangladesh⁵⁶. In Bangladesh, displacement was reported in Cox's Bazar, the world's largest refugee settlement, which is home to over 900 000 Rohingya refugees from Myanmar⁵⁷. More than 29 000 people were temporarily relocated⁵⁸. In total at least 148 lives were lost in Myanmar and over 270 000 buildings damaged or destroyed⁵⁹. The effects of Cyclone Mocha, together with an intensification of conflict and record high food prices, have severely aggravated acute food insecurity, especially among the 3.4 million vulnerable people now in need of humanitarian assistance⁶⁰.

The North Island of New Zealand suffered repeated extreme rainfall and flooding events in January and February. The most significant was on 13–14 February, when Cyclone Gabrielle passed just east

⁵¹ <https://www.mapa.gob.es/es/prensa/ultimas-noticias/el-146--del-territorio-est%C3%A1-en-emergencia-por-escasez-de-agua-y-el-274--en-alerta/tcm:30-659894>

⁵² <https://reliefweb.int/report/libya/who-health-supplies-arrive-libya-part-intensified-response-devastating-floods>
<https://reliefweb.int/report/libya/libya-flood-response-situation-report-11-october-2023>

⁵³ <https://reliefweb.int/report/greece/greece-severe-weather-and-floods-update-greek-civil-protection-hellenic-national-meteorological-service-copernicus-emsr-echo-daily-flash-11-september-2023>

⁵⁴ Libya – Storm Daniel Flash Update 8 (13 October 2023) | Displacement Tracking Matrix (iom.int) <https://dtm.iom.int/reports/libya-storm-daniel-flash-update-8-13-october-2023> <https://www.emro.who.int/media/news/101-health-workers-killed-in-libya-in-the-aftermath-of-storm-daniel.html>

⁵⁵ <https://www.preventionweb.net/media/87994/download?startDownload=true>

⁵⁶ 2023 Mid-year update (internal-displacement.org) <https://story.internal-displacement.org/2023-mid-year-update/>

⁵⁷ <https://sentinel-asia.org/EO/2023/article20230514MM.html>

⁵⁸ <https://reliefweb.int/report/bangladesh/bangladesh-cyclone-mocha-humanitarian-response-situation-report-14-may-2023>

⁵⁹ https://ahacentre.org/wp-content/uploads/2023/05/AHA-DRAFT-Situation_Report-9-TC-MOCHA-Myanmar-1.pdf

⁶⁰ UNHCR. May 2023. Flash Update #2 Cyclone Mocha. Available at: <https://reporting.unhcr.org/myanmar-emergency-flash-update-2-cyclone-mocha>

of the North Island as a post-tropical system. Daily rainfalls exceeded 500 mm in parts of the eastern North Island and Auckland (971.5 hPa) had its lowest air pressure on record. 11 deaths were reported because of Gabrielle and 4 from more localized floods in Auckland on 27–28 January. Total economic losses from the two events were estimated at US\$5.3 to 8.6 billion⁶¹, by far the costliest non-earthquake natural disaster recorded in New Zealand.

Many significant heatwaves occurred in various parts of the world during 2023. Some of the most significant were in southern Europe and North Africa, especially in the second half of July where severe and exceptionally persistent heat occurred. Italy was particularly affected, with temperatures reaching 48.2 °C on 24 July at the Sardinian sites of Lotzorai and Jerzu, only 0.6 °C below the European record set in Sicily in 2021. Among the locations experiencing record high temperatures were Tunis (Tunisia) (49.0 °C on 24 July), Tirana (Albania) (43.0 °C on 25 July), Agadir (Morocco) (50.4 °C on 11 August), and Algiers (49.2 °C on 23 July). The extreme heat shifted to southeast Europe in late July, and there were further heatwaves affecting west-central Europe in late August and early September. Numerous locations in southern France, northern Spain and western Switzerland set records during these events, including Toulouse (42.4 °C on 19 August). There was also extensive wildfire activity during the summer, particularly in Greece (both on the mainland and islands). A fire in north-eastern Greece in late August and early September that burned 93 000 hectares was reported to be the largest fire ever observed in the European Union.

Canada's wildfire season was well beyond any previously recorded. Significant fire activity began in late April, expanded during a very warm, dry May, and continued throughout the summer and into early autumn. The total area burned nationally as of 15 October was 18.5 million hectares, more than six times the 10-year average (2013–2022) and far above the previous record seasonal total of 7.1 million hectares in 1995 (Figure 19). The fires also resulted in significant and widespread smoke pollution, particularly in the heavily populated areas of eastern Canada and the north-eastern United States in the first half of June. Six deaths were directly attributed to fires, although the broader health impacts of the smoke are yet to be fully assessed.

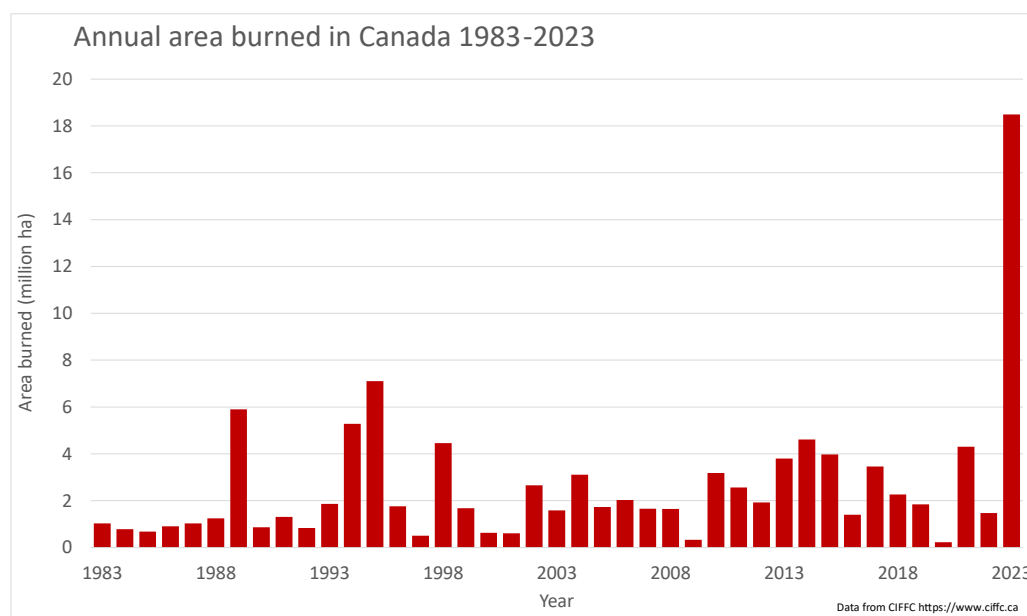


Figure 19: Annual Area Burned in Canada 1983–2023 (millions of hectares). Data from: Canadian Interagency Forest Fire Centre <https://www.cifc.ca/>

⁶¹ <https://www.treasury.govt.nz/sites/default/files/2023-04/impacts-from-the-north-island-weather-events.pdf>

The deadliest single wildfire of the year occurred in Hawaii, on the western side of the island of Maui. Extreme fire weather conditions, with low humidity and strong, gusty winds driven by a pressure gradient between strong high pressure to the north and the circulation of Hurricane Dora well to the south, combined with pre-existing drought to favour the development and rapid spread of intense fires. The most badly affected region was around the town of Lahaina, which was largely destroyed with over 2 200 structures lost. Mandatory evacuation notices were issued for 7 500 people across the area⁶². At least 99 deaths were reported⁶³, the most in a wildfire in the United States for more than 100 years. Wildfires of such intensity and speed of movement are extremely rare in the tropics.

Long-term drought persisted in north-western Africa and parts of the Iberian Peninsula, as well as parts of central and southwest Asia, and intensified in many parts of Central America, northern South America and the southern United States. Among the most significant areas of drought was an area of subtropical South America, focused on northern Argentina and Uruguay. Rainfall from January to August was 20 to 50% below average over much of northern and central Argentina, with some regions experiencing their fourth successive year of significantly below average rainfall. There were major crop losses in Argentina with wheat production in 2022–23 more than 30% below the five-year average. In Uruguay, water storages reached critically low levels, badly affecting the quality of supplies to major centres including Montevideo, although there was some improvement in the situation from August.

Long term drought in the Greater Horn of Africa was followed by heavy rain in some areas at the start of the Gu rain season (April to June). Across the Horn of Africa, weather events had displaced 1.4 million people (as of June 2023) in addition to the 2.7 million people displaced by the five consecutive seasons of drought⁶⁴. The drought reduced the capacity of the soil to absorb water, which increased flood risk when the Gu rains arrived in April and May. It was estimated that over 200 000 displacements were triggered by the resulting floods, mostly in the Belet Weyne district in Somalia, where the Shabelle river burst its banks.⁶⁵ Pastoralist communities have continued to be affected by asset losses after two consecutive years of drought. These will continue to adversely affect agricultural production and are expected to reduce cereal production 2023 compared to 2022⁶⁶.

Socio-economic impacts

Key messages:

- Food security, population displacements and impacts on vulnerable populations continue to be of concern in 2023, with weather and climate hazards exacerbating the situation in many parts of the world.
- Extreme weather and climate conditions continued to trigger new, prolonged, and secondary displacement in 2023 and increased the vulnerability of many who were already uprooted by complex multi-causal situations of conflict and violence.
- Development and implementation of local disaster risk reduction strategies have increased since the adoption of the Sendai Framework for Disaster Risk Reduction.

⁶² <https://www.disastercenter.com/FEMA%20Daily%20Ops%20Briefing%20085-2023.pdf>

⁶³ NOAA Billion-dollar disasters [https://www.ncei.noaa.gov/access/billions/events/US/2023?disasters\[\]=wildfire](https://www.ncei.noaa.gov/access/billions/events/US/2023?disasters[]=wildfire)

⁶⁴ East and Horn of Africa: Flood Snapshot (January - June 2023) | Displacement Tracking Matrix (iom.int) <https://dtm.iom.int/reports/east-and-horn-africa-flood-snapshot-january-june-2023>

⁶⁵ <https://www.internal-displacement.org/publications/impacts-of-displacement-flood-displacement-in-beledweyne-somalia>; <https://reliefweb.int/report/somalia/somalia-2023-flash-and-riverine-floods-situation-report-no-1-14-may-2023>

⁶⁶ <https://www.fao.org/3/cc6806en/cc6806en.pdf>

- One of the essential components for reducing the impact of disasters is to have effective multi-hazard early warning systems.

The events described above, and many others besides, occur in a broader context. Extreme weather and climate events interact with and in some cases trigger or exacerbate situations concerning water and food security, population mobility and environmental degradation^{67,68}.

The number of people who are acutely food insecure has more than doubled, from 135 million people before the COVID-19 pandemic to 345 million people in 2023 (in 53 monitored countries)⁶⁹. Global hunger levels remained unchanged from 2021 to 2022. However, these are still far above pre-COVID 19 pandemic levels: in 2022, 9.2% of the global population (735.1 million people) were undernourished, compared to 7.9% of the population (612.8 million people) in 2019 (Figure 20)⁷⁰. The current global food and nutrition crisis is the largest in modern human history⁷¹. Protracted conflicts, economic downturns, and high food prices, further exacerbated by high costs of agricultural inputs driven by ongoing conflict, are at the root of high global food insecurity levels. This is aggravated by the effects of climate and weather extremes. In southern Africa, for example, weather extremes, including the passage of Cyclone Freddy in February 2023, have hit the region, affecting areas of Madagascar, Mozambique, southern Malawi, and Zimbabwe. Flooding associated with the cyclone submerged extensive agricultural areas and inflicted severe damage on crops. This has exacerbated a slow economic recovery⁷².

Globally, annual economic losses from climate and weather-related disasters have significantly increased since the 2000s⁷³. In low and lower-middle-income countries, 82% of all damage and loss caused by drought concerned the agriculture sector. Between 2008 and 2018, across least developed countries and lower middle-income countries, 34% of disaster-related crop and livestock production losses were attributed to drought, followed by 19% to flooding events, 18% to severe storms and hurricanes, 9% to crop pests and animal diseases, 6% to extreme temperatures, and 1% to wildfires⁷⁴.

⁶⁷ The United Nations (2022). The Sustainable Development Goals Report 2022. New York. <https://unstats.un.org/sdgs/report/2022/>

⁶⁸ The United Nations [UN] (2023). The Sustainable Development Goals Report 2023: Special edition. Towards a Rescue Plan for People and Planet. New York. <https://unstats.un.org/sdgs/report/2023/>

⁶⁹ WFP. June 2023. WFP Global Operational Response Plan 2023. Update #8. Available at: <https://docs.wfp.org/api/documents/WFP-0000150404/download/> FAO, IFAD, UNICEF, WFP and WHO. 2023. The State of Food Security and Nutrition in the World 2023.

⁷⁰ Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. Rome, FAO. <https://doi.org/10.4060/cc3017en>

⁷¹ WFP. June 2023. WFP Global Operational Response Plan 2023. Update #8. Available at: docs.wfp.org/api/documents/WFP-0000150404/download/

⁷² FAO. 2023. Crop Prospects and Food Situation – Quarterly Global Report No. 2, July 2023. Rome. <https://doi.org/10.4060/cc6806en>

⁷³ FAO. 2021. The impact of disasters and crises on agriculture and food security: 2021. Rome. <https://doi.org/10.4060/cb3673en>

⁷⁴ FAO. 2021. The impact of disasters and crises on agriculture and food security: 2021. Rome. <https://doi.org/10.4060/cb3673en>

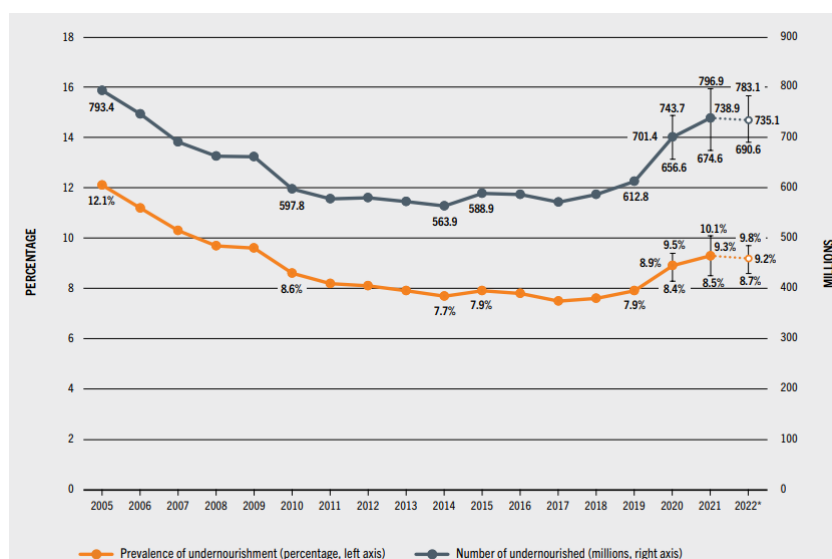


Figure 20: Global prevalence of undernourishment (as a%) and number of undernourished (in millions) since 2005. The entire series was updated to reflect new information released since the publication of *The State of Food Security and Nutrition in the World 2023*⁷⁵.

Across the globe, millions of people, including internally displaced persons, refugees, and migrants, are on the move or have been forced to flee their homes and communities because of disasters exacerbated by climate stresses and shocks. Weather hazards continued to trigger new, prolonged, and secondary displacement in 2023 and increased the vulnerability of many who were already uprooted by complex multi-causal situations of conflict and violence. Many migrants entering into Somalia found themselves stranded in June and July 2023, mostly in the city of Bossaso, the main coastal crossing location to Yemen, as they were waiting for more favourable weather conditions to cross the Gulf of Aden. In Hargeisa, a group of migrants in transition suffered from extreme heat, and some died from dehydration⁷⁶. This is a clear indication of how vulnerability to climate shocks and stresses is undermining resilience and creating new protection risks, which threaten the achievement of the SDGs.

In addition to new displacements caused by high-impact disasters in 2023, many are still enduring the prolonged effects of climate-related displacement that took place in previous years. In Pakistan, the 2022 monsoon floods, which triggered the largest disaster displacement event in a decade, continued to have longstanding impacts in 2023. Displaced communities were still recovering when heavy rains hit some districts in June 2023, causing waterborne and vector-borne diseases such as malaria, dengue, and cholera⁷⁷. Displacement in the context of climate change and environmental degradation is often multicausal. Most people move due to a combination of social, political, economic, environmental, and demographic drivers, all of which are and will be affected by climate and environmental change.

Climate related shocks and stresses in migration and displacement contexts affect people's livelihoods which entrenches poverty (SDG 1) and hunger (SDG 2), pose direct threats to their lives and well-being (SDG 3), widen inequality gaps (SDG 10), limit access to quality education (SDG 4), water and sanitation (SDG 6) as well as clean energy (SDG 7). Women and girls are among the worst

⁷⁵ FAO, IFAD, UNICEF, WFP and WHO. 2023. *The State of Food Security and Nutrition in the World 2023*. Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. Rome, FAO. <https://doi.org/10.4060/cc3017en>

⁷⁶ <https://dtm.iom.int/reports/migration-along-eastern-corridor-july-2023>

⁷⁷ <https://reliefweb.int/report/pakistan/early-needs-identification-report-monsoon-flood-affected-areas-pakistan-august-2023>

affected (SDG 5) due to pre-existing gender and socio-economic inequalities compounding their vulnerabilities⁷⁸.

To better prepare for these contexts, governments, communities, civil society, and the UN are engaged at all levels to strengthen climate resilience and effective disaster risk reduction. A main priority is the community level, where preparedness efforts including early warning systems and emergency preparedness are picking up pace⁷⁹. With 126 countries in possession of disaster risk management strategies and a total of 99 countries reporting to have local governments with disaster risk reduction strategies, development and implementation of local disaster risk reduction strategies have increased since the adoption of the Sendai Framework for Disaster Risk Reduction in 2015⁸⁰.

One of the essential components for reducing the impact of disasters is to have effective multi-hazard early warning systems, and to have effective systems in place for generating disaster risk information, creating early warnings, and disseminating them, as well as having plans to act on the warnings. As of 2023, 102 countries have reported having multi-hazard early warning systems in place, more than half of the countries in the world. The Early Warnings for All initiative was launched by the UN Secretary-General in March 2022 with the aim of ensuring that everyone on Earth is protected from hazardous weather, water, or climate events through life-saving early warning systems by the end of 2027.

⁷⁸ UNHCR Gender, Displacement, and Climate Change. July 2020. <https://www.unhcr.org/protection/environment/5f21565b4/gender-displacement-and-climate-change.html>

⁷⁹ United Nations Environment Programme (2022b). Climate Change and Security Partnership Project Final Report: March 2017-February 2022. Nairobi. <https://wedocs.unep.org/handle/20.500.11822/40549>

⁸⁰ <https://sendaiframework-mtr.undrr.org/publication/report-midterm-review-implementation-sendai-framework-disaster-risk-reduction-2015-2030>

Data sets and methods

Greenhouse gases

Estimated concentrations from 1750 are used to represent pre-industrial conditions. Calculations assume a pre-industrial mole fraction of 278.3 ppm for CO₂, 729.2 ppb for CH₄ and 270.1 ppb for N₂O.

World Data Centre for Greenhouse Gases operated by Japan Meteorological Agency
<https://gaw.kishou.go.jp/>. <https://gaw.kishou.go.jp/>.

[World Meteorological Organization (WMO). WMO Greenhouse Gas Bulletin – No. 19: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2022. Geneva, 2023]

Global temperatures

Global mean temperature series

The method for calculating global mean temperature anomalies relative to an 1850–1900 baseline is based on the assessment of long-term change and its uncertainty made by Working Group I in its contribution to the IPCC Sixth Assessment Report (IPCC AR6 WG I). In 2021, the IPCC AR6 WG I assessed change from 1850–1900 to other periods based on an average of four data sets – HadCRUT5, Berkeley Earth, NOAA Interim and Kadow et al. (2020) – which start in 1850 and are globally or near-globally complete in the modern period.

To include shorter data sets which can help to understand recent temperature changes, in the present report the estimate made by the IPCC for the temperature change between 1850–1900 and 1981–2010 is combined with estimated changes between 1981–2010 and the current year from five data sets to calculate anomalies for 2023 relative to 1850–1900. There is good agreement between the data sets on changes from 1981–2010 to the present, as this is a period with good observational coverage.

The additional uncertainty from the spread of the data sets is combined with that of the IPCC's estimate of the uncertainty in the change from 1850–1900 to 1981–2010. Global mean temperature anomalies were calculated relative to an 1850–1900 baseline using the following steps starting from time series of global monthly mean temperatures for each data set:

1. For each data set, anomalies were calculated relative to the 1981–2010 average by subtracting the mean for the period 1981–2010 for each month separately.
2. An annual mean anomaly was calculated from the monthly mean anomalies.
3. The amount of 0.69 °C was added to each series, based on the estimated difference between 1850–1900 and 1981–2010, calculated using the method from IPCC AR6 WG I (see caption for Figure 1.12 in that report).
4. The mean and standard deviation of the estimates were calculated.
5. The uncertainty in the IPCC estimate was combined with the standard deviation, assuming the two are independent and assuming the IPCC uncertainty range (0.54 °C to 0.79 °C) is representative of a 90% confidence range (1.645 standard deviations).

The number quoted in this report for 2023 (1.40 ± 0.12 °C) was calculated in this way with 1.40 °C being the mean of the five estimates and 0.03 °C the standard deviation.

Annual temperature maps

For the map of temperature anomalies for 2023, a median of five data sets was used, regridded to the spatial grid of the lowest resolution data sets (NOAAGlobalTemp, and HadCRUT5), which are presented on a 5° latitude by 5° longitude grid. The median is used in preference to the mean to minimize the effect of potential outliers in individual grid cells. The half-range of the data sets provides an indication of the uncertainty. The spread between the data sets is largest at high latitudes and in Central Africa, both regions with sparse data coverage.

Global mean temperature anomalies for 2023 relative to other periods

This table shows global mean temperature anomalies for individual data sets for 2023 (data to October) relative to four different baselines. The uncertainty indicated for the three modern baselines (1981–2010, 1991–2020 and 1961–1990) are the standard deviations of the available estimates multiplied by 1.645 to represent the 90% uncertainty range.

Period	1850–1900	1981–2010	1991–2020	1961–1990
HadCRUT5	1.40	0.71	0.52	1.05
NOAA GlobalTemp	1.37	0.68	0.50	0.99
GISTEMP	1.39	0.70	0.51	1.02
ERA5	1.43	0.74	0.55	1.07
JRA55	1.39	0.70	0.52	1.02
Mean of five datasets	1.40±0.12	0.71±0.03	0.52±0.03	1.03±0.04

The following five data sets were used, including three traditional datasets:

HadCRUT.5.0.2.0: Morice, C. P.; Kennedy, J. J.; Rayner, N. A. et al. An Updated Assessment of NearSurface Temperature Change From 1850: The HadCRUT5 Data Set. *Journal of Geophysical Research: Atmospheres* 2021, 126, e2019JD032361. <https://doi.org/10.1029/2019JD032361>. HadCRUT.5.0.2.0 data were obtained from <http://www.metoffice.gov.uk/hadobs/hadcrut5> on 24 November 2023 and are © British Crown Copyright, Met Office 2023, provided under an Open Government Licence, <http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/>.

NOAAGlobalTemp v5.1: NOAA Interim: Vose, R. S.; Huang, B.; Yin, X. et al. Implementing Full Spatial Coverage in NOAA's Global Temperature Analysis. *Geophysical Research Letters* 2021, 48, e2020GL090873. <https://doi.org/10.1029/2020GL090873>.

GISTEMP v4: GISTEMP Team, 2022: GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies, <https://data.giss.nasa.gov/gistemp/>.

Lenssen, N.; Schmidt, G.; Hansen, J. et al. Improvements in the GISTEMP Uncertainty Model. *Journal of Geophysical Research: Atmospheres* 2019, 124, 6307–6326. <https://doi.org/10.1029/2018JD029522>.

And two reanalyses (note that we do not use JRA-3Q because there is not yet a peer-reviewed paper supporting this dataset; the differences between the two are small):

JRA-55: Kobayashi, S.; Ota, Y.; Harada, Y. et al. The JRA-55 Reanalysis: General Specifications and Basic Characteristics. *Journal of the Meteorological Society of Japan. Ser. II* 2015, 93, 5–48. <https://doi.org/10.2151/jmsj.2015-001>.

ERA5: Hersbach, H.; Bell, B.; Berrisford, P. et al. ERA5 Monthly Averaged Data on Single Levels from 1940 to Present; Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 2023. <https://doi.org/10.24381/cds.f17050d7>.

Berkeley Earth and Kadow et al. were also used to assess monthly temperatures to September:

Berkeley Earth: Rohde, R. A.; Hausfather, Z. The Berkeley Earth Land/Ocean Temperature Record. Earth System Science Data 2020, 12, 3469–3479. <https://doi.org/10.5194/essd-12-3469-2020>.

Kadow, C., Hall, D.M. & Ulbrich, U. Artificial intelligence reconstructs missing climate information. Nat. Geosci. 13, 408–413 (2020). <https://doi.org/10.1038/s41561-020-0582-5>

Land temperatures and sea-surface temperatures

The land temperature assessment is based on three data sets:

CRUTEM5.0.1.0: Osborn, T. J., P. D. Jones, D. H. Lister, C. P. Morice, I. R. Simpson and I. C. Harris (2020), Land surface air temperature variations across the globe updated to 2019: the CRUTEM5 dataset, J. Geophys. Res. <https://doi.org/10.1029/2019JD032352>

CRUTEM5.0.1.0 data were obtained from <http://www.metoffice.gov.uk/hadobs/crutem5> on 31 October 2023 and are © British Crown Copyright, Met Office 2023, provided under an Open Government License, <http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/>

GHCNV4: Menne, Matthew J.; Gleason, Byron E.; Lawrimore, Jay; Rennie, Jared; and Williams, Claude N. (2017): Global Historical Climatology Network – Monthly Temperature [Global mean]. NOAA National Centers for Environmental Information. doi:10.7289/V5XW4GTH [accessed 31 October 2023].

Berkeley Earth: Rohde, R. A.; Hausfather, Z. The Berkeley Earth Land/Ocean Temperature Record. Earth System Science Data 2020, 12, 3469–3479. <https://doi.org/10.5194/essd-12-3469-2020>

The sea-surface temperature assessment is based on two data sets:

HadSST4.0.1.0: Kennedy, J. J., Rayner, N. A., Atkinson, C. P., & Killick, R. E. (2019). An ensemble data set of sea-surface temperature change from 1850: the Met Office Hadley Centre HadSST4.0.0.0 data set. Journal of Geophysical Research: Atmospheres, 124. <https://doi.org/10.1029/2018JD029867>

HadSST4.0.1.0 data were obtained from <http://www.metoffice.gov.uk/hadobs/hadsst4> on 31 October 2023 and are © British Crown Copyright, Met Office 2023, provided under an Open Government License, <http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/>

ERSSTv5: Boyin Huang, Peter W. Thorne, Viva F. Banzon, Tim Boyer, Gennady Chepurin, Jay H. Lawrimore, Matthew J. Menne, Thomas M. Smith, Russell S. Vose, and Huai-Min Zhang (2017): NOAA Extended Reconstructed Sea-Surface Temperature (ERSST), Version 5. [Global mean]. NOAA National Centers for Environmental Information. doi:10.7289/V5T72FNM [accessed 31 October 2023].

Ocean heat content

The ensemble mean is an update of the outcome of a concerted international effort⁸¹, and all products used are referenced here. Note that global ocean heat content values are given for the ocean surface area between 60°S–60°N and limited to areas deeper than 300 m in each product. The

⁸¹ von Schuckmann, K., Cheng, L., Palmer, M. D., Hansen, J., Tassone, C., Aich, V., Adusumilli, S., Beltrami, H., Boyer, T., Cuesta-Valero, F. J., Desbruyères, D., Domingues, C., García-García, A., Gentile, P., Gilson, J., Gorfer, M., Haimberger, L., Ishii, M., Johnson, G. C., ... Wijffels, S. E. (2020). Heat stored in the Earth system: where does the energy go? Earth Syst. Sci. Data, 12(3), 2013–2041. <https://doi.org/10.5194/essd-12-2013-2020>

value for 2022 is based on a subset of the products for which updates are available. A baseline of 2005–2021 is used for the Ocean Heat Content time series (Figure 4) as near-global coverage is available in this period thanks to the network of Argo sub-surface floats.

Data used up to 2022:

Cheng, L.; Trenberth, K. E.; Fasullo, J. et al. Improved estimates of ocean heat content from 1960 to 2015, *Science Advances* 2017, 3 (3), e1601545. <https://doi.org/10.1126/sciadv.1601545>

Gaillard, F.; Reynaud, T.; Thierry, V. et al. In Situ–Based Reanalysis of the Global Ocean Temperature and Salinity with ISAS: Variability of the Heat Content and Steric Height, *Journal of Climate* 2016, 29 (4), 1305–1323. <https://doi.org/10.1175/JCLI-D-15-0028.1>

Ishii, M.; Fukuda, Y.; Hirahara, S. et al. Accuracy of Global Upper Ocean Heat Content Estimation Expected from Present Observational Data Sets. *SOLA* 2017, 13, 163–167. <https://doi.org/10.2151/sola.2017-030>

Kuusela, M., & Giglio, D. (2023) Global Ocean Heat Content Anomalies based on Argo data (2.0.0) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.7562281>

Levitus, S.; Antonov, J. I.; Boyer, T. P. et al. World Ocean heat content and thermosteric sea level change (0–2 000 m) 1955–2010. *Geophysical Research Letters* 2012, 39 (10), L10603. <https://doi.org/10.1029/2012GL051106>

Lyman, J. M.; Johnson, G. C. Estimating Global Ocean Heat Content Changes in the Upper 1800 m since 1950 and the Influence of Climatology Choice. *Journal of Climate*, 2014, 27 (5), 1945–1957. <https://doi.org/10.1175/JCLI-D-12-00752.1>

von Schuckmann, K.; Le Traon, P.-Y. How well can we derive Global Ocean Indicators from Argo data? *Ocean Science* 2011, 7 (6), 783–791. <https://doi.org/10.5194/os-7-783-2011>. Data available at: <https://marine.copernicus.eu/access-data/ocean-monitoring-indicators>

In addition, data used up to 2021:

Desbruyères, D. G. ; Purkey, S. G. ; McDonagh, E. L. et al. Deep and abyssal ocean warming from 35 years of repeat hydrography, *Geophysical Research Letters* 2016, 43 (19), 310–356. <https://doi.org/10.1002/2016GL070413>

Desbruyères, D., McDonagh, E. L., King, B. A., & Thierry, V. (2017). Global and Full-Depth Ocean Temperature Trends during the Early Twenty-First Century from Argo and Repeat Hydrography. *Journal of Climate*, 30(6), 1985–1997. <https://doi.org/10.1175/JCLI-D-16-0396.1>

Good, S. A., Martin, M. J., & Rayner, N. A. (2013). EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates (15197, trans.). *Journal of Geophysical Research: Oceans*, 118(12), 6704–6716. <https://doi.org/10.1002/2013JC009067>

Hosoda, S.; Ohira, T.; Nakamura, T. A monthly mean dataset of global oceanic temperature and salinity derived from Argo float observations. *JAMSTEC Report of Research and Development*, 2008, 8, 47–59. https://www.jstage.jst.go.jp/article/jamstecr/8/0/8_0_47/article

Kuusela M.; Stein, M. L. Locally stationary spatio-temporal interpolation of Argo profiling float data. *Proceedings of the Royal Society A* 2018, 474, 20180400. <http://dx.doi.org/10.1098/rspa.2018.0400>

Li, H.; Xu, F.; Zhou, W. et al. Development of a global gridded Argo data set with Barnes successive corrections, *Journal of Geophysical Research: Oceans* 2017, 122 (2), 866–889, <https://doi.org/10.1002/2016JC012285>

Roemmich, D.; Gilson, J. The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program, *Progress in Oceanography*, 2009, 82 (2), 81–100. <https://doi.org/10.1016/j.pocean.2009.03.004>

Roemmich, D., Church, J., Gilson, J., Monselesan, D., Sutton, P., & Wijffels, S. (2015). Unabated planetary warming and its ocean structure since 2006 (I3631, trans.). *Nature Climate Change*, 5, 240. <https://doi.org/10.1038/nclimate2513>

In addition, data used up to 2020:

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., van den Broeke, M. R., Monaghan, A. J., & Velicogna, I. (2011). Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters*, 38(18). <https://doi.org/10.1029/2011GL048794>

Domingues, C. M., Church, J. A., White, N. J., Gleckler, P. J., Wijffels, S. E., Barker, P. M., & Dunn, J. R. (2008). Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature*, 453(7198), 1090–1093. <https://doi.org/10.1038/nature07080>

Li, Y., Church, J. A., McDougall, T. J., & Barker, P. M. (2022). Sensitivity of Observationally Based Estimates of Ocean Heat Content and Thermal Expansion to Vertical Interpolation Schemes. *Geophysical Research Letters*, 49, e2022G. <https://doi.org/10.1029/2022GL101079>

Wijffels, S., Roemmich, D., Monselesan, D., Church, J., & Gilson, J. (2016). Ocean temperatures chronicle the ongoing warming of Earth. *Nature Climate Change*, 6(2), 116–118. <https://doi.org/10.1038/nclimate2924>

Sea level

GMSL from CNES/Aviso+ <https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/data-acces.html#c12195> Copernicus Climate Change Service (C3S), 2018:

Sea Level Daily Gridded Data from Satellite Observations for the Global Ocean from 1993 to Present. C3S CDS, <https://doi.org/10.24381/cds.4c328c78>

Marine heatwaves and cold-spells

MHWs are categorized as moderate when the sea-surface temperature (SST) is above the ninetieth percentile of the climatological distribution for five days or longer; the subsequent categories are defined with respect to the difference between the SST and the climatological distribution average: strong, severe, or extreme, if that difference is, respectively, more than two, three or four times the difference between the ninetieth percentile and the climatological distribution average (Hobday et al., 2018). MCS categories are analogous but counting days below the tenth percentile, except for the 'ice' category. This category is given to any MCS when the threshold for the occurrence on any given day of the event is below -1.7°C (Schlegel et al., 2021). These are therefore considered to be conditions related to sea-ice, and not extreme temperature fluctuations.

The baseline used for MHWs and MCSs is 1982–2011, which is shifted by one year from the standard normal period of 1981–2010 because the first full year of the satellite SST series on which it is based is 1982. This period has not been updated to the current standard normal period of 1991–

2020 because the shifting of the baseline has a significant effect on the results and would not allow for comparison of MHW/MCS statistics with previous versions of this report.

All MHWs and MCSs are detected using the NOAA daily Optimum Interpolation Sea-Surface Temperature (OISST) v2.1 dataset (Huang et al. 2021).

Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C.,... & Wernberg, T. (2016). A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, 141, 227–238. <https://doi.org/10.1016/j.pocean.2015.12.014>

Hobday, A. J., Oliver, E. C., Gupta, A. S., Benthuyssen, J. A., Burrows, M. T., Donat, M. G.,... & Smale, D. A. (2018). Categorizing and naming marine heatwaves. *Oceanography*, 31(2), 162–173. <https://www.jstor.org/stable/26542662>

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B.,... & Zhang, H. M. (2021). Improvements of the daily optimum interpolation sea-surface temperature (DOISST) version 2.1. *Journal of Climate*, 34(8), 2923–2939. <https://doi.org/10.1175/JCLI-D-20-0166.1>

Schlegel, R. W., Darmaraki, S., Benthuyssen, J. A., Filbee-Dexter, K., & Oliver, E. C. (2021). Marine cold-spells. *Progress in Oceanography*, 198, 102684.

Ice sheets

Mankoff, K., X. Fettweis, A. Solgaard, P. Langen, M. Stendel, B. Noël, M. van den Broeke, N. Karlsson, J.E. Box, and K. Kjeldsen (2021) Greenland ice sheet mass balance from 1840 through next week <https://doi.org/10.22008/FK2/OHI23Z>, GEUS Dataverse, V704

Mankoff, K. D., Fettweis, X., Langen, P. L., Stendel, M., Kjeldsen, K. K., Karlsson, N. B., Noël, B., van den Broeke, M. R., Solgaard, A., Colgan, W., Box, J. E., Simonsen, S. B., King, M. D., Ahlstrøm, A. P., Andersen, S. B., and Fausto, R. S.: Greenland ice sheet mass balance from 1840 through next week, *Earth Syst. Sci. Data*, 13, 5001–5025, <https://doi.org/10.5194/essd-13-5001-2021>, 2021.

Sea-ice

Data are from the EUMETSAT OSI SAF Sea-Ice Index v2.2 (OSI-SAF, based on Lavergne et al., 2019 – <https://osisaf-hl.met.no/v2p2-sea-ice-index>) and the National Snow and Ice Data Center (NSIDC) v3 Sea-Ice Index (Fetterer et al., 2017). Sea-ice concentrations are estimated from microwave radiances measured from satellites. Extent is the area of ocean grid cells where the sea-ice concentration exceeds 15%. There are modest differences in the absolute extent between data sets, but they agree well on the year-to-year changes and trends. In the main text of the report, NSIDC values are reported for absolute extents, and rankings. Comparison figures for OSI SAF are given in the table.

Metric	NSIDC	OSI SAF
Arctic daily minimum	4.23 million km ² , 19 September. sixth lowest on record	4.71 million km ² , 16 September. sixth lowest on record
Arctic daily maximum	14.62 million km ² , 6 March, fifth lowest on record	14.64 million km ² , 3 March
Antarctic daily minimum	1.79 million km ² , 21 February, lowest on record	2.0 million km ² , 16 February, lowest on record
Antarctic daily maximum	16.96 million km ² , 10 September, lowest on record	17.6 million km ² , 12 September, lowest on record

OSI SAF Sea-ice index 1978-onwards, version 2.2 (2023), OSI-420. EUMETSAT Ocean and Sea-Ice Satellite Application Facility. Data extracted from [Sea-ice index | OSI SAF \(eumetsat.int\)](https://eumetsat.int/sea-ice-index)

Fetterer, F.; Knowles, K.; Meier, W. N. et al., 2017, updated daily. Sea-Ice Index, Version 3. Boulder, Colorado, USA. National Snow and Ice Data Center (NSIDC), <https://nsidc.org/data/G02135/versions/3>.

Lavergne, T. Sørensen, A. M.; Kern, S. et al. Version 2 of the EUMETSAT OSI SAF and ESA CCI Sea-Ice Concentration Climate Data Records. The Cryosphere 2019, 13 (1), 49–78. <https://doi.org/10.5194/tc-139-2019>.

Precipitation

The following Global Precipitation Climatology Centre (GPCC) data sets were used in the analysis:

First Guess Monthly, https://doi.org/10.5676/DWD_GPCC/FG_M_100

Monitoring Product (Version 2022), https://doi.org/10.5676/DWD_GPCC/MP_M_V2022_100

Full Data Monthly (Version 2022), https://doi.org/10.5676/DWD_GPCC/FD_M_V2022_100

Precipitation Climatology (Version 2022), https://doi.org/10.5676/DWD_GPCC/CLIM_M_V2022_100

In Figure 18, Iceland is shown as being much drier than the long-term average and parts of China much wetter. These features are due to a change in the way that real time data are processed and are not reflective of actual conditions.

Contributors

Members

Algeria, Andorra, Argentina, Armenia, Australia, Bahrain, Barbados, Belgium, Belize, Bosnia and Herzegovina, Brazil, Brunei, Bulgaria, Canada, Chile, China, Côte d'Ivoire, Croatia, Cyprus, Czech Republic, Denmark, Ecuador, Estonia, Finland, France, Georgia, Germany, Hungary, Iceland, India, Iran (Islamic Republic of), Ireland, Israel, Italy, Japan, Jordan, Kazakhstan, Latvia, Libya, Luxembourg, Malaysia, Mauritius, Mexico, Morocco, Myanmar, Netherlands, New Zealand, Norway, Paraguay, Peru, Poland, Republic of Korea, Republic of Moldova, Russian Federation, Saudi Arabia, Singapore, Slovakia, Slovenia, South Africa, Sweden, Switzerland, Thailand, Türkiye, Ukraine, United Arab Emirates, United Kingdom of Great Britain and Northern Ireland, United Republic of Tanzania, United States of America, Uruguay, Venezuela (Bolivarian Republic of), Viet Nam.

Individual contributors

Vicente Anzellini (IDMC), Chris Atkinson (Met Office), Omar Baddour (WMO), Paul M Barker (University of New South Wales), Jorge Alvar-Beltrán (FAO), Jana Birner (UNHCR), Nicholas Bishop (IOM), Jessica Blunden (NOAA), Tim Boyer (NOAA NCEI), Anny Cazanave (Legos), Xuan Che (UNDRR), Lijing Cheng (Institute of Atmospheric Physics (IAP), Center for Ocean Mega-Science), John Church (University of New South Wales), Damien Desbruyeres (Ifremer), Catia Domingues (NOC), Robert Dunn (Met Office), Arianna Gialletti (FAO), Pini Giancarlo (WFP), Donata Giglio (University of Colorado), John E Gilson (SCRIPPS), Alashiya Gordes (FAO), Atsushi Goto (WMO), Flora Gues (CELAD, Mercator Ocean International), Peer Hechler (WMO), Christopher Hewitt (WMO), Shigeki Hosoda (JAMSTEC), Matthias Huss (ETH Zürich), Amanda Ignatia (UNHCR), Kirsten Isensee (IOC/UNESCO), Gregory C Johnson (NOAA PMEL), Christopher Kadow (DKRZ), Hideki Kanamaru (FAO), Maarten Kappelle (UNEP), John Kennedy (WMO Expert), Rachel Killick (Met Office), Brian King (NOC), Nicolas Kolodziejczyk (University of Brest), Animesh Kumar (UNDRR), Mikael Kuusela (Carnegie Mellon)

University), Gernot Laganda (WFP), Lancelot Leclercq (Legos), Yuehua Li (Yunnan University), Ricardo Locarnini (NOAA NCEI), John Lyman (NOAA PMEL), Shawn Marshall (Environment and Climate Change Canada (ECCC) and University of Calgary), Jesse Mason (WFP), Jutta May (UNDRR), Trevor McDougall (University of New South Wales), Brian Menounos (University of Northern British Columbia), Audrey Minère (Mercator Ocean International), Didier Paolo Monselesan (CSIRO), Sarah Purkey (Scripps), James Reagan (NOAA NCEI, University of Maryland), Dean Roemmich (Scripps), Lev Neretin (FAO), Julien Nicolas (ECMWF), Elisabeth Du Parc (IOM), Sylvain Ponsérre (IDMC), Ileana Sinziana Puscas (IOM), Claire Ransom (WMO), David Robinson (Rutgers State University of New Jersey), Bonifacio Rogerio (WFP), Kanako Sato (JAMSTEC), Katsunari Sato (JMA), Abhishek Savita (GEOMAR), Robert W Schlegel (Sorbonne Université, CNRS, Laboratoire d'Océanographie de Villefranche), Katherina Schoo (IOC/UNESCO), Serhat Sensoy (Turkish State Meteorological Service), Fumi Sezaki (JMA), Jose Álvaro Silva (WMO), Mike Sparrow (WMO/WCRP), Johan Stander (WMO), Toshio Suga (Tohoku University, JAMSTEC), Oksana Tarasova (WMO), Caterina Tassone (WMO/GCOS), Blair Trewin (Bureau of Meteorology), Karina von Schuckmann (Mercator Ocean International), Ying Wang (UNEP), Susan E Wjiffels (CSIRO, Woods Hole), Abdel-Lathif Younous (WFP), Markus Ziese (DWD, GPCC)

Institutions

Bureau of Meteorology, Australia; Carnegie Mellon University, USA; Center for Ocean Mega-Science, Chinese Academy of Sciences, China; CELAD, France; Commonwealth Scientific and Industrial Research Organization, CSIRO Oceans and Atmosphere, Tasmania, Australia; Deutsches Klimarechenzentrum, DKRZ, Germany; Deutscher Wetterdienst, DWD, Germany; European Centre for Medium-range Weather Forecasts, ECMWF, UK; Environment and Climate Change Canada, ECCC, Canada; ETH Zürich; GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany; Global Precipitation Climatology Centre, GPCC, Germany; Hong Kong Observatory; Ifremer, France; IAP, Chinese Academy of Sciences, China; International Displacement Monitoring Centre (IDMC); Japan Marine Earth Science and Technology, JAMSTEC, Japan; Japan Meteorological Agency, JMA, Japan; Laboratoire d'Océanographie de Villefranche, France; Legos, France; Met Office, UK; Mercator Ocean International, France; National Oceanic and Atmospheric Administration (NOAA) National Centres for Environmental Information (NCEI), USA; National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL), USA; National Oceanography Centre, Southampton, UK ; Ocean Scope, France ; Rutgers State University of New Jersey; Scripps Institution of Oceanography, University of California San Diego, USA; Sorbonne Université, France; Tohoku University, Japan ; Turkish State Meteorological Service, Türkiye; University of Brest, France ; University of Calgary, Canada; University of Colorado, USA; Cooperative Institute for Satellite Earth Systems Studies, University of Maryland, USA ; University of New South Wales, Australia; University of Northern British Columbia; Woods Hole Oceanographic Institution, USA; Yunnan University, China;

UN Agencies

- Food and Agriculture Organization, FAO
- Intergovernmental Oceanographic Commission of UNESCO, IOC/UNESCO
- International Organization for Migration, IOM
- United Nations Environment Programme, UNEP
- United Nations High Commissioner for Refugees, UNHCR
- United Nations Office for Disaster Risk Reduction, UNDRR
- World Food Programme, WFP.