STATE OF THE CLIMATE IN 2023

Special Supplement to the
Bulletin of the American Meteorological Society
Vol. 105, No. 8, August 2024

Cover Credit:

Ice Worm Glacier in the North Cascade mountains of Washington, United States, which was under continuous annual monitoring from 1984 onward and disappeared in 2023. Large photo: The location of former Ice Worm Glacier in 2023. Inset photo: Ice Worm Glacier in 1986. Photo credits Mauri Pelto. 13 August 2023 is the date for the main photo. 16 August 1986 is the date for the inset photo.

How to cite this document:

Special Supplement to the Bulletin of the American Meteorological Society, Vol. 105, No. 8, August 2024 https://doi.org/10.1175/2024BAMSStateoftheClimate.1. Compiled by NOAA's National Centers for Environmental Information, *State of the Climate in 2023* is based on contributions from scientists from around the world. It provides a detailed update on global climate indicators, notable weather events, and other data collected by environmental monitoring stations and instruments located on land, water, ice, and in space.

Citing the complete report:

Blunden, J. and T. Boyer, Eds., 2024: "State of the Climate in 2023". *Bull. Amer. Meteor. Soc.*, **105** (8), Si–S483 https://doi.org/10.1175/2024BAMSStateoftheClimate.1.

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STATE OF THE CLIMATE IN 2023

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Abstract

—J. BLUNDEN AND T. BOYER

In 2023, La Niña conditions that generally prevailed in the eastern Pacific Ocean from mid-2020 into early 2023 gave way to a strong El Niño by October. Atmospheric concentrations of Earth's major greenhouse gases—carbon dioxide, methane, and nitrous oxide—all increased to record-high levels. The annual global average carbon dioxide concentration in the atmosphere rose to 419.3±0.1 ppm, which is 50% greater than the pre-industrial level. The growth from 2022 to 2023 was 2.8 ppm, the fourth highest in the record since the 1960s.

The combined short-term effects of El Niño and the long-term effects of increasing levels of heat-trapping gases in the atmosphere contributed to new records for many essential climate variables reported here. The annual global temperature across land and oceans was the highest in records dating as far back as 1850, with the last seven months (June–December) having each been record warm. Over land, the globally averaged temperature was also record high. Dozens of countries reported record or near-record warmth for the year, including China and continental Europe as a whole (warmest on record), India and Russia (second warmest), and Canada (third warmest). Intense and widespread heatwaves were reported around the world. In Vietnam, an all-time national maximum temperature record of 44.2°C was observed at Tuong Duong on 7 May, surpassing the previous record of 43.4°C at Huong Khe on 20 April 2019. In Brazil, the air temperature reached 44.8°C in Araçuaí in Minas Gerais on 20 November, potentially a new national record and 12.8°C above normal.

The effect of rising temperatures was apparent in the cryosphere, where snow cover extent by June 2023 was the smallest in the 56-year record for North America and seventh smallest for the Northern Hemisphere overall. Heatwaves contributed to the greatest average mass balance loss for Alpine glaciers around the world since the start of the record in 1970. Due to rapid volume loss beginning in 2021, St. Anna Glacier in Switzerland and Ice Worm Glacier in the United States disappeared completely. In August, as a direct result of glacial thinning over the past 20 years, a glacial lake on a tributary of the Mendenhall Glacier in Alaska burst through its ice dam and caused unprecedented flooding on Mendenhall River near Juneau.

Across the Arctic, the annual surface air temperature was the fourth highest in the 124-year record, and summer (July–September) was record warm. Smaller-than-normal snow cover extent in May and June contributed to the third-highest average peak tundra greenness in the 24-year record. In September, Arctic minimum sea ice extent was the fifth smallest in the 45-year satellite record. The 17 lowest September extents have all occurred in the last 17 years.

In Antarctica, temperatures for much of the year were up to 6°C above average over the Weddell Sea and along coastal Dronning Maud Land. The Antarctic Peninsula also experienced well-above-average temperatures during the 2022/23 melt season, which contributed to its fourth consecutive summer of above-average surface melt. On 21 February, Antarctic sea ice extent and sea ice area both reached all-time lows, surpassing records set just a year earlier. Over the course of the year, new daily record-low sea ice extents were set on 278 days. In some instances, these daily records were set by a large margin, for example, the extent on 6 July was 1.8 million km^2 lower than the previous record low for that day.

Across the global oceans, the annual sea surface temperature was the highest in the 170-year record, far surpassing the previous record of 2016 by 0.13°C. Daily and monthly records were set from March onward, including an historic-high daily global mean sea surface temperature of 18.99°C recorded on 22 August. Approximately 94% of the ocean surface experienced at least one marine heatwave in 2023, while 27% experienced at least one cold spell. Globally averaged ocean heat content from the surface to 2000-m depth was record high in 2023, increasing at a rate equivalent to ~0.7 Watts per square meter of energy applied over Earth's surface. Global mean sea level was also record high for the 12th consecutive year, reaching 101.4 mm above the 1993 average when satellite measurements began, an increase of 8.1±1.5 mm over 2022 and the third highest year-over-year increase in the record.

A total of 82 named tropical storms were observed during the Northern and Southern Hemispheres' storm seasons, below the 1991–2020 average of 87. Hurricane Otis became the strongest landfalling hurricane on record for the west coast of Mexico at 140 kt (72 m s^{-1}), causing at least 52 fatalities and $12–16 billion U.S. dollars in damage. Freddy became the world's longest-lived tropical cyclones on record, developing into a tropical cyclone on 6 February and finally dissipating on 12 March. Freddy crossed the full width of the Indian Ocean and made one landfall in Madagascar and two in Mozambique. In the Mediterranean Sea—outside of traditional tropical cyclone basins—heavy rains and flooding from Storm Daniel killed more than 4300 people and left more than 8000 missing in Libya.

The record-warm temperatures in 2023 created conditions that helped intensify the hydrological cycle. Measurements of total-column water vapor in the atmosphere were the highest on record, while the fraction of cloud area in the sky was the lowest since records began in 1980. The annual global mean precipitation total over land surfaces for 2023 was among the lowest since 1979, but global one-day maximum totals were close to average, indicating an increase in rainfall intensity.

In July, record-high areas of land across the globe (7.9%) experienced extreme drought, breaking the previous record of 6.2% in July 2022. Overall, 29.7% of land experienced moderate or worse categories of drought during the year, also a record. Mexico reported its driest (and hottest) year since the start of its record in 1950. In alignment with hot and prolonged dry conditions, Canada experienced its worst national wildfire season on record. Approximately 15 million hectares burned across the country, which was more than double the previous record from 1989. Smoke from the fires were transported far into the United States and even to western European countries. August to October 2023 was the driest three-month period in Australia in the 104-year record. Millions of hectares of bushfires burned for weeks in the Northern Territory. In South America, extreme drought developed in the latter half of the year through the Amazon basin. By the end of October, the Rio Negro at Manaus, a major tributary of the Amazon River, fell to its lowest water level since records began in 1902.

The transition from La Niña to El Niño helped bring relief to the prolonged drought conditions in equatorial eastern Africa. However, El Niño along with positive Indian Ocean dipole conditions also contributed to excessive rainfall that resulted in devastating floods over southeastern Ethiopia, Somalia, and Kenya during October to December that displaced around 1.5 million people. On 5 September, the town of Zagora, Greece, broke a national record for highest daily rainfall (754 mm in 21 hours, after which the station ceased reporting) due to Storm Daniel; this one-day accumulation was close to Zagora's normal annual total.

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STATE OF THE CLIMATE IN 2023

INTRODUCTION

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Special Online Supplement to the *Bulletin of the American Meteorological Society* Vol. 105 No. 8, August, 2024

https://doi.org/10.1175/2024BAMSStateoftheClimate_Intro.1
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Introduction

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How to cite this document:
Introduction is one chapter from the *State of the Climate in 2023* annual report and is available from https://doi.org/10.1175/2024BAMSStateoftheClimate_Intro.1. Compiled by NOAA's National Centers for Environmental Information, *State of the Climate in 2023* is based on contributions from scientists from around the world. It provides a detailed update on global climate indicators, notable weather events, and other data collected by environmental monitoring stations and instruments located on land, water, ice, and in space. The full report is available from https://doi.org/10.1175/2024BAMSStateoftheClimate.1.

Citing the complete report:
Blunden, J. and T. Boyer, Eds., 2024: "State of the Climate in 2023". *Bull. Amer. Meteor. Soc.*, **105** (8), Si–S483 https://doi.org/10.1175/2024BAMSStateoftheClimate.1.

Citing this chapter:
Boyer, T., J. Blunden, and R J. H. Dunn, 2024: Introduction [in "State of the Climate in 2023"]. *Bull. Amer. Meteor. Soc.*, **105** (8), S1–S11, https://doi.org/10.1175/2024BAMSStateoftheClimate_Intro.1.

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2. INTRODUCTION

T. Boyer, J. Blunden, and R. J. H. Dunn

The year 2023 was marked by the highest global mean surface temperature on record, exceeding the previous record-high year (2016) by a large margin of 0.13°C to 0.17°C, according to a range of scientific analyses presented in this report. This record high was evident in many other global climate indicators (Plate 1.1; Chapter 2, Global Climate). For example, humid-heat indices, which are relevant to human comfort and safety in ambient air temperature and humidity, were also record high in 2023, with humid-heat intensity (anomaly of maximum daily wet-bulb temperature) having doubled the value from the previous record year (1998). Sidebars 2.1, 3.1, and 5.2 detail the extreme heat observed across the globe in 2023 and its impacts across land, ocean, and ice-covered regions. Still, as is evident from the compendium of statistics, analyses, and events across this year's *State of the Climate* report, cause and effect of a changing climate are more complex than simply the measure of surface temperatures. The year 2023 began in the La Niña phase of the El Niño–Southern Oscillation, having been the prevalent phase over much of the previous three years. A transition occurred during the year that led to the establishment of an El Niño in April/May/June, which reached the threshold necessary to be classified as strong by August/September/October (Chapter 4; The Tropics). The El Niño–Southern Oscillation is a coupled atmosphere–ocean system where surface temperatures are not the only factor, though they are a distinct indicator of its state. For example, the Madden-Julian Oscillation (a transient rainfall suppression/enhancement atmospheric phenomenon) contributed to the westerly wind bursts that hastened the breakdown of the La Niña in the early part of the year and the buildup of the El Niño into June. The timing of the establishment and strengthening of El Niño atmospheric patterns was critical in 2023, as it roughly coincided with the Atlantic Hurricane season. Despite favorable ocean conditions over the Gulf of Mexico and much of the North Atlantic (i.e., tropical cyclone heat potential above the threshold conducive to hurricane generation), the Gulf of Mexico had a below-average year for tropical cyclone activity in 2023, which is typical during El Niño. Atypically, the whole North Atlantic basin had an above-average season for both number of cyclones and accumulated cyclone energy.

The Gulf of Mexico example shows the value of the *State of the Climate* report in bringing together information from different disciplines and across geographic scales from global to regional to local. Another example, the disappearance of Ice Worm Glacier in the Pacific Northwest region of the United States, is depicted on the cover of the report. For the first time, all reference glaciers of the World Glacier Monitoring Service lost mass in 2023. While Ice Worm Glacier was not a reference glacier, it had been monitored continuously for 40 years. Both Ice Worm Glacier and St. Anna Glacier (also known as St. Annafirn Glacier) in Switzerland, the other glacier which disappeared in 2023 (after having been monitored for 12 years), were very small glaciers (less than 0.5 km^2 area) when monitoring began, so their disappearance did not alter to any degree the global alpine glacier mass balance. However, these glacier disappearances are reflective of the global pattern of glacial mass loss. Within 10 km of Ice Worm Glacier, five other glaciers have disappeared since 2015. Local and regional events such as these emphasize the impacts of a changing climate at a scale, which makes it easier to understand the statistics and analyses of climate at the global scale. Chapter 7, Regional Climates, provides an exhaustive listing of air temperature, precipitation, and significant events in regions and subregions across the globe. It is here that local impacts, the statistics and analyses of events, and trends at larger scales are most minutely detailed. Moreover, pairing this regional/local information with the information from the other chapters of the *State of the Climate* can lead to a better understanding of the complex factors that contribute to local conditions and events, and provides us with a clearer understanding of global climate. The cover of this chapter (Chapter 1; Introduction) shows satellite imagery of the Rio Negro River as it flows past Manaus, Brazil. In October 2023, the water level on the Rio Negro at the port of Manaus was at its lowest level since 1902. The factors that led to the low water level are the hydrological cycles affected by both the La Niña at the beginning of the year and the El Niño later in the year as well as record-high sea surface temperatures globally (Espinoza et al. 2024). There are numerous other details at the regional and local level in the *State of the Climate*—such as Hurricane Otis' unexpected intensification from Category 1 to Category 5 (Sidebar 4.1), the record extent of wildfires in Canada (Sidebar 7.1), the record-high temperatures in northern China (Sidebar 7.4), and the record-low sea ice extent in the Southern Ocean (section 6f)—from which we could extract or already have extracted a better understanding of the local and global climate system.

The compilation of the *State of the Climate* is possible due to the dedication of the chapter editors and 592 section authors from 59 countries. Plate 1.1 provides information for essential climate variables detailed in the report in the form of 36 time series, showing the climate variables for 2023 in the context of the long-term record. The sequence of the *State of the Climate in 2023* is similar to previous years: Chapter 1, Introduction (i.e., this chapter); Chapter 2, Global Climate; Chapter 3, Global Oceans; Chapter 4, The Tropics; Chapter 5, The Arctic; Chapter 6, Antarctica and the Southern Ocean; and Chapter 7, Regional Climates, which covers the seven regions of North America, Central America and the Caribbean, South America, Africa, Europe and the Middle East, Asia, and Oceania. In a notable change from previous years, Chapter 8, Relevant datasets and sources, has been removed. Instead, the datasets used in the *State of the Climate* are found in appendices at the ends of Chapters 2–6 and are separated by section. This is intended to make it easier for researchers to find and access the datasets used for the statistics and analysis in the individual sections, in the hope that they will utilize the datasets and the information provided in the *State of the Climate* to further understanding of Earth's climate system on global, regional, and local scales. Also new to this year's report are sections on humid-heat extremes over land (section 2d2), which were introduced last year as a sidebar and serve as a climate indicator more directly connected to human health as opposed to surface temperature. Another new addition is a section on stratospheric aerosols (section 2g5), an indicator that was introduced in the *State of the Climate in 2019* and is instrumental in tracking the ongoing effects of the Hunga Tonga–Hunga Ha'apai eruption of 2022. The section on lightning flashes has been replaced by a section on thunder hours, which is a proxy for lightning activity.

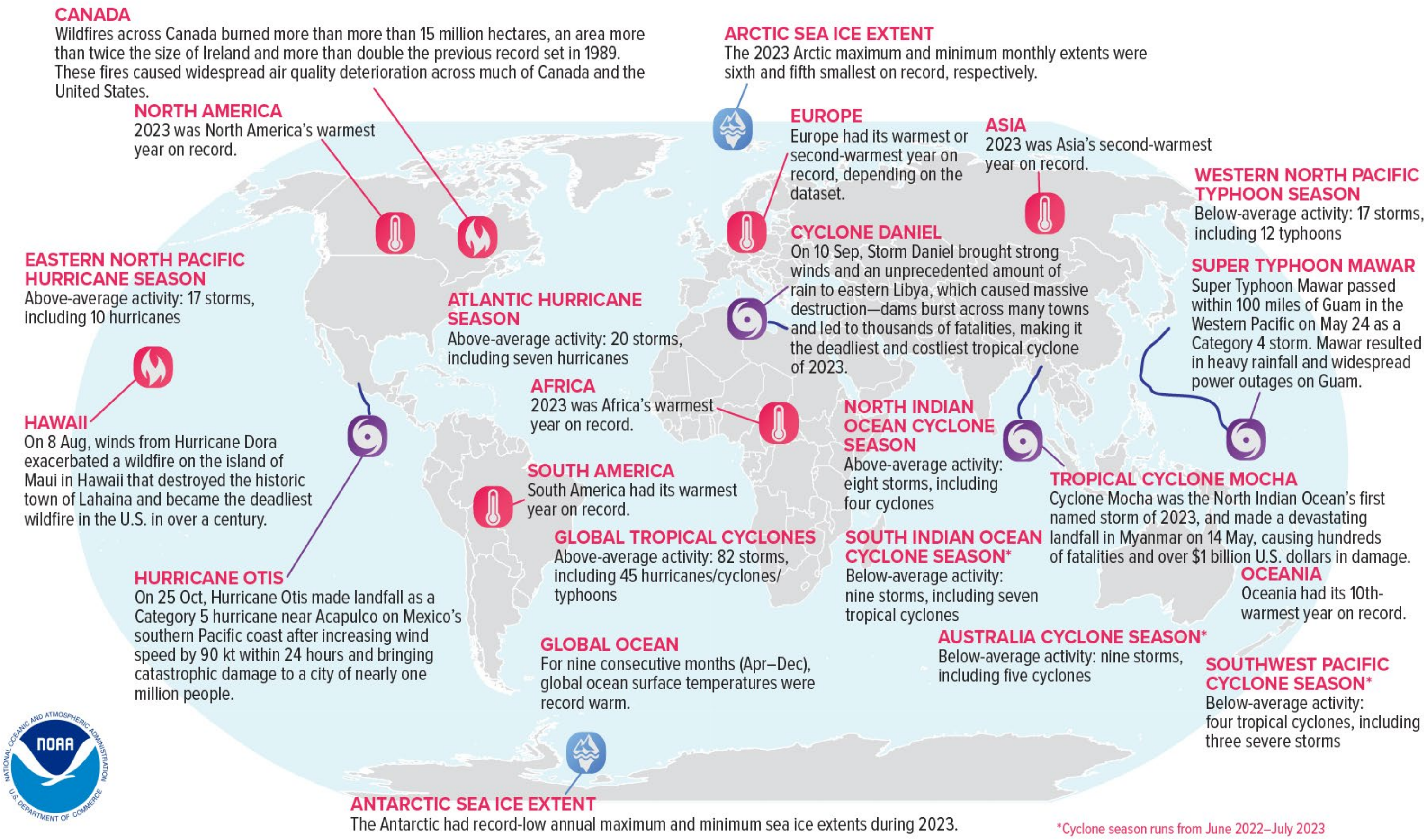
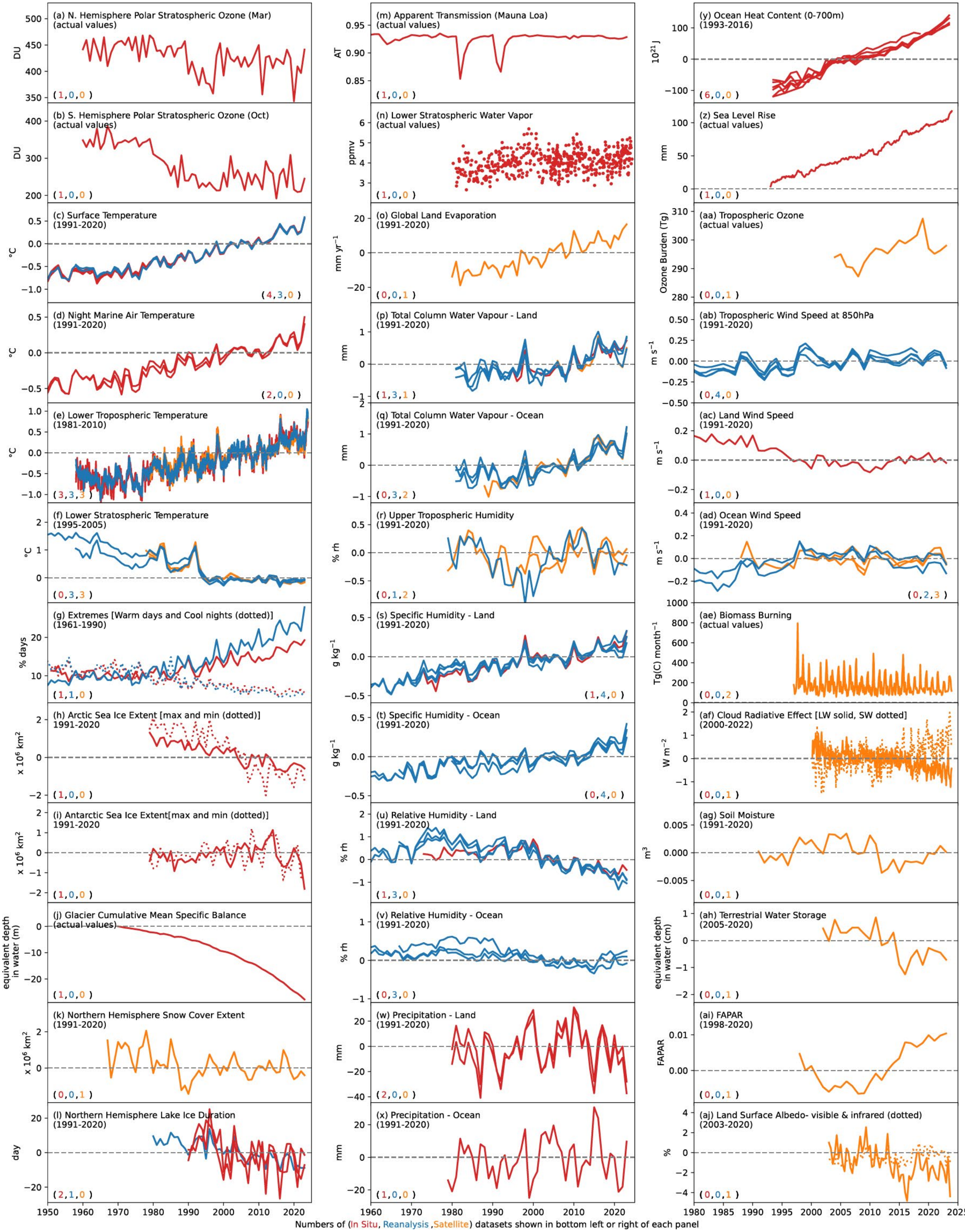


Fig. 1.1. Geographical distribution of selected notable climate anomalies and events in 2023.

Plate 1.1. (Next page.) Global (or representative) average time series for essential climate variables through 2023. Anomalies are shown relative to the base period in parentheses, although base periods used in other sections of the report may differ. The numbers in the parentheses in the lower left or right side of each panel indicate how many in situ (red), reanalysis (blue), and satellite (orange), datasets are used to create each time series in that order. (a) Northern Hemisphere (NH) polar stratospheric ozone (Mar); (b) Southern Hemisphere (SH) polar stratospheric ozone (Oct); (c) surface temperature; (d) night marine air temperature; (e) lower tropospheric temperature; (f) lower stratospheric temperature; (g) extremes (warm days [solid] and cool days [dotted]); (h) Arctic sea ice extent (max [solid]) and min [dotted]); (i) Antarctic sea ice extent (max [solid] and min [dotted]); (j) glacier cumulative mean specific balance; (k) NH snow cover extent; (l) NH lake ice duration; (m) Mauna Loa apparent transmission; (n) lower stratospheric water vapor; (o) global land evaporation; (p) total column water vapor – land; (q) total column water vapor – ocean; (r) upper tropospheric humidity; (s) specific humidity – land; (t) specific humidity – ocean; (u) relative humidity – land; (v) relative humidity – ocean; (w) precipitation – land; (x) precipitation – ocean; (y) ocean heat content (0–700 m); (z) sea level rise; (aa) tropospheric ozone; (ab) tropospheric wind speed at 850 hPa; (ac) land wind speed; (ad) ocean wind speed; (ae) biomass burning; (af) cloud radiative effect; (ag) soil moisture; (ah) terrestrial groundwater storage; (ai) fraction of absorbed photosynthetically active radiation (FAPAR); (aj) land surface albedo – visible (solid) and infrared (dotted).


(a) N. Hemisphere Polar Stratospheric Ozone (Mar) (actual values)
(b) S. Hemisphere Polar Stratospheric Ozone (Oct) (actual values)
(c) Surface Temperature (1991-2020)
(d) Night Marine Air Temperature (1991-2020)
(e) Lower Tropospheric Temperature (1981-2010)
(f) Lower Stratospheric Temperature (1995-2005)
(g) Extremes [Warm days and Cool nights (dotted)] (1961-1990)
(h) Arctic Sea Ice Extent [max and min (dotted)] 1991-2020
(i) Antarctic Sea Ice Extent[max and min (dotted)] 1991-2020
(j) Glacier Cumulative Mean Specific Balance (actual values)
(k) Northern Hemisphere Snow Cover Extent (1991-2020)
(l) Northern Hemisphere Lake Ice Duration (1991-2020)
(m) Apparent Transmission (Mauna Loa) (actual values)
(n) Lower Stratospheric Water Vapor (actual values)
(o) Global Land Evaporation (1991-2020)
(p) Total Column Water Vapour - Land (1991-2020)
(q) Total Column Water Vapour - Ocean (1991-2020)
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(s) Specific Humidity - Land (1991-2020)
(t) Specific Humidity - Ocean (1991-2020)
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(v) Relative Humidity - Ocean (1991-2020)
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(y) Ocean Heat Content (0-700m) (1993-2016)
(z) Sea Level Rise (actual values)
(aa) Tropospheric Ozone (actual values)
(ab) Tropospheric Wind Speed at 850hPa (1991-2020)
(ac) Land Wind Speed (1991-2020)
(ad) Ocean Wind Speed (1991-2020)
(ae) Biomass Burning (actual values)
(af) Cloud Radiative Effect [LW solid, SW dotted] (2000-2022)
(ag) Soil Moisture (1991-2020)
(ah) Terrestrial Water Storage (2005-2020)
(ai) FAPAR (1998-2020)
(aj) Land Surface Albedo- visible & infrared (dotted) (2003-2020)
Numbers of (In Situ, Reanalysis ,Satellite) datasets shown in bottom left or right of each panel

Essential Climate Variables

J. BLUNDEN, T. BOYER, AND R. J. H. DUNN

The following variables are considered fully monitored in this report, in that there are sufficient spatial and temporal data, with peer-reviewed documentation to characterize them on a global scale:

- Surface atmosphere: air pressure, precipitation, temperature, water vapor, wind speed and direction
- Upper atmosphere: Earth radiation budget, temperature, water vapor, wind speed and direction
- Atmospheric composition: carbon dioxide, methane and other greenhouse gases, ozone
- Ocean physics: ocean surface heat flux, sea ice, sea level, surface salinity, sea surface temperature, subsurface salinity, subsurface temperature, surface currents, surface stress
- Ocean biogeochemistry: ocean color
- Ocean biogeosystems: plankton
- Land: albedo, river discharge, snow

The following variables are considered partially monitored, in that there is systematic, rigorous measurement found in this report, but some coverage of the variable in time and space is lacking due to observing limitations or availability of data or authors:

- Atmospheric composition: aerosols properties, cloud properties, precursors of aerosol and ozone
- Upper atmosphere: lightning
- Ocean physics: subsurface currents
- Ocean biogeochemistry: inorganic carbon
- Land: above-ground biomass, anthropogenic greenhouse gas fluxes, fire, fraction of absorbed photosynthetically active radiation, glaciers, groundwater, ice sheets and ice shelves, lakes, permafrost, soil moisture
- Surface atmosphere: surface radiation budget

The following variables are not yet covered in this report, or are outside the scope of it.

- Ocean physics: sea state
- Ocean biogeochemistry: nitrous oxide, nutrients, oxygen, transient tracers
- Ocean biogeosystems: marine habitat properties
- Land: anthropogenic water use, land cover, land surface temperature, latent and sensible heat fluxes, leaf area index, soil carbon

Acknowledgements

The editors thank the BAMS editorial staff, in particular Bryan Hanssen, who provided technical guidance and oversaw publication of the report; Andrea Herbst, who provided peer review support; and Nicole Rietmann, who oversaw the hundreds of citations and references this year; and the NCEI Graphics team for facilitating the construction of the report and executing the countless number of technical edits needed. We thank our technical editor Lukas Noguchi for his dedication and attention to detail. We also express our gratitude to Dr. Timothy DelSole, who served as the AMS special editor for this report. Finally, we thank all of the authors and chapter editors who provide these valuable contributions each year, always with an aim to improve and expand their analyses for the readers.

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