State of the Climate in Europe 2022

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

PROGRAMME OF THE EUROPEAN UNION

Copernicus
Europe's eyes on Earth

IMPLEMENTED BY ECMWF

Climate Change Service
climate.copernicus.eu

WMO-No. 1320

Cover photo: Mammatus explosion, photo taken by Boris Jordan (Germany), WMO 2021 Calendar Competition.

WMO-No. 1320

Chair, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03
Email: publications@wmo.int

ISBN 978-92-63-11320-7

Contents

Key messages

Europe is the fastest-warming of all the WMO regions, warming twice as much as the global average since the 1980s. In 2022, the annual average temperature was between the second and fourth highest on record, depending on the data set used, and summer was the warmest. In many countries in western and south-western Europe, 2022 was the warmest year on record.

Precipitation was below average across much of the region in 2022. It was the fourth dry year in a row on the Iberian Peninsula, and the third consecutive dry year in the mountain regions of the Alps and Pyrenees.

The lack of precipitation, in particular winter snow, combined with high summer temperatures, contributed to the largest loss of glacial ice recorded in the European Alps.

The Greenland Ice Sheet continued to lose mass during 2022, and in September periods of exceptional warmth led to widespread surface melt.

In 2022, sea-surface temperatures across the North Atlantic area of the WMO Europe region were the warmest on record and large portions of the region's seas were affected by strong or even severe and extreme marine heatwaves. The rates of surface ocean warming, particularly in the eastern Mediterranean Sea, the Baltic and Black Seas, and the southern Arctic were more than three times the global average.

High-impact weather and climate events in 2022 resulted in more than 16 000 reported fatalities, almost entirely attributed to the exceptional heatwaves Europe experienced during the summer. The most severe heatwave occurred in mid-July, with record-breaking temperatures in many locations. The temperature reached 40 °C in the United Kingdom for the first time, with a reading of 40.3 °C in Coningsby on 19 July.

Drought also affected much of the region, particularly during spring and summer. The combination of dry conditions and extreme heat fuelled numerous wildfires and the second largest burnt area in the region on record. Large wildfires occurred in France, Spain, Portugal, Slovenia and Czechia.

Storms and floods led to dozens of fatalities, with many cases of localized flooding from intense rainfall, a derecho (a long-lived band of thunderstorms and destructive winds) that affected parts of southern and central Europe in August, and three successive storms in one week of February in north-west Europe.

Despite the year being characterized by warm conditions, some areas were affected by cold spells and heavy snowfall, including Türkiye, the Syrian Arab Republic, Greece and Montenegro. A widespread cold spell also affected much of northern and western Europe in December. Reykjavik, Iceland, recorded the coldest December for 100 years.

Wind and solar power represented 22.3% of European Union electricity in 2022, overtaking fossil gas (20%) for the first time. More electricity was generated by these two renewable resources than by any other power source. Monitoring and understanding their temporal and spatial variability is increasingly important due to the growing importance they have for the European energy mix.

Climate information is an important element of improving the resilience and operations of energy systems. While 80% of WMO Members in Europe are providing some climate information for the energy sector, less than 50% provide monthly to seasonal climate predictions for the energy sector, bringing to light the untapped potential of NMHSs in supporting energy transition and greater climate resilience of the energy sector.

Foreword

The WMO *State of the Climate in Europe 2022* is the second of an annual series successfully launched last year. This joint publication by the WMO Regional Association for Europe (WMO RA VI) and the European Union's Copernicus Climate Change Service summarizes the state of the climate, and the extreme and high-impact weather and climate events in 2022 for the WMO RA VI (Europe) domain, in the context of long-term climate variability and climate change.

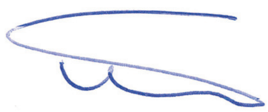
The report makes use of climate observing systems and brings together valuable contributions from Members, while supporting their needs on climate monitoring, climate change and climate services. The latest data and information on impacts, risks and policy from United Nations agencies and European Union (EU) partners complement the physical science overview. The present report also considers the scientifically robust findings from the recent Sixth Assessment Report (AR6)[1] and Synthesis Report (SYR)[2] of the Intergovernmental Panel on Climate Change (IPCC), and from the Copernicus *European State of the Climate 2022*[3] report.

Europe is the fastest-warming of the six defined WMO regions and in 2022 many countries in western and south-western Europe had their warmest year on record. Summer was the hottest ever recorded: the high temperatures exacerbated the severe and widespread drought conditions, fuelled violent wildfires that resulted in the second largest burnt area on record, and led to thousands of heat-associated excess deaths.

Early warnings are fundamental in anticipating and reducing the impacts of the increasing number of extreme events. WMO, along with the United Nations Office for Disaster Risk Reduction (UNDRR), International Telecommunication Union (ITU) and the International Federation of Red Cross and Red Crescent Societies (IFRC), is leading the United Nations Early Warnings for All initiative, launched by United Nations Secretary-General António Guterres during the World Leaders Summit at the 2022 United Nations Climate Change Conference, COP27. The action plan will strengthen Earth system observations and monitoring, predictive and warning capabilities globally, with benefits for populations and economic sectors.

Energy is the focus area of the climate policy section in the present *State of the Climate in Europe 2022* report, and there is some good news. For the first time in the EU, more electricity was generated by wind and solar than by fossil gas. Increasing use of renewables and low-carbon energy sources is crucial to reduce dependence on fossil fuels, and provides an important contribution towards climate neutrality and mitigation of human-induced climate change. Climate services play a key role in ensuring the resilience of energy systems to climate-related shocks, in planning operations, and in informing measures to increase energy efficiency, among other relevant applications.

I take this opportunity to congratulate the lead authors, experts and scientists for their excellent contributions to this report. I also thank the National Meteorological and Hydrological Services (NMHSs), the WMO Regional Climate Centre Network for Europe, the Copernicus Climate Change Service (C3S), sister United Nations agencies, EU partners and all contributing institutions for their outstanding support to this publication.



Prof. Petteri Taalas
Secretary-General, WMO

Preface

The societal value of a systematic analysis of the changing climate is becoming increasingly more evident, as it allows us to better anticipate future extremes and prepare for the impacts of a warmer world.

The *State of the Climate in Europe 2022* provides, once more, a detailed and accurate account of a series of unprecedented climate events that have affected our region. The year-to-year variability of the climate is apparent when comparing the 2021 report – where our attention was inevitably drawn to the severe storms and devastating flooding which affected western Europe – to the current report, where extreme high temperatures and prolonged drought came to the forefront.

The record-breaking heat stress that Europeans experienced in 2022 was one of the main drivers of weather-related excess deaths in Europe. Unfortunately, this cannot be considered a one-off occurrence or an oddity of the climate. Our current understanding of the climate system and its evolution, clearly presented in the latest report of the Intergovernmental Panel on Climate Change (IPCC), informs us that these kinds of events are part of a pattern that will make heat stress extremes more frequent and more intense across the region.

With the steady growth in the renewable fraction of the European energy mix comes a closer dependency of our system on the variability of weather and climate. Describing these changes and understanding the drivers behind such fluctuations is becoming more important. The present report provides valuable information on the climate as a resource to support our transition towards a net-zero society.

I encourage readers to go beyond the informative figures and the clear statistics contained in these pages and take this as a stimulus to fundamentally alter the way in which we look at the data describing the world around us.

The Copernicus Climate Change Service (C3S), funded by the European Commission, has been working along with WMO towards the operationalization of climate service provision so that every citizen in the region can have easy access to high-quality, open and free data about the world we live in. The present report is a key step in this process, as it allows this data to speak for itself. The climate is rapidly changing, and we need to use all the tools we have to adapt to the conditions we will face in the years to come.

The report is the result of a collective effort involving many individuals and institutions across the entire region. I would like to thank the lead authors and the editorial team, but also the many people behind the scenes who made the publication of this report possible.

Dr Carlo Buontempo
Director, Copernicus Climate Change Service
European Centre for Medium-range Weather Forecasts (ECMWF)

Global climate context

The global annual mean near-surface temperature in 2022 was 1.15 °C [1.02 °C to 1.28 °C] above the 1850–1900 pre-industrial average. The year 2022 was either the fifth or the sixth warmest year on record according to six data sets,[4] despite the cooling effect of La Niña. The years 2015 to 2022 were the eight warmest years on record in all data sets.[5]

Atmospheric concentrations of the three major greenhouse gases reached new record observed highs in 2021, the latest year for which consolidated global figures are available, with levels of carbon dioxide (CO_2) at 415.7 ± 0.2 parts per million (ppm), methane (CH_4) at 1 908 ± 2 parts per billion (ppb) and nitrous oxide (N_2O) at 334.5 ± 0.1 ppb – respectively 149%, 262% and 124% of pre-industrial (before 1750) levels (Figure 1). Real-time data from specific locations, including Mauna Loa[6] (Hawaii, United States of America) and Kennaook/Cape Grim[7] (Tasmania, Australia) indicate that levels of CO_2, CH_4 and N_2O continued to increase in 2022.

Over the past two decades, the ocean warming rate has increased, and the ocean heat content in 2022 was the highest on record. Ocean warming and accelerated loss of ice mass from the ice sheets contributed to the rise of the global mean sea level by 4.62 mm per year between 2013 and 2022, reaching a new record high in 2022. Between 1960 and 2021, the ocean absorbed about 25% of annual anthropogenic emissions of CO_2 into the atmosphere,[8] and CO_2 reacts with seawater and lowers its pH. The limited number of long-term observations in the open ocean have shown a decline in pH, with a reduction of the average global surface ocean pH of 0.017–0.027 pH units per decade since the late 1980s. This process, known as ocean acidification, affects many organisms and ecosystem services,[9] and threatens food security by endangering fisheries and aquaculture.

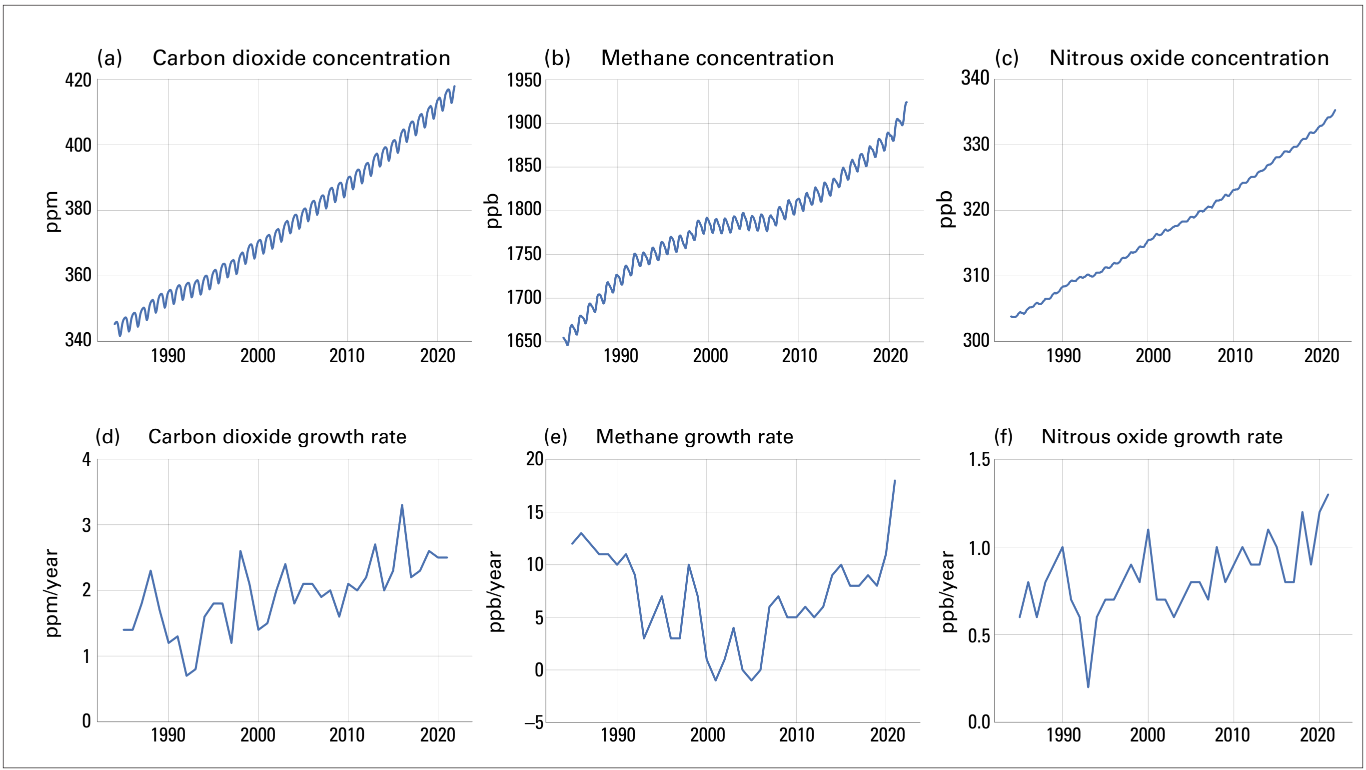


Figure 1. Top row: Monthly globally averaged mole fraction (measure of atmospheric concentration), from 1984 to 2021, of (a) CO_2 in parts per million, (b) CH_4 in parts per billion and (c) N_2O in parts per billion. Bottom row: the growth rates representing increases in successive annual means of mole fractions for (d) CO_2 in parts per million per year, (e) CH_4 in parts per billion per year and (f) N_2O in parts per billion per year

Regional climate

The following sections analyse key indicators of the state of the climate in Europe (WMO Region VI – Europe; see the domain map in the Region domain subsection under Data sets and methods at the end of the report). One such indicator that is particularly important, temperature, is described in terms of anomalies, or departures from a reference period. For global mean temperature, the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC)[10] uses the reference period 1850–1900 for calculating anomalies in relation to pre-industrial levels. However, this pre-industrial reference period cannot be used in all regions as a baseline for calculating regional anomalies, due to insufficient data for calculating region-specific averages prior to 1900. Instead, the 1991–2020 climatological standard normal reference period is used for computing anomalies in temperature and other indicators. Regional temperature anomalies can also be expressed relative to the reference period 1961–1990. This is a fixed reference period recommended by WMO for assessing long-term temperature change. In the present report, exceptions to the use of these baseline periods for the calculation of anomalies, where they occur, are explicitly noted.

TEMPERATURE

The surface air temperature impacts human and natural systems. It can affect health, agriculture and energy demand, as well as growth cycles in natural environments. Extreme temperatures have a particular impact on human health. In Europe, temperatures have warmed significantly during the industrial era. Since the 1980s, Europe has warmed at a rate of +0.5 °C per decade, more than twice the global average, making it the fastest-warming of the WMO regions.[11]

The 2022 annual average temperature for Europe[12] was between the second and fourth highest on record, with an anomaly of 0.79 °C [0.70 °C–0.91 °C] above the 1991–2020 average (Figure 2(a)) and an anomaly of 1.83 °C [1.73 °C–1.92 °C] above the 1961–1990 average. Almost the entire region saw annual average temperatures in 2022 above the 1991–2020 average by more than 0.5 °C; only north-western Iceland and a small part of Türkiye saw temperatures slightly below average. The largest deviations from the average occurred across the European part of the Arctic, and in the south-western parts of the region. Much of south-western Europe was more than 1 °C above the 1991–2020 average in 2022, with some areas more than 2 °C above average (Figure 2(b)).

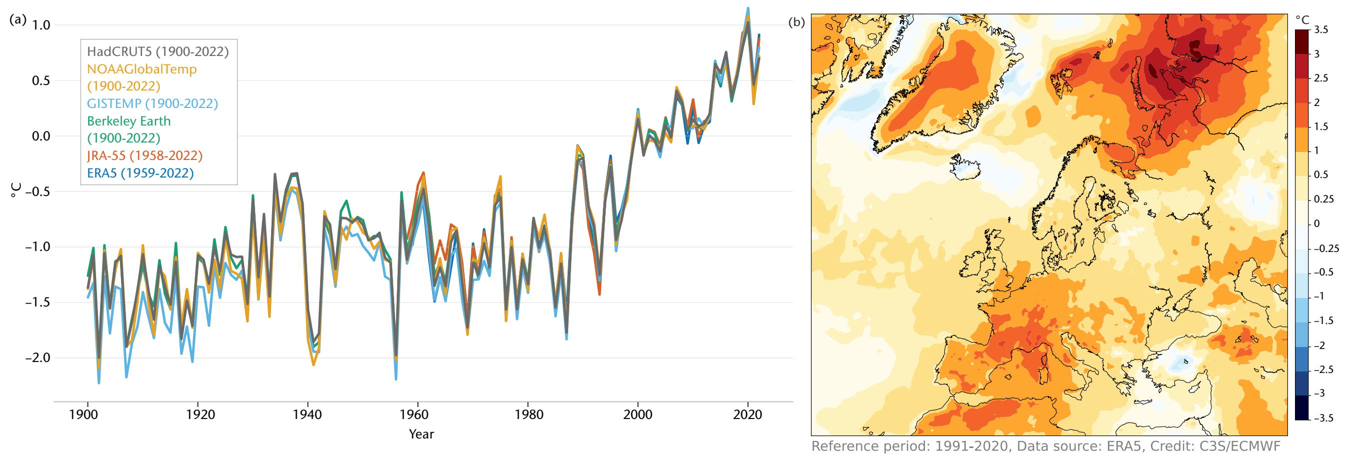


Figure 2. (a) Annual average surface air temperature anomaly (°C) over Europe, as defined by the WMO Region VI (see the Region domain subsection under Data sets and methods), for 1900–2022, using data from six data sets (for land only), and (b) for 2022 from ERA5 reanalysis, compared to the 1991–2020 reference period.
Source: (a) WMO. Note: HadCRUT5, Berkeley Earth, NOAAGlobalTemp and GISTEMP are based on in situ observations. ERA-5 and JRA-55 are reanalysis data sets. (b) ERA5 reanalysis from Copernicus Climate Change Service (C3S)/European Centre for Medium-range Weather Forecasts (ECMWF). For details of the data sets and plotting, see the Temperature subsection under Data sets and methods at the end of the present report.

Europe as a whole also saw its warmest summer on record (based on seasonal anomalies dating back to 1950).[13] Record high annual temperatures were reported in western and south-western Europe (where several countries had their warmest year, including Belgium, France, Germany, Ireland, Italy, Luxembourg, Portugal, Spain, Switzerland and the United Kingdom of Great Britain and Northern Ireland). The Arctic has been warming at a rate well above the global average since the 1990s, and over north-western Siberia in 2022 annual average temperatures were more than 3 °C above the 1991–2020 average.

PRECIPITATION

Precipitation, an essential variable for monitoring climate, usually has more spatial and temporal variability than temperature. Lack of precipitation leads to droughts, while its excess can cause floods and/or high river discharge and soil moisture.

On average, the majority of WMO Region VI received below-average precipitation amounts in 2022 compared to the 1991–2020 reference period (Figure 3(a)). The largest annual precipitation deficits were found to the south of the Gulf of Finland, in southern France and north-west Italy, and across the islands in the Aegean Sea and the Middle East. Conversely, the highest annual precipitation excesses were seen along the northern Scandinavian coast, from the Pripet Marshes (southern Belarus, north-west Ukraine) to the Volga Uplands (European part of Russian Federation), around the Costa Blanca (Spain), Crete (Greece), the Outer Hebrides (north-west of Scotland) and across the Faroe Islands (Denmark). The year 2022 was the fourth drier-than-average year in a row for the Iberian Peninsula, and it was the third consecutive drier-than-average year in mountain regions of the Alps and Pyrenees.

Anomalies of the highest daily precipitation total of the year (RX1) relative to the long-term 1991–2020 mean are shown in Figure 3(b). The largest regions with positive RX1 anomalies, as marked with blue colours, are located in east Europe. There are further locations in other parts of Europe that had positive

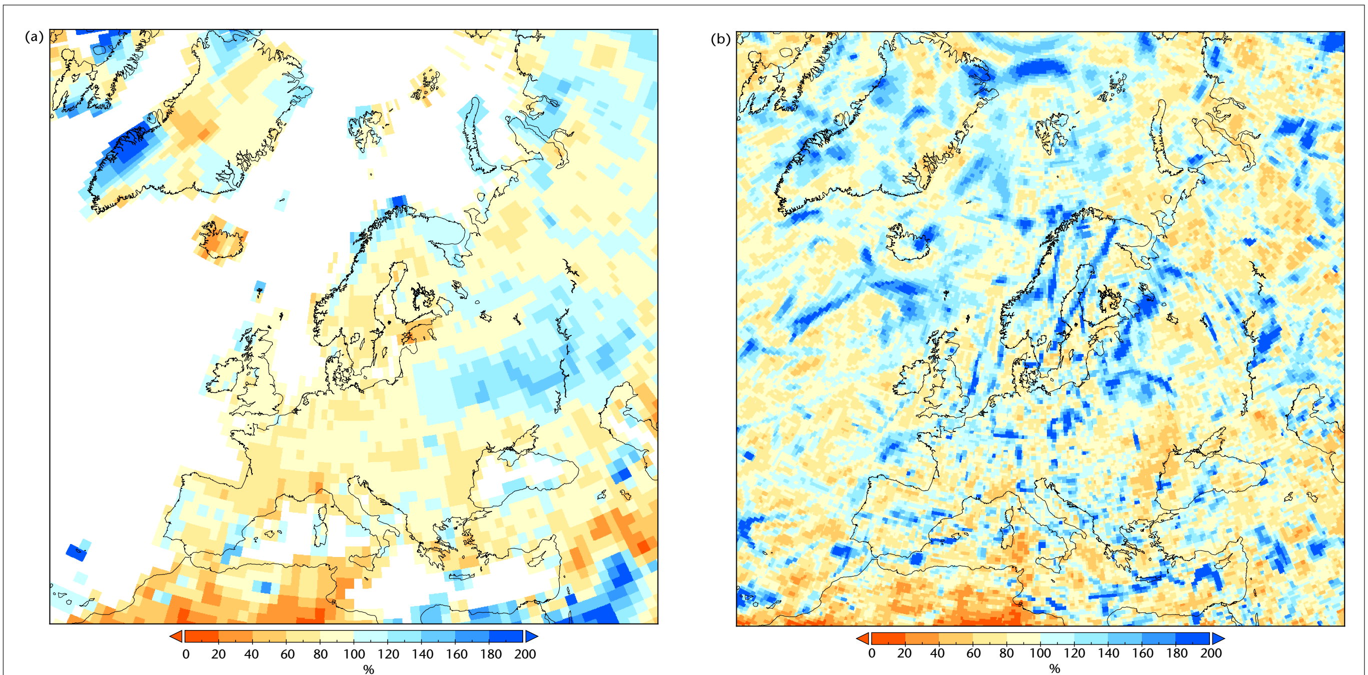


Figure 3. (a) Relative anomaly of the annual precipitation total in 2022 with reference to 1991–2020. Yellow, orange and red colours indicate a precipitation deficit while blue regions experienced a precipitation excess. (b) Deviation of the highest daily precipitation amount (RX1) in 2022 from the reference period 1991–2020. Blue indicates regions where RX1is higher than the annual mean, while in brownish coloured regions the RX1 was below the long-term mean.
Source: (a)Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst (DWD), Germany; (b) ECMWF ERA5

RX1 anomalies, even though the annual total was below normal (for example, in western, southern and central Europe). On the other hand, not all regions with above-normal annual rainfall totals had positive RX1 anomalies (for example, around the Costa Blanca).

CRYOSPHERE

The cryosphere is the frozen water part of the Earth system, including ice sheets, ice shelves, glaciers, snow cover, permafrost (frozen ground), sea ice, and river and lake ice, all of which can be found within the region. The cryosphere is experiencing large changes as the Earth warms, and it plays an important role within the climate system, as summarized below.[14]

GLACIERS AND GREENLAND ICE SHEET

Ice on land, in the form of ice sheets and glaciers, plays an important role in Earth's climate system through its ability to store vast amounts of water away from the oceans for long periods of time, and through its effect on the surface albedo reflecting incoming short-wave radiation. Any change in ice mass stored on land, such as when ice sheets and glaciers grow or shrink, has not only an impact on the local climate but also affects the global mean sea level. Glaciers and ice sheets gain mass through accumulation of snow, and lose mass mainly through surface melting via interactions with the atmosphere or at their frontal regions via interactions with lake or ocean water.

In Europe, glaciers lost a volume of about 880 km^3 of ice from 1997 to 2022. Glaciers in the Alps recorded the largest ice losses over this period, with an average reduction in ice thickness of 34 m (Figure 4).[15] In 2022, glaciers in the European Alps experienced a new record mass loss of more than 3 m water equivalent in one single year, caused by very low winter snow amounts and a very warm summer. Several dust storms led to substantial deposition of Saharan dust on many European glaciers, which contributed to an accelerated melting of the winter snowpack.[16]

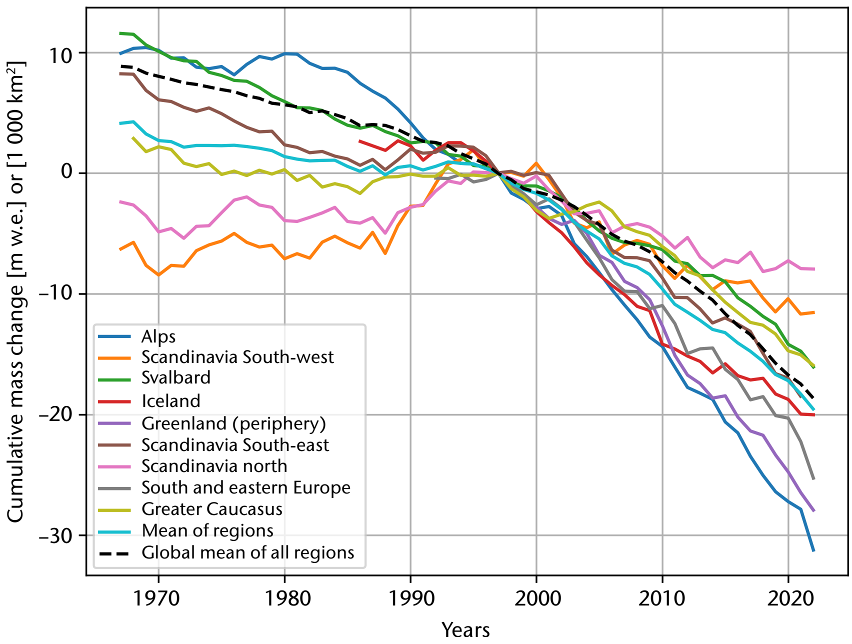


Figure 4. Cumulative glacier mass changes in Europe from 1967 to 2022, for glaciers with long-term records in nine different regions. Mass balance values are given in metres of water equivalent (m w.e.), relative to 1997.
Source: Data from the World Glacier Monitoring Service (WGMS) (2021, updated). Graphic originally published as part of the C3S Climate Indicators – Glacier Indicator, as at 20 April 2023: https://climate.copernicus.eu/climate-indicators/glaciers.

The Greenland Ice Sheet lost 5 362 ± 527 Gt of ice between 1972 and 2021, contributing 14.9 ± 1.5 mm to global mean sea-level rise.[17] In 2021, the latest year for which consolidated data are available (Figure 5), the Greenland Ice Sheet lost 234 ± 86 Gt of ice, which is less than in the record year of 2019, during which ice losses in Greenland reached a peak value of 444 ± 93 Gt, due to an intense surface melting event. Independent estimates from different sources indicate that the Greenland Ice Sheet continued to lose mass during the 2022 mass balance year.[18] Further, in September 2022, Greenland experienced widespread surface melt, with the largest September melt in more than two decades.

SEA ICE

Sea-ice extent in the European Arctic sector[19] remained relatively close to its 1991–2020 average from January until mid-May, before falling rapidly to below-average levels in early June, and levelling off around mid-July (Figure 6). At its annual minimum in September, the monthly mean extent was 6% below average, the fourteenth lowest in the 1979–2022 satellite record. It then remained consistently below average from October onwards. September 2022 was in sharp contrast with September 2021, when sea ice in the European Arctic sector reached its lowest extent on record, at 40% below average. The 2021 record came from record low extent in the Greenland Sea. In 2022, sea-ice extent in this part of the domain remained relatively close to average throughout the year. The rapid drop in late May and early June 2022 resulted from warm southerly winds over the Barents Sea which caused a rapid northward drift and retreat of the sea-ice edge. Sea-ice extent in this part of the European Arctic sector remained below average until the end of the year, mainly due to much below-average sea-ice cover between Svalbard (Norway) and Franz Josef Land (Russian Federation).

Sea-ice extent in the Baltic Sea is often characterized by its winter maximum extent. During the 2021/2022 winter, a maximum of about 93 000 km^2 was reached in early February, making the season a "weak ice winter".[20] This was the tenth lowest maximum extent within the last four decades and fifty-fifth lowest within the full data record of more than 300 years.[21]

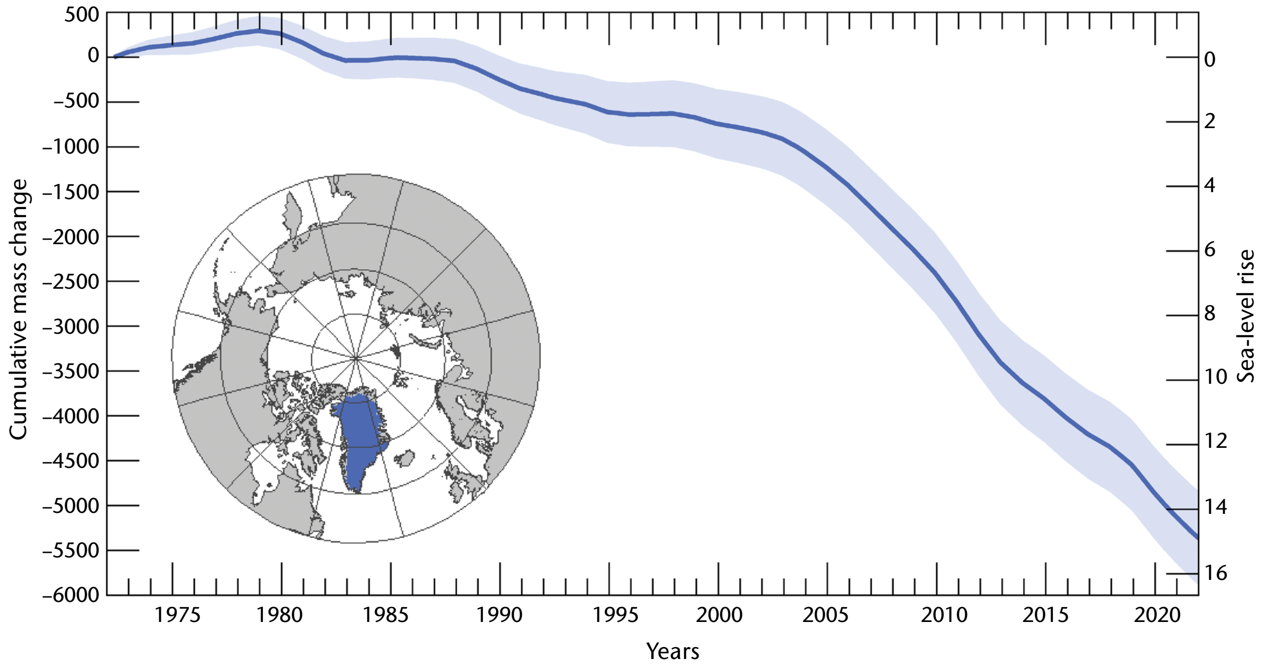


Figure 5. Cumulative mass balance of Greenland Ice Sheet and the corresponding contributions to global mean sea level, between 1972 and 2021 (year label indicates the start of the year). The shading represents the cumulative uncertainty.
Source: Data from the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE): http://imbie.org/

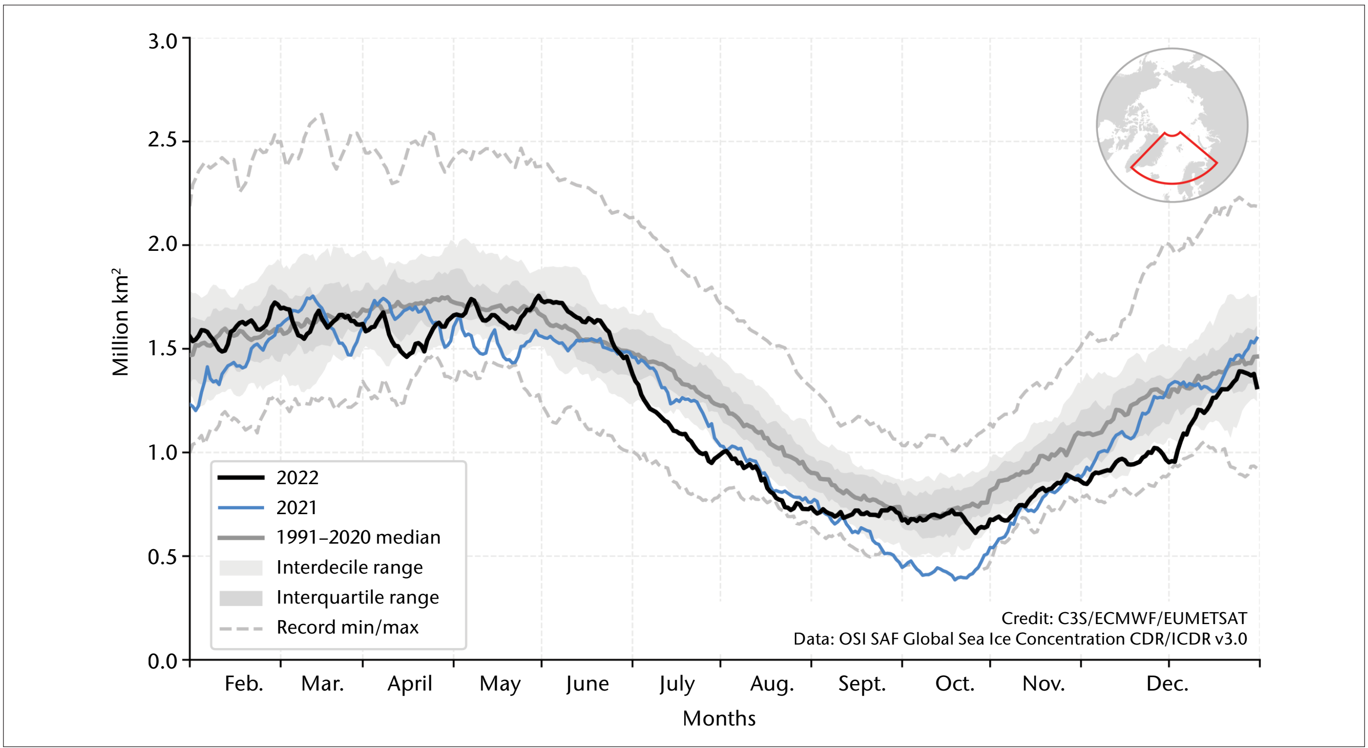


Figure 6. Total daily sea-ice extent in the European Arctic sector for 2021 (blue) and 2022 (black). The plot shows in grey shades the daily median (solid line), interdecile range (light shading) and interquartile range (dark shading) during the 1991–2020 reference period, as well as the daily minimum and maximum during 1979–2022 (dashed lines). The European Arctic sector is outlined in red on the inset map.
Source: Sea-ice extent derived from the EUMETSAT Ocean and Sea Ice Satellite Application Facilities (OSI SAF) Global Sea Ice Concentration (Interim) Climate Data Record v3.0: https://osi-saf.eumetsat.int/products/osi-430-a

OCEAN

WMO Region VI includes several major ocean basins, subregions and big lakes: the eastern Atlantic sector of the Arctic, the North, Baltic, Mediterranean and Black Seas, as well as part of the Caspian Sea. These play a major role in determining the climate and weather conditions of the region and are highly impacted by the globally and regionally changing climate.

SEA-SURFACE TEMPERATURE

The sea surface is the boundary between the ocean and atmosphere. Its temperature is key to monitoring the flows of energy between the two and to understanding the role the oceans are playing in shaping the weather and climate. Sea-surface temperature (SST) provides a key indication of ocean warming, and ocean heat content provides information about warming at depth. There has been an overall warming of all major ocean basins of the region during the industrial era, although the rate of warming differs.

The year 2022 was the warmest on record for average SST across the North Atlantic area of the WMO Europe region, following the long-term trend of an increase of 0.23 °C ± 0.04 °C per decade (Figure 7(b), 1)). By comparison, global mean SST has increased over recent decades at a rate of 0.15 °C ± 0.01 °C per decade. The area-wide SST trend is exceeded at the subregional level, with the highest rates in the Black Sea, at 0.54 °C ± 0.10 °C per decade, followed by the Baltic Sea, at 0.48 °C ± 0.11 °C per decade, and then by the Mediterranean Sea, at a rate of 0.38 °C ± 0.05 °C per decade (Figure 7(b), 2) to 4)). Likewise, the highest rates of surface ocean warming regionally, exceeding the global mean warming rates by 3 to 4 times, are observed in the eastern part of the region, such as in the southern Arctic, the entire Baltic and Black Seas, and the eastern basin of the Mediterranean Sea (Figure 7(a)). The rest of the Mediterranean basin is affected by warming 2 to 3 times the global mean surface ocean warming rate, whereas the north-west European Shelf area is warming at a rate of 0.1 °C–0.2 °C per decade. At the most western margin, slight cooling is reported from the past quarter of a decade, which is associated with variations in this area, referred to as the North Atlantic warming hole or cold blob, and which is further discussed in the Ocean heat content section.

OCEAN HEAT CONTENT

Oceans have taken up to 90% of the extra heat induced by the anthropogenic emission of greenhouse gases. This has resulted in a noticeable warming which will be irreversible on centennial to millennial timescales.[22,23,24] The IPCC has concluded that "It is *virtually certain* that the global upper ocean (0–700 m depth) has warmed since the 1970s and *extremely likely* that human influence is the main driver".[25]

In recent years the average warming of the upper ocean (0–700 m depth) in the region (see area in black line as indicated in Figure 8(a)) has been dominated by year-to-year variations in the subpolar North Atlantic, superposing the long-term warming trend.[26] The uncertainty of the warming rate is high and the trend is not significant (Figure 8(b)). At the regional scale, this heating is most evident in the Mediterranean Sea, reaching up to more than 2 W m^{-2} in the eastern basin. At the Atlantic margin, regional ocean warming rates are around 0.5–1.0 W m^{-2}. More precisely, the area at the most western edge of the WMO Region VI domain is characterized by decadal-scale cooling and reaches up to more than –2 W m^{-2} over the 1993–2022 period (Figure 8(a)). Changes in this area are associated with the so-called North Atlantic warming hole, also called the North Atlantic cold blob – a feature which has been linked to phenomena such as changes in the high-latitude ocean circulation and air-sea processes linked to changes in low cloud coverage.[27,28]

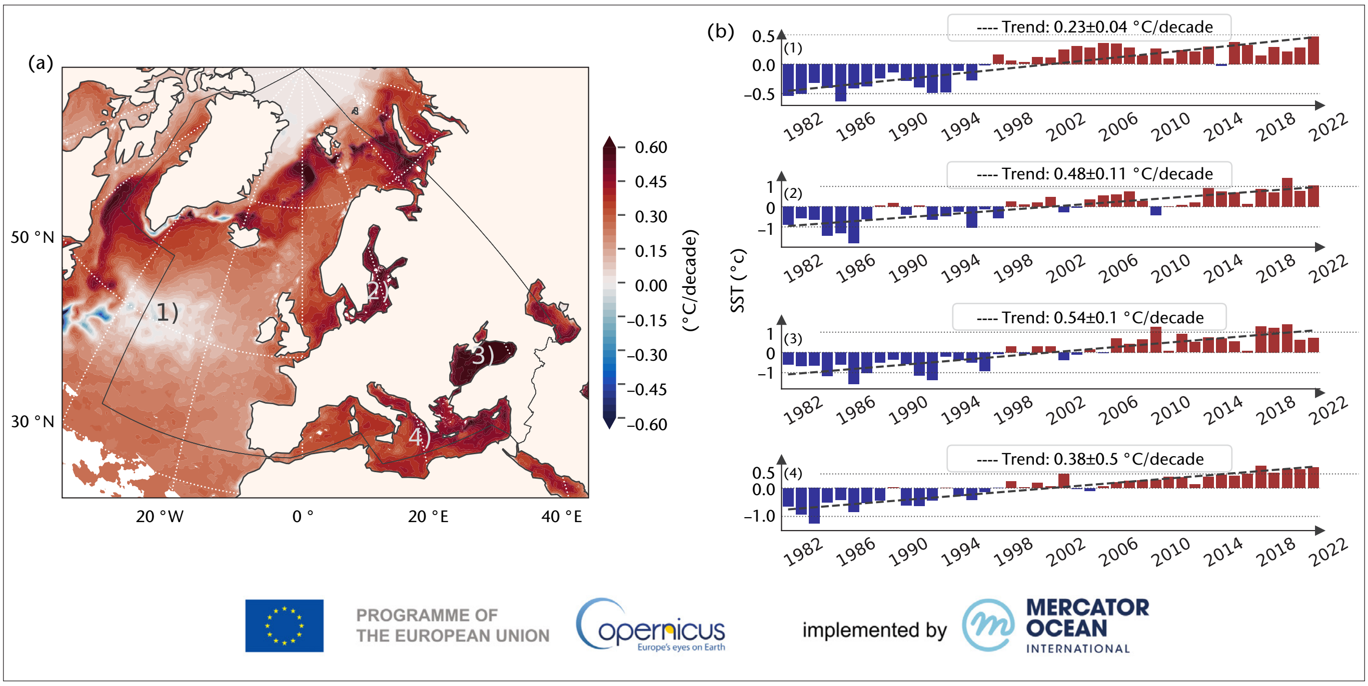


Figure 7. (a) Trends in SST (°C per decade) over the period 1982–2022. (b) Area-averaged time series of SST anomalies (°C) relative to the 1982–2022 reference period for the areas indicated on 7(a): 1) North Atlantic; 2) Baltic Sea; 3) Black Sea; and 4) Mediterranean Sea. The WMO area for Europe is indicated with a black line.
Source: Copernicus Marine Service/Mercator Ocean International, France. Derived from the remote sensing product for 1982–2021 (see https://doi.org/10.48670/moi-00168), and for 2022 (see https://doi.org/10.48670/moi-00165), downloaded from the Copernicus Marine Service.

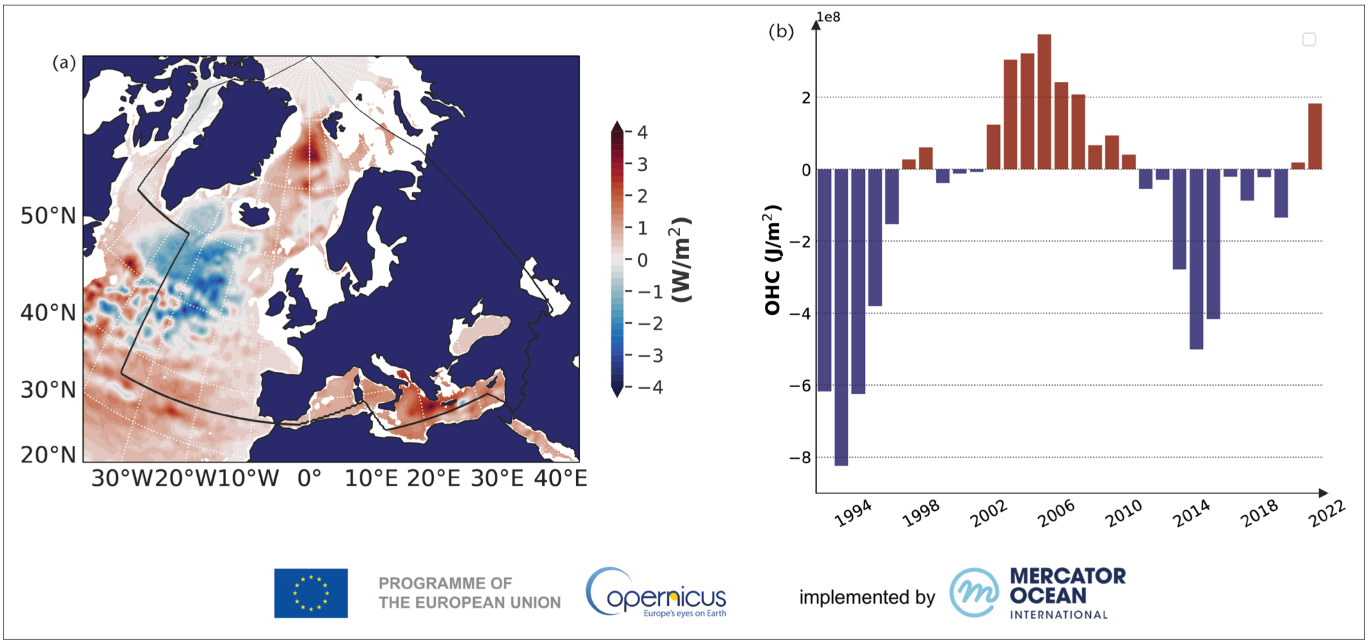


Figure 8. (a) Regional ocean heat content (0–700 m depth) anomalies for 2022 (relative to 2005–2022 climatology). The WMO area for Europe is indicated with a black line. White areas indicate regions where the ocean is shallower than 300 m, which have been excluded in this analysis due to limitations in ocean measurement density. (b) Ocean heat content annual anomalies over the period 1993–2022 (relative to 2005–2022 climatology). *Source:* Copernicus Marine Service/Mercator Ocean International, France, from an observational-based product distributed by the Copernicus Marine Service (https://doi.org/10.48670/moi-00052)

SEA LEVEL

Changes in mean sea level reflect both the thermal expansion of the ocean in response to warming, and the loss of mass from ice sheets and glaciers.[29] Long-term and interannual variations in sea level are observed at global and regional scales. These variations can affect coastal communities, where sea-level variations can be superimposed on the effects of land subsidence and uplift, and can be a hazard in the form of increased risk from coastal inundation for those exposed and vulnerable.[30] Since 1993, global mean sea level has increased at an average rate of 3.4 ± 0.3 mm/year.[31] Regionally, absolute sea-level trends as seen from satellites show spatial variations, with trends from 2–4 mm/year over most of the European seas[32] (Figure 9).[33]

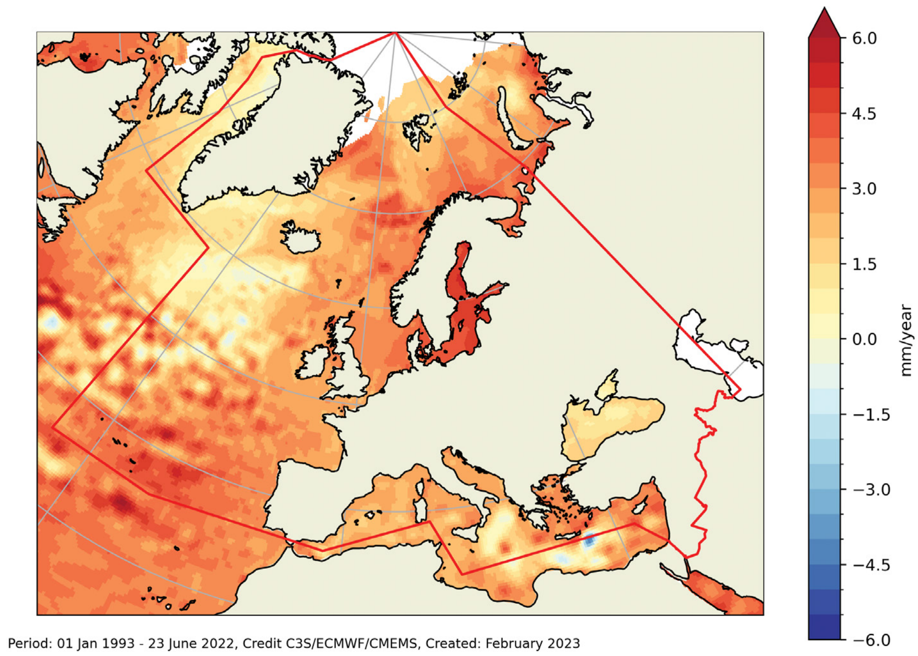


Figure 9. Sea-level trends (mm/year) from satellite altimetry from January 1993 to June 2022. The data have not been adjusted for glacial isostatic adjustment nor for the TOPEX-A instrumental drift. The red line indicates the WMO Region VI – Europe.
Source: Copernicus Marine Environment Monitoring Service (CMEMS) Ocean Monitoring Indicator, based on the C3S sea-level product

Major atmospheric circulation patterns of the region in 2022

In terms of the regional climate, despite the warming trends over decadal timescales, year-to-year variability does occur in response to certain climate drivers. Throughout most of 2022, the monthly mean temperature averaged over WMO Region VI was warmer than normal. The North Atlantic Oscillation (NAO), which describes changes in the strength of two recurring pressure patterns in the atmosphere over the North Atlantic, has a key role in climate variability in the Europe region.

The NAO was positive from the start of the year well into March, contributing to the warm start of the year for much of Europe and the warm spell in northern Europe in March (see Figure 10, monthly NAO index in 2022). The associated strong jet brought some of the named storms in February, and a blocking situation which occurred in spring 2022 was associated with a cold snap in April.

During summer, consistent with a positive NAO index, a band of high pressure, extending over the central North Atlantic, western Europe and north-eastern Europe, contributed to record-breaking temperatures and dry conditions across these regions. The prolonged periods of anticyclonic conditions, and the persistent lack of precipitation in large areas of Europe from winter to summer, enhanced the occurrence of heatwaves during the summer.

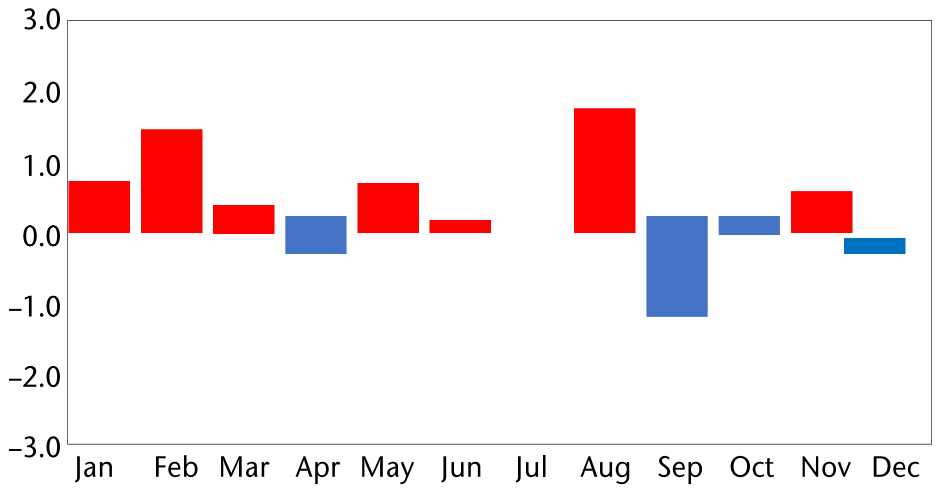


Figure 10. North Atlantic Oscillation (NAO) index monthly mean values, in 2022
Source: Data from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC)

Extreme events and their impacts

OVERVIEW

In the region, 2022 was characterized by several weather-, climate- and water-related extreme events. A selection of some exceptional events is described in the following subsections.

Based on information in the Emergency Events Database (EM-DAT)[34] there were 40 meteorological, hydrological and climate-related hazards in Europe in 2022, which resulted in 16 365 reported fatalities and 156 000 people directly affected (Figure 11). About 67% of the events were flood- and storm-related, leading to dozens of fatalities and accounting for 99.9% of the total economic damages (about US$ 2 billion, which is much less compared to the US$ 50 billion total in 2021 mainly due to the floods in July 2021 in western and central Europe). Much more severe, in terms of mortality, were the heatwaves (13% of all events) for which 16 305 excess deaths were reported, representing 99.6% of all fatalities. Impacts of extreme events in 2022 might have been worse, if not included in the database due to data unavailability.

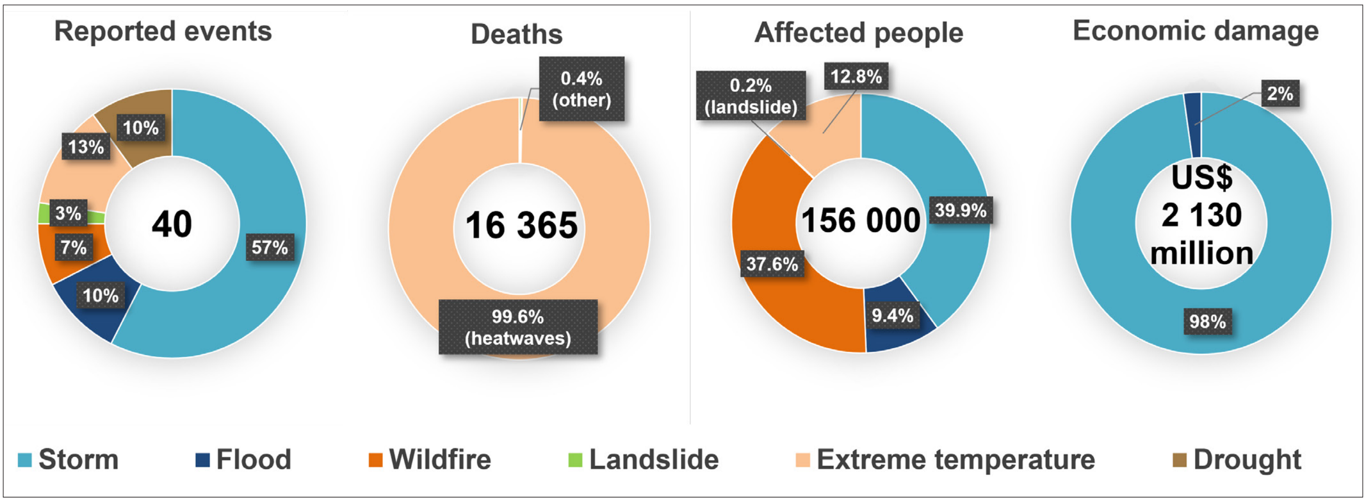


Figure 11. Weather-, climate- and water-related extreme events in Europe during 2022. Note: Impact numbers for some disaster occurrences may be lacking due to data unavailability. Some transnational events may be reported individually by the affected countries.
Source: Data from EM-DAT

HEAVY PRECIPITATION AND FLOODS

On 11 January, Storm *Diomedes* over the eastern Mediterranean caused heavy rain especially in Greece, and in particular the eastern region of Thessaly, the Sporades islands and neighbouring prefectures of Macedonia. The National Observatory of Athens meteorological station in the village of Portaria recorded more than 340 mm of rainfall in a period of 16 hours, a value that approaches the annual rainfall total of Athens (378 mm at Thissio station near the centre of Athens). Two people died in floods in the Central Macedonia region, while another fatality occurred in Karditsa city in the Thessaly region.

A number of locations around southern Europe were affected by heavy rain and flooding during September. In central Italy, torrential rain triggered flooding in the Marche region on 15–16 September. Many areas were left without electricity, telecommunications or drinking water. People took refuge on the roofs of houses and in trees to escape the flooding. Rain totals amounted to 419 mm in 12 hours, the equivalent of four months' worth of average rainfall. Several streams and rivers broke their banks. On 16 September, the Italian Council of Ministers declared a state of emergency for 12 months. In Croatia, at the end of September, a total of 287.5 mm of rain fell in 24 hours in Rijeka (from 0500 UTC on 28 September to 0500 UTC on 29 September). This exceeds the previous highest 24-hour precipitation value recorded at this station in September 2013 (248.9 mm). The rain caused damaging flash floods, with one fatality in Rijeka.

Heavy rain and hail caused severe damage in eastern and central Spain in November. Flooding was reported in the Valencia, Castile and León regions. Valencia airport was closed due to flooding. Totals of 150–300 mm in 48 hours were measured in several places in these regions, including, for example, 208.4 mm at Valencia airport. Several November precipitation records were broken at the airport: the most intense shower (66.1 mm in one hour), daily total precipitation (148.4 mm) and total precipitation for November (211.1 mm).

On 12 December, Storm *Gaia* brought heavy rain of over 200 mm in 24 hours, causing flooding in parts of Antalya province in Türkiye. Finike in Antalya recorded 253.8 mm of rain in 24 hours. The rain caused several streams to overflow, resulting in damaging floods and transport problems. Flooding caused damage to around 500 vehicles, around 100 houses, and over 1 200 hectares of crops and farmland.

DROUGHTS

Drought affected much of Europe throughout the year. Due to the positive winter NAO and blocking conditions, drought prevailed in large regions of south-western Europe in winter (December 2021 to February 2022) (Figure 12(a)). By the end of February, 96% of Portugal was under severe or extreme drought.

In spring, precipitation and soil moisture deficits were affecting very broad areas of Europe, except on the Iberian Peninsula where precipitation led to improved conditions temporarily (Figure 12(b)). The extent of drought conditions reached a peak at the beginning of August. This came after western and central Europe had also recently experienced drought in the summers of 2018, 2019 and 2020.

Low flows were recorded in some of Europe's major rivers. Low water levels on the River Po affected crop production and allowed seawater to intrude almost 40 km inland, affecting river ecosystems. The extremely poor snowfall season also contributed to the critically low levels of the River Po and other rivers. On 4 July, the Italian Government declared a state of emergency for five regions, home to 42% of the Italian population. Insufficient water availability led to a reduction in both hydro- and thermo-electric power production. In some regions, such as Lombardy, the scarcity of precipitation reduced total water reserves (lakes, reservoirs and water equivalent of snow) below the minimum observed in the last 15 years.

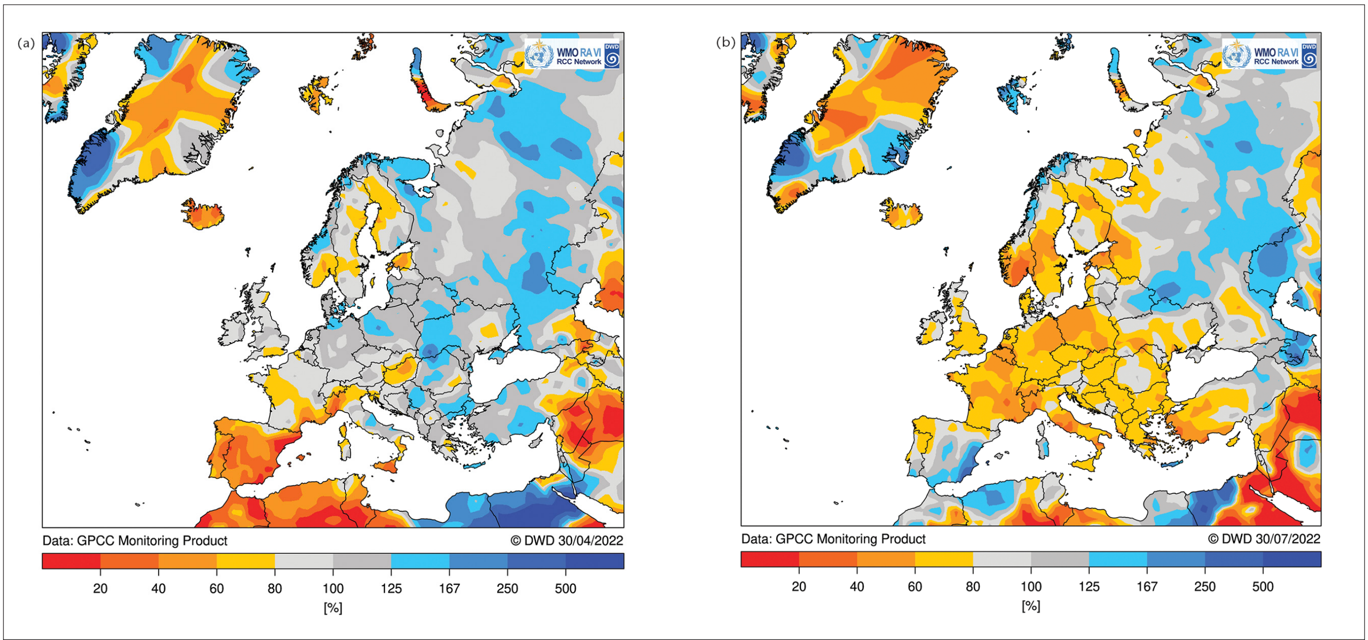


Figure 12. (a) Precipitation (percentage of the 1991–2020 average) for winter 2021/22 and (b) spring 2022
Source: Global Precipitation Climatology Centre (GPCC), DWD, Germany

In mainland France, by mid-August, 71 out of 96 departments were affected by water-use restrictions due to drought alerts. Some areas experienced a total lack of running water. Farmers could no longer irrigate their fields, with serious consequences on agricultural production. France had its driest January to September, and the United Kingdom and Uccle (Belgium) had their driest January to August since 1976.

Both hydro- and thermo-electric power production were reduced due to well below-average precipitation leading to low levels of rivers and water reservoirs. In France, low river flows and high river-water temperatures led to output being reduced at some nuclear power stations.[35]

In Portugal and Spain, the hydrologic year (October 2021 to September 2022) precipitation deficit was reflected in water reservoir levels. The Spanish water reserve decreased to 41.9% of its total capacity by 26 July, with even lower capacity in some basins, such as the Guadalquivir in southern Spain, at 25.6%.

Drought was also extensive in central Europe, with impacts on agriculture. In Germany, harvest was reduced for cereals, and later in summer, for sugar beets, maize and grapes. Several locations on the Rhine River registered new local record low water levels. Three states in west-central Germany had their driest summer on record, in a region which had experienced extreme flooding the previous summer. In Poland, around 64% of the water gauge stations in the national observation network recorded low water levels in rivers. The period from May to mid-August was the second driest in western Switzerland since measurements began in 1864.

The second driest summer, followed by the second warmest autumn led to the formation of dry conditions and water deficit in Armenia, starting from the end of July to September. Towards the end of the year, a severe drought started developing in Türkiye and persisting over the Syrian Arab Republic. The continuing unusually dry conditions led to water deficits. Food prices in the Syrian Arab Republic almost doubled compared to 2021, a situation that was further exacerbated by the conflict in Ukraine. In the Syrian Arab Republic, 13.9 million people (64% of the population) faced food insecurity.[36]

HEATWAVES AND WILDFIRES

Europe experienced several exceptional heatwaves during the summer (Figure 13). The most severe occurred in mid-July, with record-breaking temperatures in many locations. The temperature reached 40 °C in the United Kingdom for the first time, with a reading of 40.3 °C in Coningsby on 19 July, 1.6 °C above the previous national record (38.7 °C at the Cambridge Botanic Gardens on 25 July 2019). In Ireland, 33.0 °C on 18 July at Phoenix Park, County Dublin, was the highest temperature since 1887. Numerous locations broke previous records by more than 3 °C, particularly in northern England and western France. The daily mean Central England Temperature was 2.8 °C above its previous highest value in 250 years of daily data. In Germany, 40.1 °C in Hamburg-Neuwiedenthal on 20 July was the northernmost 40 °C reading on record. The heat extended as far north as Sweden, where 37.2 °C in Målilla on 21 July was the country's highest temperature since 1947. North-east Europe had major heatwaves in mid-August, with records set in Finland, Estonia, Latvia and western Russian Federation, where temperatures reached 31.1 °C in St. Petersburg.

The heat also spread to the east and south. In Slovakia, the daily maximum air temperature on 21 July (40.0 °C) represents the third highest value for July and the fourth highest ever in the history of measurement there. A new monthly record was reached in Slovenia (39.4 °C) on 23 July, and the second hottest day since 1881 occurred in Zagreb in Croatia (39.1 °C). In Portugal, temperatures reached 47.0 °C in Pinhão in July, the highest July temperature recorded in the country. A number of June record high temperatures were set in Italy, including 40.0 °C at the Roma-Urbe station (Rome) on 27 June. On 13 August, numerous records were broken for the highest monthly maximum and minimum temperatures on the Balearic Islands in Spain. For the first time, temperatures at the Ibiza airport station exceeded 40 °C.

Estimated mortality due to heat alone is hard to establish, as mortality rates were also affected by COVID-19. Nevertheless, official estimates place the number of excess deaths at around 4 600 deaths in Spain,[37]

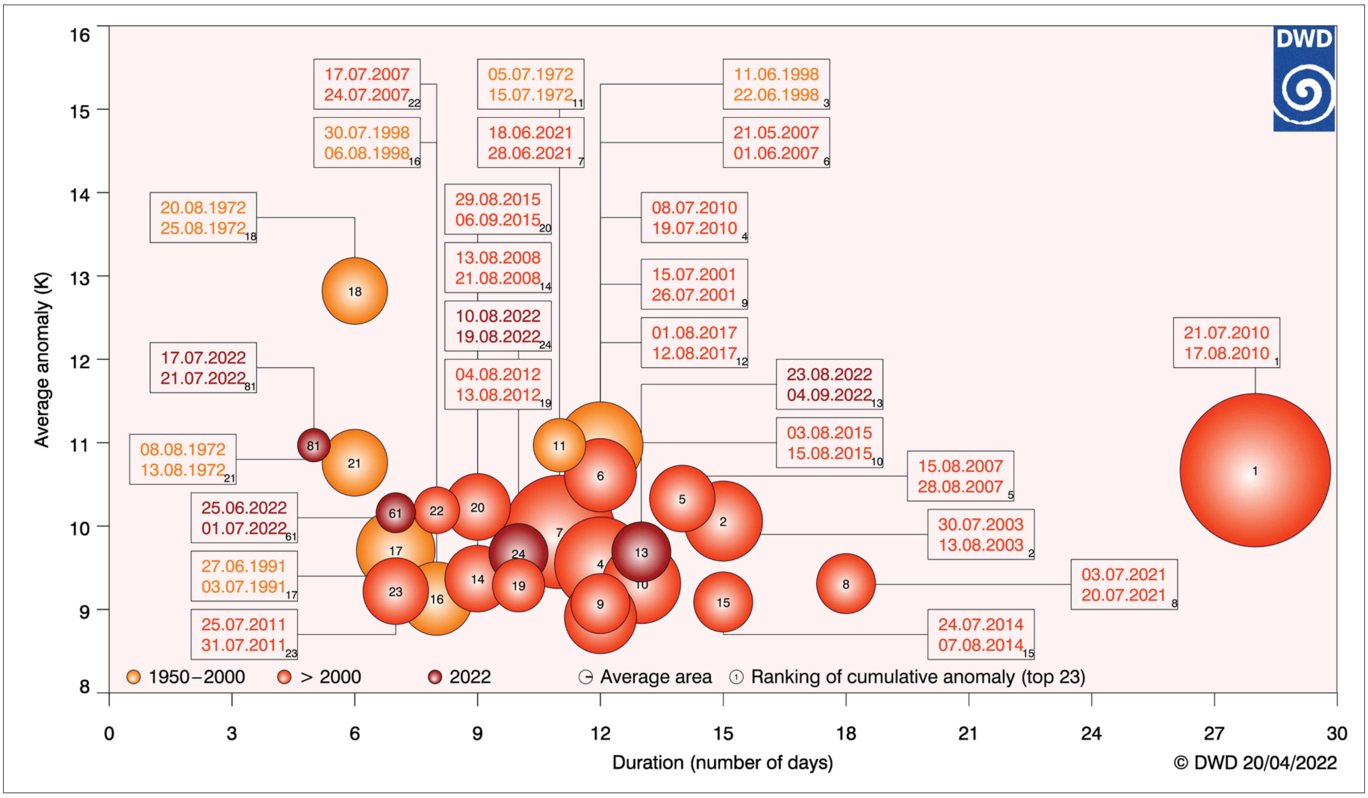


Figure 13. The 23 most severe heatwaves in Europe, 1950–2022, numbered in order of severity from 1–23. Heatwaves in 2022 are coloured dark red. *Source:* DWD: https://www.dwd.de/EN/ourservices/rcccm/int/rcccm_int_hwkltr.html. See also note on methodology here.

4 500 in Germany,[38] 2 800 in the United Kingdom (among those aged 65 years and older),[39] 2 800 in France[40] and 1 000 in Portugal.[41]

Heat and drought conditions fuelled numerous wildfires across the region, resulting in the second largest burnt area on record (after 2017). Large wildfires occurred in France, Spain, Portugal, Slovenia and Czechia, and many other countries also saw larger-than-average burnt areas during 2022. The European Forest Fire Information System (EFFIS) estimated a total burnt area across the EU of more than 800 000 hectares.[42]

Armenia experienced the second warmest autumn since 1935, while the warm spell observed in the second half of November produced record-breaking daily maximum temperatures at more than 10 stations. Temperatures at the stations located above 1 km above sea level reached 22 °C.

MARINE HEATWAVES

A marine heatwave is a relatively long period of unusually high ocean temperatures in a region.[43] Such heatwaves are emerging as pervasive stressors to marine ecosystems globally. Marine heatwaves pose a threat to important ecosystems at the individual, population and community levels, especially to coral reefs and seagrass beds. They can trigger the migration of species and mass extinctions and lead to significant economic losses in fisheries and aquaculture. The frequency, duration and intensity of marine heatwaves are increasing significantly with current anthropogenic global warming.[44]

In 2022, large portions of the region were affected by strong or even severe and extreme marine heatwaves. Some marine heatwave periods lasted approximately 4–5 months, such as in the western Mediterranean Sea, the English Channel, the southern Arctic and the northern Barents and Kara Seas (Figure 14). Other areas affected by severe to extreme marine heatwaves lasting about 1–2 months include the western

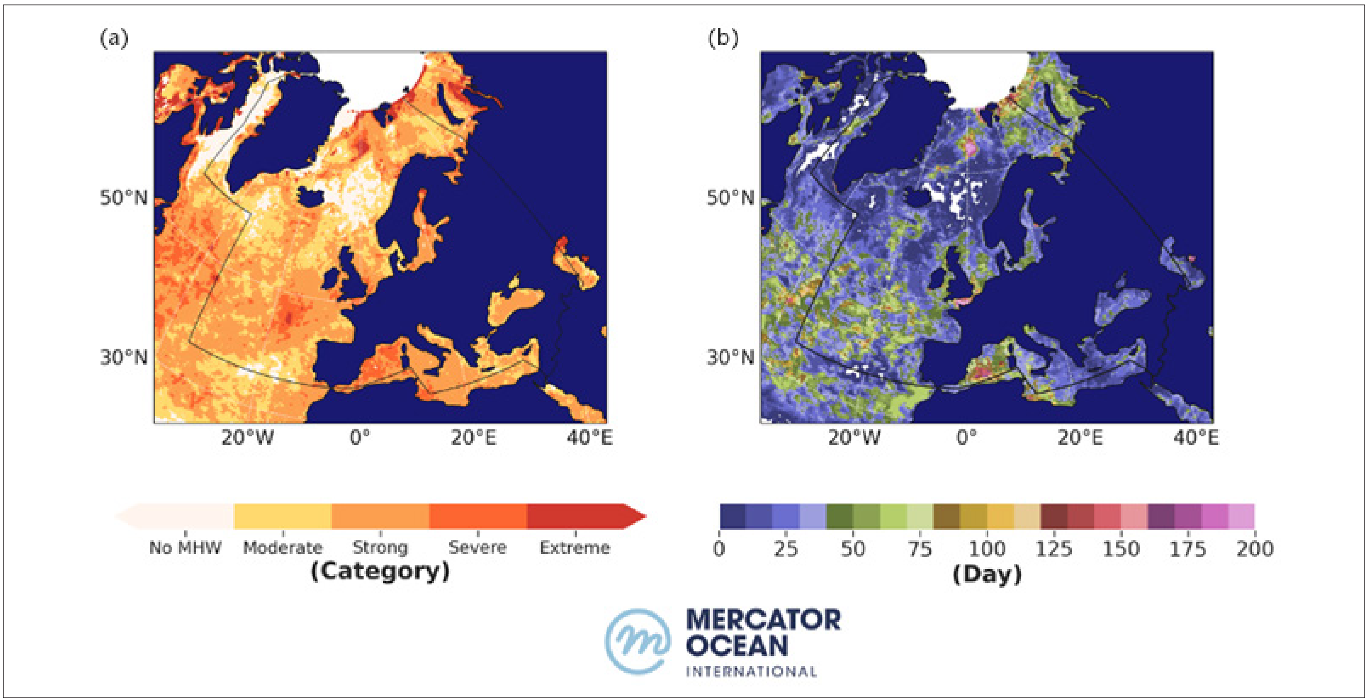


Figure 14. Map showing (a) the highest marine heatwave category (for definitions, see the Marine heatwave and marine cold spell subsection under Data sets and methods) experienced at each pixel in 2022 and (b) the maximum duration of marine heatwaves over the year 2022
Source: Mercator Ocean International, France. Derived from the remote sensing product https://doi.org/10.48670/moi-00168 for 1982–2021, and https://doi.org/10.48670/moi-00165 for 2022, downloaded from the Copernicus Marine Service.

Mediterranean Sea, the Barents and Kara Seas, the south-western Baltic Sea, the North Sea and large parts of the North Atlantic Ocean (including to the south-west of Ireland and the Bay of Biscay area). For example, in the Mediterranean Sea, sea-surface temperature anomalies for summer 2022 (June–August) reached values as high as +4.6 °C locally, exceeding the values of summer 2003, which held the previous record high.[45] The heatwave intensity was highest in the northern parts of the western Mediterranean, decreasing to the south and to the east. In the Ligurian Sea, the maximum intensity of the heatwave was reached on 21 July and continued to be notable into September.

COLD WAVES, HEAVY SNOW AND FREEZING

Although the year 2022 was characterized by numerous warm spells, a few significant cold events and heavy snowfalls occurred.

In south-eastern Türkiye, snowfall and cold temperatures on 18–19 January left vehicles stranded on a major highway, with aid being delivered by helicopters. Such weather conditions are rare for the region, with temperatures of –3 °C recorded in Gaziantep (where the 1991–2020 mean minimum is 0.4 °C), and –34.4 °C in the Özalp district at high elevation. These wintry conditions also affected the north-western Syrian Arab Republic and hundreds of refugee camps along the Turkish border. The temperature in Aleppo dropped to –2 °C, and in Kamishli to –9.8 °C. Many tents were unable to withstand the weight of the snowfall.

A severe winter storm named *Elpida* (or *Elpis*) affected Greece, including the capital Athens, on 24–26 January with temperatures dropping to –14 °C, and heavy snow. Authorities closed schools, public offices and all private businesses in the capital, except supermarkets, pharmacies and gas stations. At least 200 000 homes and businesses in Athens were without power, some of them for several days. While snow is rare in central Athens and on the Aegean islands, this was the second time within 12 months that this region experienced an intense snowstorm and disruption to traffic. The previous occurrence was in February 2021.

Storm *Elpis* also affected Israel, leading to heavy snow. Jerusalem experienced the largest snowfall since 2015, with snow depth reaching 15–25 cm.

For the second consecutive year, widespread frosts in early April resulted in crop losses in western and central Europe. Damage to agriculture was widespread, but less severe than during a similar episode in 2021. The worst affected countries were France, Germany, Spain and Austria, with orchards and vineyards particularly badly affected. The nationally averaged minimum temperature in France dropped to –1.5 °C on 4 April, marking the country's coldest April morning since 1947.

A cold spell also impacted north-west Europe in December, the most significant cold event since December 2010. Iceland recorded its coldest December since 1973, and in the capital, Reykjavik, the coldest December for 100 years.

SEVERE WINDSTORMS

In the last week of January, storms from higher latitudes moved past Scandinavia and continued further to the south-east, passing eastern central Europe. The most powerful of them was Storm *Malik*, which crossed eastern central Europe on 29–30 January. At least six people were killed after the winter storm brought hurricane-force winds to northern and central Europe, causing coastal surges and leaving hundreds of thousands without power. The worst affected were the United Kingdom, Denmark, Poland and Germany, where homes and cars were destroyed, bridges shut, trains cancelled and ferries docked, as coastal surges led to flooding. Gusts of around 110–140 km/h were measured in coastal regions and on islands in the German North Sea and Baltic Sea, and of around 100 km/h between Hamburg and Berlin. The storm also caused damage in Poland and Czechia, with fatalities and widespread power outage. In János Hill, Budapest, wind speeds of 127.4 km/h were recorded, setting a new national record for Hungary (the previous record was observed at Örsöd station, Budapest, in 1979).

From 16–21 February, three successive windstorms passed western Europe and northern central Europe. The most significant of them was Storm *Eunice*, which crossed Ireland, England and Wales on 18 February. A gust of 196 km/h at The Needles (on the Isle of Wight) was the highest on record in England. Four deaths occurred during the storm in the United Kingdom, one death in Ireland and a further two in Belgium, while more than a million households in England and Wales lost power.

An exceptional derecho, a long-lived band of thunderstorms and destructive winds, affected parts of southern and central Europe on 18 August, bringing severe winds and heavy rainfall, on a track which extended 1 600 km from the Balearic Islands (Spain) across Corsica (France), Italy, Slovenia, Austria and Czechia. The system reached its peak severity over Corsica, where wind gusts of 225 km/h were recorded, the strongest reliably observed wind gust on record for metropolitan France. Five deaths were reported. There was also significant damage in Italy, where hail reached 8 cm in diameter.

On 23 October, an EF3 tornado (the third most intense rating for a tornado on the Enhanced Fujita Scale) crossed northern France and caused significant damage. Its path length was 206 km, the longest recorded in France.

Climate policy and climate action in the energy sector

The focus in this year's report – on climate policy and climate action in the energy sector – was chosen because of the importance of this sector for low-carbon energy transitions. This is expanded upon below, followed by an analysis of current efforts to deploy renewable energies, as well as an analysis of the meteorological potential for renewables. The importance of climate services for the energy sector, in particular for solar and wind renewable resources and also for nuclear energy, as well as the growing impacts of extreme weather, are highlighted. This section is supplemented by a sidebar on the use of renewable energy sources for agrifood systems.

LOW-CARBON ENERGY TRANSITIONS

One of the central goals of the Paris Agreement, ratified by 195 parties, is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 °C above pre-industrial levels, and to pursue efforts to limit the temperature increase even further, to 1.5 °C. The IPCC AR6 concluded that in global modelled pathways that limit warming to 1.5 °C (likelihood > 50%) with no or limited overshoot, global CO_2 emissions reach net zero in the early 2050s.46 In view of this, many governments in Europe have committed to pursuing paths to achieve carbon ("climate")-neutrality by 2050–2070, with deep cuts in energy sector emissions, and remaining emissions compensated by carbon capture and increasing sinks in the land-use sector. Energy systems need to integrate low- and zero-carbon technologies through interplay of different technologies. The interconnection between technology and sustainable energy sources, like wind and solar, highlights the importance of technology interacting alongside innovation, research and global collaboration to attain carbon neutrality by 2050.

Transitioning to a low-carbon energy system requires deploying clean energy technologies and infrastructure. This includes integrating renewable energy sources and energy storage technologies and enhancing grid infrastructure while ensuring energy affordability and security. To achieve carbon neutrality, action is needed to maximize the use of these technologies. Thus, efforts are needed towards identifying the right technology interplay by raising awareness, developing policy frameworks and financing a just transition towards carbon-neutral energy systems.

RENEWABLE ENERGIES – COMMITMENT

The EU has agreed to raise the binding renewable energy target from 32% to at least 42.5% by 2030, which will represent almost a doubling from 2019 levels.[47] In addition, other European parties to the Paris Agreement have included renewable energy targets in their Nationally Determined Contributions (NDCs). For example, Albania is committed to reaching 42% of renewable energy in final energy consumption by 2030.

There is still a long way to go to achieve these goals. In 2019, in Europe the global share of renewable energy sources amounted to 14.3% of the total final energy consumption (Figure 15). In 2022, in Europe wind and solar generated 22.3% of EU electricity, for the first time overtaking fossil gas (20%), and coal power (16%).[48] This was due to a combination of factors, including a significant increase in solar power capacity installed in 2022. Additionally, the annual surface solar radiation recorded in Europe in 2022 was the highest ever recorded since 1983 (beginning of the satellite data record), 4.9% above the average for the 1991–2020 reference period.[49,50]

RENEWABLE ENERGY POTENTIAL

The production of emission-free energy from solar, wind and hydropower is becoming increasingly important. Therefore, the analysis of the associated meteorological variables – surface solar radiation, wind speed and precipitation – are also of increasing interest.

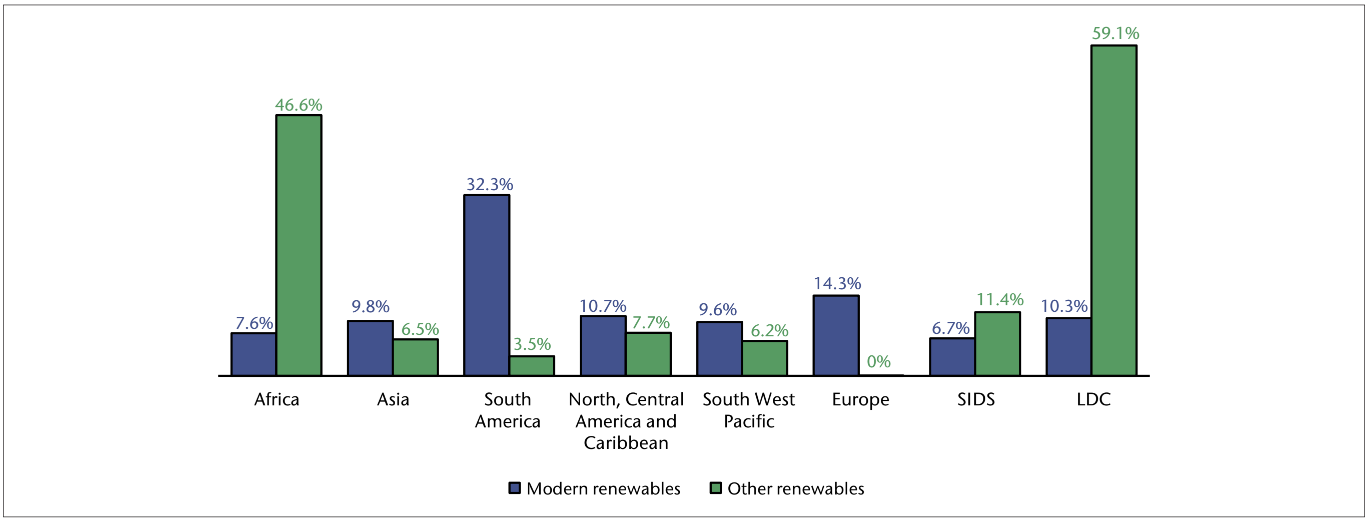


Figure 15. Percentage share of modern renewable energy systems and other renewable systems in 2019, by region
Source: Data on Sustainable Development Goal (SDG) 7.2 – Renewable energy are sourced from the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) and the United Nations Statistics Division (UNSD) and analysed by WMO to fit its regional classification.

Figure 16 shows the long-term average potentials for photovoltaic (PV), wind and hydropower.[51,52,53] Generally, more surface solar radiation is available in the south of Europe due to the solar angle and reduced cloud coverage. Wind power potential is generally higher over the ocean, especially off the coast of Ireland and Portugal. In addition, the Aegean Sea has higher wind speeds, which might be interesting for new wind power plant installations. Hydropower is directly linked to the topography of Europe.

As these renewable energy sources are intermittent in nature, it is important to also look at their variability, which is very different for the three meteorological variables that drive the potential for these energy sources. This is highlighted by the monthly means of wind speed (–40% to +80%) and precipitation (±30%), which are much more variable, compared to the long-term average, than surface solar radiation (about ±15%).[54] Solar and wind tend to complement each other throughout the year: solar radiation is higher in late spring and summer while wind intensity is usually higher in winter. Monitoring and understanding the temporal and spatial variability of these two important renewable energy resources is increasingly important due to their growing importance for the European energy mix.

Over the 30-year period 1991–2020, surface solar radiation shows a clear positive trend for Europe, whereas wind speed and precipitation do not show a significant trend.[55] Over the last five years, a continuous increase in surface irradiance was recorded, whereas less precipitation can be noticed for the same time period, with emerging consequences for hydropower production in some regions.

CLIMATE SERVICES FOR THE ENERGY SECTOR

Climate variability from months to seasons to years, and long-term climate change are impacting every aspect of the energy sector: the volume of and ways in which energy is consumed ("demand"); the productivity of each energy-generating technology ("supply"); and the combined physical and non-physical infrastructure that ensures safe and reliable operations ("the grid"). An inability to consider the full array of zero carbon-emitting and climate resilient energy technology options could thwart the world's ability to reach net zero while maintaining the security of energy supply. The energy sector decision-making, regulations, plant designs and operating practices must all be adapted to a climate volatile future.

Climate services – the provision and use of climate information in decision-making, encompassing data collection, monitoring, analysis, predictions and projections of climate variables – play a key role supporting global energy transition to achieve net zero. Climate services are essential for renewable energy, including

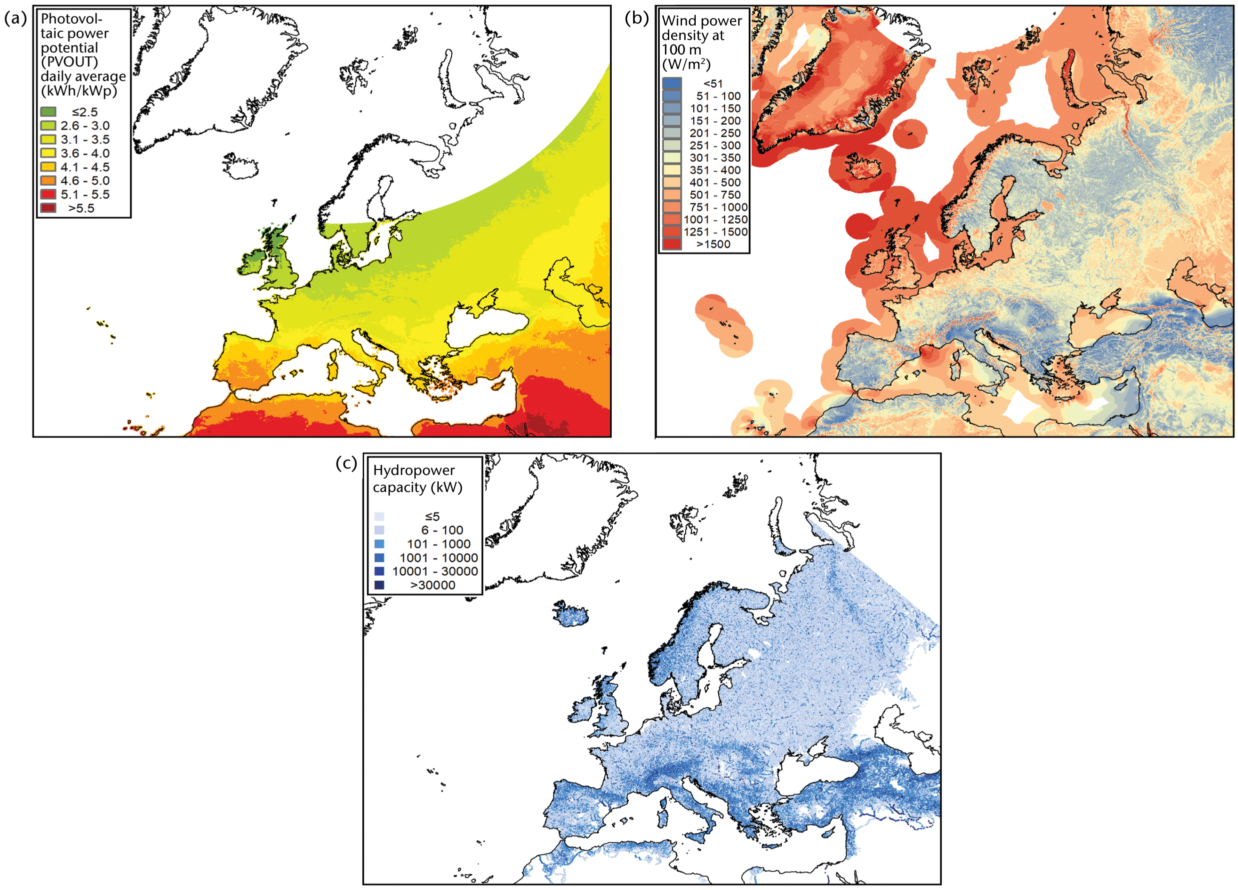


Figure 16. (a) Long-term average daily sum of electricity production from a 1 kW peak grid-connected solar PV power plant for the period 1994–2018; (b) An estimate of mean wind power density at 100 m above surface level globally for the period 1998–2017; (c) An estimate of potential hydropower (hydropower capacity)
Source: (a) Global Solar Atlas 2.0; (b) Global Wind Atlas, v.3; (c) Global Potential Hydropower Locations Research Dataset

for: site selection, resource assessment and financing; operations, maintenance, and management of energy systems; electricity integration into the grid; and impact assessment of energy systems.

Furthermore, climate services are needed to ensure the resilience of energy systems to climate-related shocks, and to inform measures to increase energy efficiency. Risk assessments addressing planning for and early warning of extreme events affecting energy supply and demand can help the industry to anticipate, absorb, accommodate, and recover from adverse impacts.

According to a survey of National Meteorological and Hydrological Services (NMHSs) conducted by the WMO, 83% of Members in Europe reported providing climate services for energy. Only less than half of Members provide climate predictions for the energy sector (Figure 17), bringing to light the untapped potential of NMHSs in supporting energy transition, as well as the efforts required to ensure a greater resilience of the energy sector.

NUCLEAR ENERGY

Increasingly frequent extreme weather conditions and rapidly growing shares of renewable energy generation place a growing premium on climate-resilient energy sources. A diverse and resilient energy foundation from decarbonized energy sources like nuclear, hydropower, geothermal and others will play an important role in accommodating renewables and successfully decarbonizing global energy systems.

Globally, interruptions to nuclear power operations due to adverse climatic conditions have increased over the past three decades, with the steepest inclines seen between 2003–2006, and again from 2010–2018 but remain a small fraction of the overall output from nuclear power stations worldwide. Climate-related energy losses make up a very small but growing share of total nuclear outages over time. In 2022, reported weather-related production losses accounted for approximately 0.35% of global nuclear energy generation, up from 0.29% five years earlier. Nearly 60% of reported weather-related nuclear production losses since 2017 were associated with plants located by rivers or lakes. Low river flows, but mainly the increasing temperatures and hot extremes are the largest contributors to climate-linked full outages in western Europe.

Novel analysis pairing localized climate projections by the IPCC and nuclear site locations show that under worsening climate scenarios in the long-term, southern Europe could see some of the largest global percentage increases in extreme temperatures above 40 °C and in number of consecutive dry days. This result, particularly for potential nuclear plant sites in southern Europe, underscores the necessity of establishing adaptation provisions associated with strict safety revisions, if the decision is taken that plants should continue to operate. It is worth noting that of the 100 GW of nuclear capacity currently under construction or planned by IAEA Member States, more than 60% are located on the seacoast, so less affected by cooling water issues.

IMPACT OF EXTREME WEATHER ON THE ENERGY SECTOR

Ever more frequent and destructive weather conditions have growing implications for the supply, demand and infrastructure of the world's energy system. Extreme heat, heavy precipitation, droughts, coastal and river floods and tropical cyclones will make the design and the implementation of climate resilience plans for the global energy system even more complex, but all the more necessary. On the demand side, climate impact data and scenarios will help operators adjust their system monitoring to meet new demand patterns altered by a changing climate. Seasonal and sub-seasonal forecasts can help to identify (with different levels of confidence) anomalous climate patterns and conditions associated with the potential development of extreme climate events, such as heatwaves and droughts, thereby supporting decision-making in advance and contributing to ensure the continuity of grid services. In terms of supply, climate and energy system modelling is increasingly necessary for plant and grid operators, with information needed at specific localities and over diverse time horizons in order to consider the changing climate risks.

A system-level approach is paramount, including the improvement of effective risk management measures involving a wide array of stakeholders to ensure a heightened level of coordination.

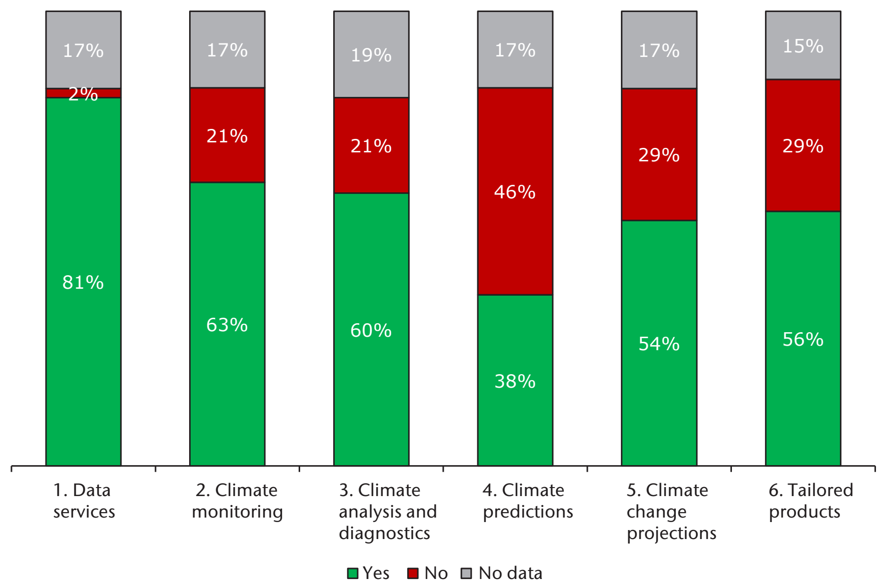


Figure 17. Percentage of European NMHSs providing climate services to the energy sector, by type of product

Use of renewable energy sources for agrifood systems[56]

Energy is essential for food security and development. Finding green and resilient solutions that can support sustainable agrifood system transformation and its innovation is an important goal. However, there is a big challenge: to disconnect fossil fuel use from food system transformation without hampering food security.

Renewable energy can play a critical role in meeting needs for electricity, not only in primary production, but also in secondary activities, such as drying, cooling, storage, transport and distribution of food. Various renewable energy applications being deployed along agrifood chains are demonstrating the benefits of such solutions. As an example, solar irrigation is being widely adopted to improve access to water. Life-cycle emissions for solar-powered water pumping are estimated to be 95% to 98% lower than for pumps powered by grid electricity or diesel fuel.

In Europe, over the past two decades, energy consumption in agriculture has remained stable, even as production has grown, thanks to increased efficiencies and agronomic progress (Figure 18). Between 2000 and 2012, energy intensity in agriculture fell by 20% (increase of energy efficiency). At the same time, continuing to meet energy needs through fossil fuels poses significant problems in terms of accessibility, affordability, resilience to supply and price shocks, and environmental effects, particularly climate change.

The agrifood sector is one of the contributors to greenhouse gas emissions, which will need to be strongly reduced along the agrifood chain. Mitigation strategies additionally rely on energy efficiency improvements. In Europe, significant opportunities to improve energy efficiency can be found in production activities. Beyond mitigation, integration of renewables in agrifood systems also strengthens adaptation, adding resilience to the extreme weather events and resource shortages caused by climate change.

Scaling-up the use of renewable energy in agrifood systems will require concerted efforts between government, the private sector, financing institutions, academia, and international and non-governmental organizations. Governments will continue to play a crucial role through public financing to facilitate deployment, and by investing in an enabling ecosystem that promotes technological innovation; sets standards and ensures quality; imparts knowledge and skills; raises awareness among stakeholders and the public; and builds infrastructure for market access. When effectively designed and implemented, use of renewable energy in agrifood systems has the potential to contribute to multiple Sustainable Development Goals.

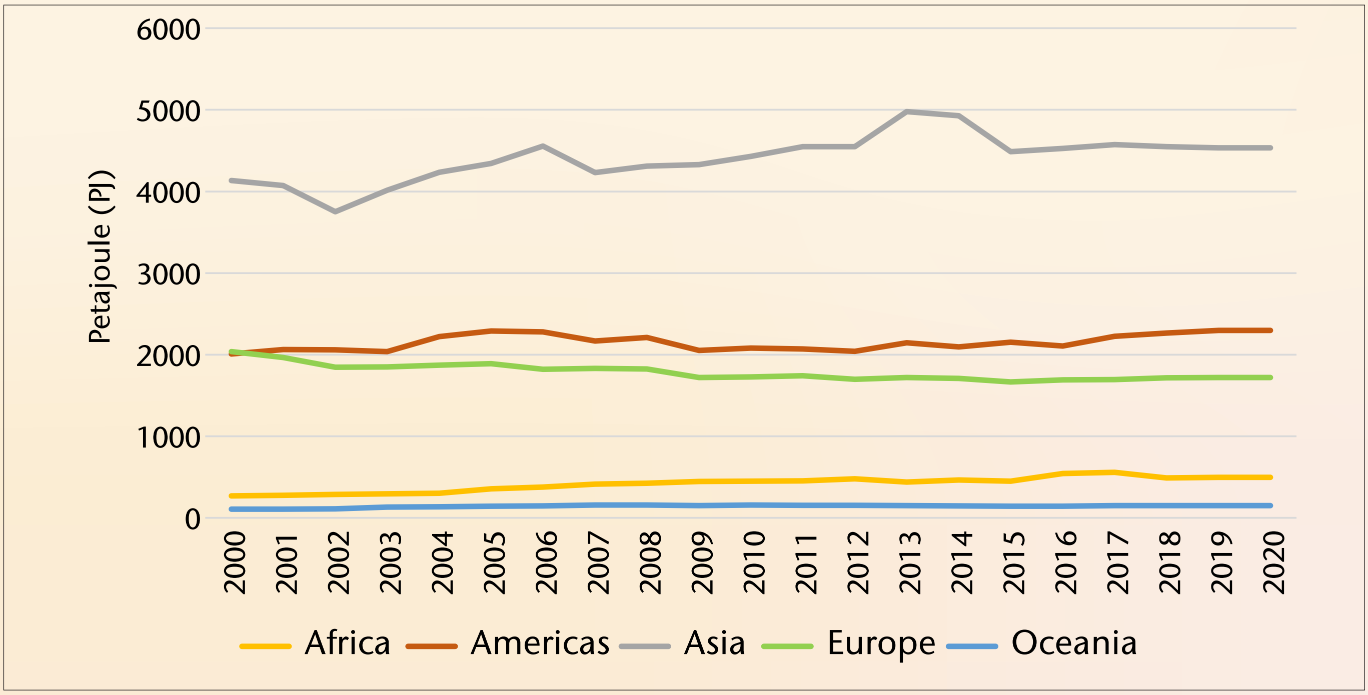


Figure 18. On-farm energy used (energy consumption) in agrifood systems, by region, 2000–2020
Source: Data from the Food and Agriculture Organization Corporate Statistical Database, FAOSTAT

Observational basis for climate monitoring

Climate monitoring is performed by a network of observing systems covering the atmosphere, the ocean, hydrology, the cryosphere and the biosphere. Each of these areas is monitored in different ways by a range of organizations. Cutting across all these areas, satellite observations provide major contributions to global climate monitoring.

In 1992, the Global Climate Observing System (GCOS) was established by WMO, the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Science Council (ISC) to coordinate and facilitate the development and improvement of global climate observations. GCOS has identified a set of Essential Climate Variables (ECVs) that together provide the information necessary to understand, model and predict the trajectory of the climate as well as plan mitigation and adaptation strategies (Figure 19). The status of the observational basis for these ECVs is published in regular status reports. GCOS also identifies in implementation reports what is needed to improve the system.

In 2022, GCOS released its latest Implementation Plan[57] in response to the findings of the 2021 GCOS Status Report, to the implications arising from the IPCC Sixth Assessment Report and to recent scientific studies on the climate cycles. The publication provides recommendations for a sustained and fit for purpose Global Climate Observing System.

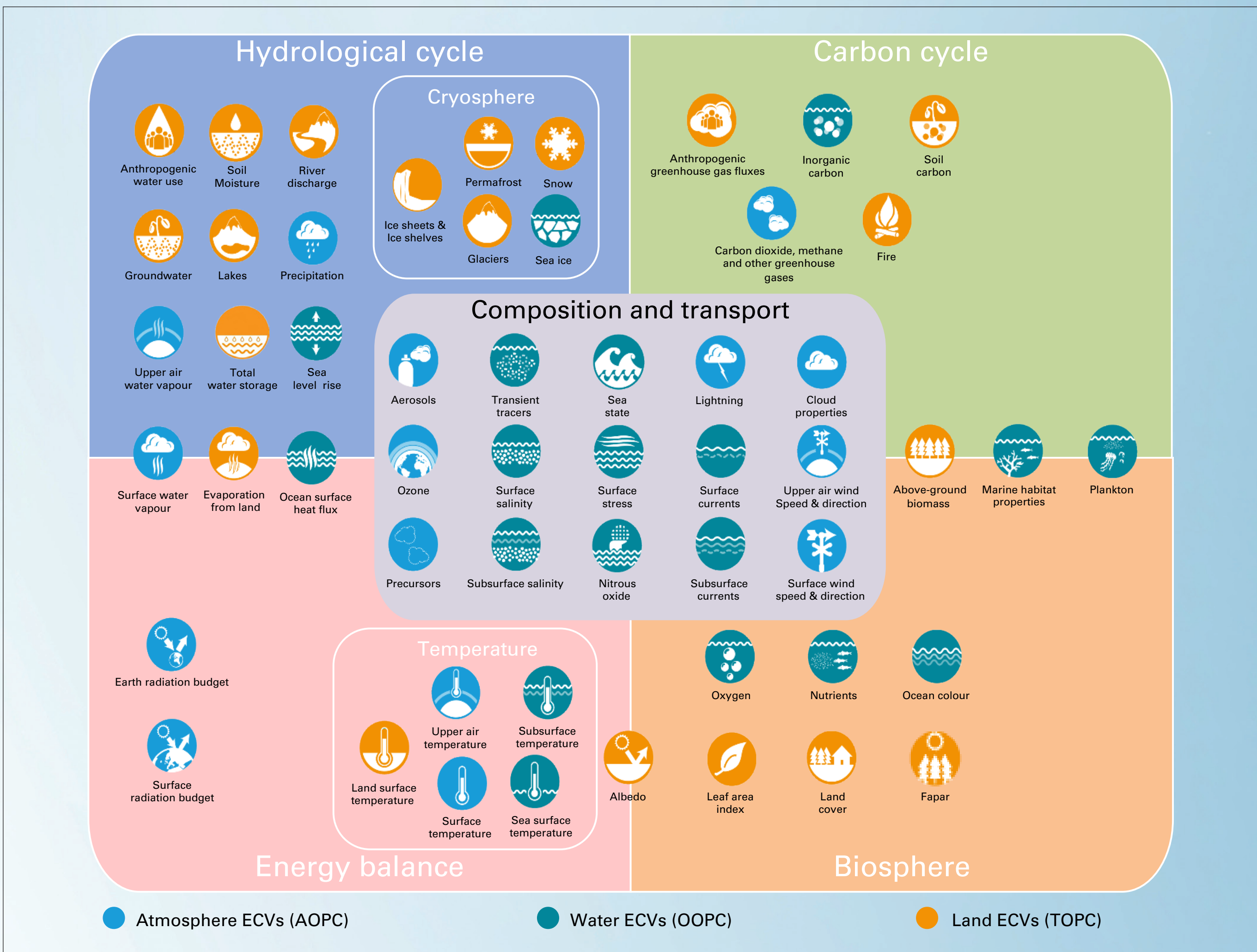


Figure 19. ECVs identified by GCOS and the climate cycles. Many ECVs contribute to understanding several different cycles –this figure only indicates the main links.

In addition to observations provided by the GCOS-coordinated Global Surface Network (GSN) and Global Upper-Air Network (GUAN), National Meteorological and Hydrological Services (NMHSs) of WMO Members provide a more comprehensive and widespread network of observations, acquired primarily for operational weather prediction. The WMO Global Basic Observing Network (GBON), a globally designed network with prescribed capabilities and observing schedules, and for which international data exchange is mandatory, will provide critically needed observations for numerical weather prediction and will help substantially strengthen climate reanalysis.

In order to provide the necessary financial and technical assistance for the implementation and operation of GBON in the poorest and most poorly observed areas of the globe, WMO, the United Nations Development Programme (UNDP) and UNEP have established the Systematic Observations Financing Facility (SOFF). SOFF has raised significant funds for supporting observations in least developed countries and small island developing States and commenced its implementation phase in 2023.

Complementing the observations of the physical and dynamic properties of the atmosphere, the WMO Global Atmospheric Watch (GAW) coordinates atmospheric composition measurements, ensuring that reliable and accurate data are obtained from measurements made by WMO Members, research institutions and/or agencies and other contributing networks.

Observations of ocean physics, biogeochemistry, biology and ecosystems are coordinated through the Global Ocean Observing System (GOOS). The GOOS Observations Coordination Group (OCG) monitors the performance of these observations[58] and produces an annual Ocean Observing System Report Card. Ocean observations are generally made widely available to international users.

In the terrestrial domain, there is a wider group of observing networks. Hydrological observations are generally operated by NMHSs and coordinated through WMO. A number of specialized Global Terrestrial Networks (GTNs), for example, on hydrology (including lakes and rivers), permafrost, glaciers, land use, and biomass, also contribute to GCOS. Data exchange agreements are generally less developed for the terrestrial networks, and many important observations are not made available to international users.

The Committee on Earth Observation Satellites/Coordination Group for Meteorological Satellites (CEOS/CGMS) Joint Working Group on Climate (WGClimate) bases the development of satellite observations for climate on the ECV requirements established by GCOS. It has produced an ECV Inventory that includes records for 766 climate data records for 33 ECVs covering 72 separate ECV products, with more planned. WGClimate is also working on actions arising from the Implementation Plan. Satellite observations have near-global coverage. Used with ground-based observations, either as complementary data sets, or for validation and calibration, they form an invaluable part of the global observing system.

Data sets and methods

REGION DOMAIN

The focus of this report is WMO Region VI, the extent of which can be seen on the map in Figure20.[59,60]

Where possible, numbers for Europe refer to this region; however, in some cases aggregated data refer to other similar but slightly different regions, such as the European Union,[61] World Health Organization (WHO) European Region[62] or United Nations Economic Commission for Europe (UNECE) region.[63] Where this is the case, the region name is explicitly mentioned.

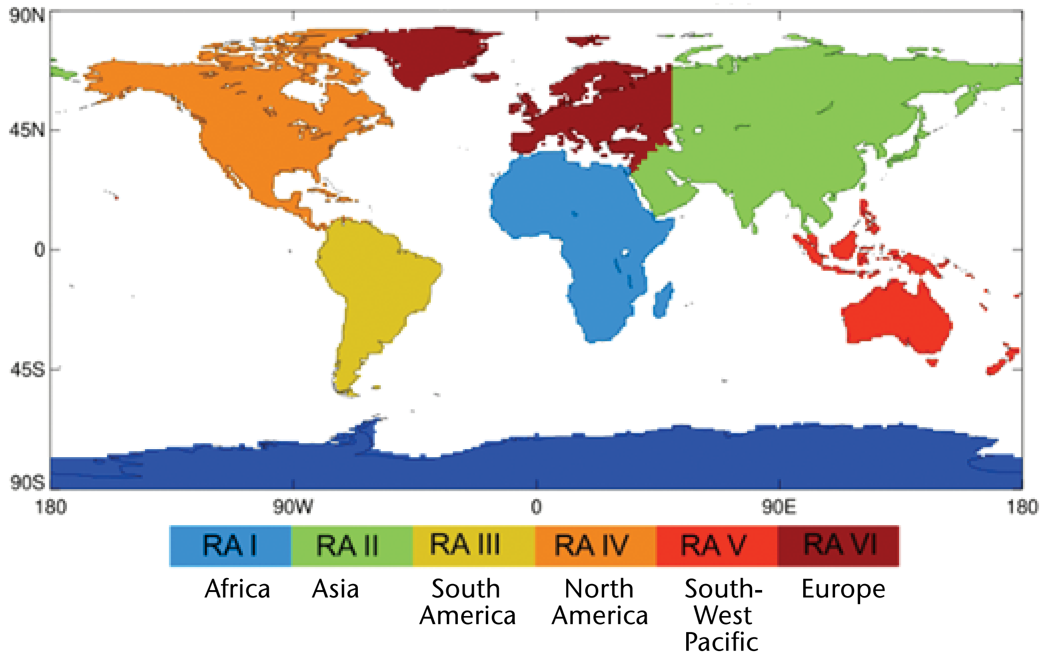


Figure 20. Map of WMO Regional Association (RA) areas. WMO Region VI is the focus of the present report.

TEMPERATURE

Six data sets (cited below) were used in the calculation of regional temperature. Regional mean temperature anomalies were calculated relative to 1961–1990 and 1991–2020 baselines using the following steps:

1. Read the gridded data set;

2. Regrid the data to 1° latitude × 1° longitude resolution. If the gridded data are higher resolution, then take a mean of grid boxes within each 1° × 1° grid box. If the gridded data are lower resolution, then copy the low-resolution grid box value into each 1° × 1° grid box that falls inside the low-resolution grid box;

3. For each month, calculate the regional area average using only those 1° × 1° grid boxes whose centres fall over land within the region;

4. For each year take the mean of the monthly area averages to get an annual area average;

5. Calculate the mean of the annual area averages over the periods 1961–1990 and 1991–2020;

6. Subtract the 30-year period average from each year to get anomalies relative to that base period.

The following six data sets were used:

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 data are available here.

ERA5 – Hersbach, H.; Bell, B.; Berrisford, P. et al. The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society* **2020**, *146* (730), 1999–2049. https://doi.org/10.1002/qj.3803. The data are available here.

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* (12), 6307–6326. https://doi.org/10.1029/2018JD029522. The data are available here.

HadCRUT.5.0.1.0 – Morice, C. P.; Kennedy, J. J.; Rayner, N. A. et al. An Updated Assessment of Near-Surface Temperature Change From 1850: The HadCRUT5 Data Set. *Journal of Geophysical Research: Atmospheres* **2021**, *126* (3). https://doi.org/10.1029/2019JD032361. The data are available here.

JRA55 – Kobayashi, S.; Ota, Y.; Harada, Y. et al. The JRA55 Reanalysis: General Specifications and Basic Characteristics. *Journal of the Meteorological Society of Japan*. Ser. II **2015**, *93* (1), 5–48. https://doi.org/10.2151/jmsj.2015-001, https://www.jstage.jst.go.jp/article/jmsj/93/1/93_2015-001/_article. The data are available here.

NOAAGlobalTemp v5 – Zhang, H-M.; Huang, B.; Lawrimore, J. et al. NOAA Global Surface Temperature Dataset (NOAAGlobalTemp), Version 5.0. *NOAA National Centers for Environmental Information*. doi: 10.25921/9qth-2p70. Huang, B.; Menne, M. J.; Boyer, T. et al. Uncertainty Estimates for Sea Surface Temperature and Land Surface Air Temperature in NOAAGlobalTemp Version 5. *Journal of Climate* **2020**, *33* (4), 1351–1379. https://journals.ametsoc.org/view/journals/clim/33/4/jcli-d-19-0395.1.xml. The data are available here.

Temperature in situ data from National Meteorological and Hydrological Services were also used.

PRECIPITATION

GPCC: see https://gpcc.dwd.de for a description of the GPCC data sets

ERA5 – Hersbach, H.; Bell, B.; Berrisford, P. et al. The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society* **2020**, *146* (730), 1999–2049. https://doi.org/10.1002/qj.3803. The data are available here.

Precipitation in situ data from National Meteorological and Hydrological Services were also used.

Note: In Figure 3(a), Iceland is shown as being drier than the long-term average. In fact, it was wetter than average in Iceland during the year (see the annual report from Iceland: https://www.vedur.is/um-vi/frettir/tidarfar-arsins-2022). The discrepancy is likely due to a change in the way that real-time data are processed.

GLACIERS

The cumulative mass balance estimates considered here are based on long-term in situ observations, which are compiled by the World Glacier Monitoring Service (WGMS) in annual calls for data from a scientific collaboration network across more than 40 countries worldwide. The estimates given here are from a subset of global and European reference glaciers (WGMS 2021, updated and earlier reports).

GREENLAND ICE SHEET

The Greenland Ice Sheet time series of mass change is compiled from 27 satellite-based estimates of ice sheet mass balance as part of the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) (http://imbie.org/) and is freely available at https://data.bas.ac.uk/metadata.php?id=GB/NERC/BAS/PDC/01477.

SEA-SURFACE TEMPERATURE

Four gridded data sets for sea-surface temperature (SST) were used:

ERSSTv5: Data and documentation

ESA CCI/C3S SST Climate Data Record v2.1: Data and documentation

HadISST1: Data and documentation

HadSST.4.0.1.0: Data and documentation

Graphics and information for SST of the European regional seas can be found at https://climate.copernicus.eu/climate-indicators/sea-surface-temperature.

SEA ICE

The sea ice section uses sea-ice extent time series derived from the EUMETSAT OSI SAF Global Sea Ice Concentration Climate Data Record (CDR) and Interim CDR v3.0 (OSI-450-a and OSI-430-a), as well as winter maximum sea-ice extent data for the Baltic Sea from the Finnish Meteorological Institute: https://www.eea.europa.eu/data-and-maps/figures/maximum-extent-of-ice-cover-2. Sea-ice extent is calculated as the area of ocean grid cells where the sea-ice concentration exceeds 15%.

Baltic sea-ice winter description is available at: https://www.bsis-ice.de/Beschreibung_Eiswinter2022/Eiswinter2022en.html

OCEAN HEAT CONTENT

CMEMS Ocean Monitoring Indicator based on the C3S sea-level product:

https://climate.copernicus.eu/climate-indicators/about-data#Sealevelindicator and

https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/global-ocean-mean-sea-level-trend-map-observations

SEA LEVEL

CMEMS Ocean Monitoring Indicator based on the C3S sea-level product:

https://climate.copernicus.eu/climate-indicators/about-data#Sealevelindicator and

https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/global-ocean-mean-sea-level-trend-map-observations

MARINE HEATWAVE AND MARINE COLD SPELL

Marine heatwaves (MHWs) are categorized as moderate when the sea-surface temperature (SST) is above the 90th 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 90th percentile and the climatological distribution average (Hobday et al., 2018). Marine cold spell (MCS) categories are analogous, but are categorized with reference to sea-surface temperatures below the 10th percentile. The baseline period used for MHWs and MCSs is 1982–2011.

Hobday, A. J.; Oliver, E. C. J.; Sen Gupta, A. et al. Categorizing and Naming Marine Heatwaves. *Oceanography* **2018**, *31* (2), 162–173. https://doi.org/10.5670/oceanog.2018.205.

NOAA OISST v2: Optimum Interpolation Sea Surface Temperature (OISST): Banzon, V.; Smith, T. M.; Chin, T. M. et al. A Long-term Record of Blended Satellite and in situ Sea-surface Temperature for Climate Monitoring, Modeling and Environmental Studies. *Earth System Science Data* **2016**, *8* (1), 165–176. https://doi.org/10.5194/essd-8-165-2016.

NORTH ATLANTIC OSCILLATION (NAO)

http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml

DROUGHT

GPCC data (https://gpcc.dwd.de and https://www.dwd.de/EN/ourservices/rcccm/int/rcccm_int_spi.html), in situ data from National Meteorological and Hydrological Services, and information from WMO RA VI Regional Climate Centre (RCC)-Network Offenbach Node on Climate Monitoring (RCC Node-CM) (https://www.dwd.de/EN/ourservices/rcccm/int/rcccm_int_sse.html)

WILDFIRES

Information from RA VI RCC Node-CM: https://www.dwd.de/EN/ourservices/rcccm/int/rcccm_int_sse.html

EFFIS burned area index for Europe: https://effis.jrc.ec.europa.eu/apps/effis.statistics/estimates/EU/2021/2006/2020

COLDS SPELLS AND SNOW

In situ data from National Meteorological and Hydrological Services were used.

SEVERE STORMS WITH STRONG WINDS

Wind in situ data from National Meteorological and Hydrological Services were used.

EM-DAT DATA

EM-DAT data were used for historical climate impact calculations: http://www.emdat.be). EM-DAT is a global database on natural and technological disasters, containing essential core data on the occurrence and effects of more than 21 000 disasters around the world, from 1900 to present. EM-DAT is maintained by the Centre for Research on the Epidemiology of Disasters (CRED) at the School of Public Health of the Université catholique de Louvain located in Brussels, Belgium.

The indicators used for mortality, number of people affected, and economic damage are total deaths, number affected and total damages ('000 US$), respectively.

CLIMATE SERVICES

The WMO RA VI Regional Climate Centre (RCC) Network provides data, climate monitoring and long-range forecasting services to WMO Members in the region. Access to the services is via https://www.rccra6.org.

The Copernicus Climate Change Service (C3S) provides data and climate monitoring for Europe, the Arctic and the globe. Key monitoring products include the monthly Climate Bulletin and the annual European State of the Climate report.

2022 State of Climate Services: Energy (WMONo. 1301)

WMO analysis of NDCs, based on the WMO analysis of parties' NDCs and further complemented by the United Nations Framework Convention on Climate Change (UNFCCC) synthesis report: UNFCCC. *Nationally Determined Contributions (NDC) under the Paris Agreement: Synthesis Report by the Secretariat*; UNFCCC: Glascow, 2021.

Checklist for Climate Services Implementation (Members' climate services capacity, based on responses to this Checklist, can be viewed here under the tab "Services")

List of contributors

MEMBERS' NATIONAL METEOROLOGICAL AND HYDROLOGICAL SERVICES

Andorra, Armenia, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Ireland, Israel, Italy, Jordan, Kazakhstan, Latvia, Lithuania, Luxembourg, Malta, Netherlands (Kingdom of the), North Macedonia, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Syrian Arab Republic, Türkiye, Ukraine, United Kingdom.

ORGANIZATIONS

Administration des services techniques de l'agriculture (ASTA), Luxembourg; Bundesamt für Seeschifffahrt und Hydrographie (BSH), Germany; Bureau of Meteorology (BOM), Australia; Centre for Polar Observation and Modelling (CPOM), Northumbria University, UK; Centre national d' études spatiales (CNES), France; Collecte Localisation Satellites (CLS), France; Deutscher Wetterdienst (DWD), Germany; Copernicus Climate Change Service, European Centre for Medium-range Weather Forecasts (C3S, ECMWF); Food and Agriculture Organization of the United Nations (FAO); Hydrometeorology and Monitoring Center State Non-commercial Organization of the Ministry of Environment (HMC SNCO), Armenia; International Atomic Energy Agency (IAEA); Issue-based Coalition on Sustainable Food Systems; Issue-based Coalition on Environment and Climate Change; European Commission (EC), Joint Research Centre (JRC); Laboratoire d' études en géophysique et océanographie spatiales (LEGOS), France; Mercator Océan International, France; Met Office Hadley Centre, UK; National Oceanic and Atmospheric Administration (NOAA), USA; United Nations Economic Commission for Europe (UNECE); United Nations Environment Programme (UNEP); University of Reading, UK; World Glacier Monitoring Service (WGMS).

INDIVIDUAL CONTRIBUTORS (by alphabetical order of last name)

Rebecca Emerton (coordinating lead author, ECMWF), Andrew Ferrone (coordinating lead author, ASTA), Stefan Rösner (coordinating lead author, DWD), Omar Baddour (WMO), Natalia Berghi (WMO), Peter Bissoli (DWD), Roxana Bojariu (National Meteorological Administration, Romania), Roberta Boscolo (WMO), Iva Brkic (UNECE), Walker Darke (UNECE), Frank Dentener (EC-JRC), Ewan Dunlop (EC-JRC), Yannice Faugere (CLS), Valentina Gasbarri (FAO), Atsushi Goto (WMO), Veronica Grasso (WMO), Charlotte Griffiths (UNECE), Peer Hechler (WMO), John Kennedy (WMO), Sari Lappi (WMO), David Lavers (ECMWF), Brianna Lazerwitz (IAEA), Dario Liguti (UNECE), Atsushi Minami (JMA), Nakiete Msemo (WMO), Benoit Meyssignac (LEGOS), Sergiy Nevmyvanyi (FAO), Julien Nicolas (ECMWF), Inès Otosaka (CPOM), Henri Paillere (IAEA), Frank Paul (University of Zurich, WGMS), Kornélia Radics (WMO), Claire Ransom (WMO), Anthony Rea (WMO), Maarit Roebeling (DWD), Tania Santivanez (FAO), Reinhard Schiemann (University of Reading), Gerard van der Schrier (Koninklijk Nederlands Meteorologisch Instituut, KNMI), Karina von Schuckmann (Mercator Ocean), Serhat Sensoy (Meteoroloji Genel Müdürlüğü (MGM), Türkiye), Jose Alvaro Silva (WMO), Andrea Toreti (EC-JRC), Blair Trewin (BOM), Hari Tulsidas (UNECE), Michael Zemp (University of Zurich, WGMS), Markus Ziese (DWD).

Endnotes

1 https://www.ipcc.ch/assessment-report/ar6/

2 https://www.ipcc.ch/report/sixth-assessment-report-cycle/

3 Copernicus Climate Change Service (C3S). *European State of the Climate 2022*; C3S, 2023. https://climate.copernicus.eu/esotc/2022.

4 Data are from the following data sets: Berkeley Earth, ERA5, GISTEMP v4, HadCRUT.5.0.1.0, JRA-55, NOAAGlobalTemp v5. For details regarding these, see Data sets and methods section in the *State of the Global Climate 2022* (WMO-No. 1316).

5 World Meteorological Organization (WMO): *State of the Global Climate 2022* (WMO-No. 1316). Geneva: 2023.

6 http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html

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

8 Friedlingstein, P.; O'Sullivan, M.; Jones, M. W. et al. Global Carbon Budget 2022, *Earth System Science Data* **2022**, *14*, 4811–4900. https://doi.org/10.5194/essd-14-4811-2022.

9 Intergovernmental Panel on Climate Change (IPCC). *Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.-O.; Roberts, D. C.; Masson-Delmotte, V. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2019. https://www.ipcc.ch/srocc/.

10 Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2021. https://www.ipcc.ch/report/ar6/wg1/.

11 See https://www.metoffice.gov.uk/hadobs/monitoring/regional/wmo_ra_vi.html for a graphic showing the trend for the globe and for the various WMO regions for different 30-year periods. Temperatures for the WMO regions are defined over land only, while global temperatures are defined over all surfaces.

12 Defined over all land within WMO Region VI (see map in the Data sets and methods section). This region includes Greenland in the west and extends further east by almost 20° longitude compared to the definition of Europe used for the Copernicus Climate Change Service (C3S) European State of the Climate report and the European Environment Agency (EEA) temperature indicator. Thus some differences in ranking are to be expected.

13 Seasonal anomalies and rankings are based on the ERA5 reanalysis dating back to 1950, using a slightly different definition of Europe, as described in footnote (2) of the C3S European State of the Climate report 2022: https://climate.copernicus.eu/esotc/2022/temperature.

14 For a brief overview of the cryosphere and its components, see https://climate.copernicus.eu/climate-indicators/cryosphere. For comprehensive overviews on the state of knowledge concerning all components of the cryosphere, see: Integrated Global Observing Strategy (IGOS). *Cryosphere Theme Report: For the Monitoring of our Environment from Space and from Earth* (WMO/TD-No. 1405). WMO: Geneva, 2007. See also Lemke, P.; Ren, J.; Alley, R. B. et al. Observations: Changes in Snow, Ice and Frozen Ground. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Solomon, S.; Qin, D.; Manning, M., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2007. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter4-1.pdf. See also United Nations Environment Program (UNEP). *Global Outlook for Ice and Snow*; 2007. https://wedocs.unep.org/20.500.11822/13696. See also Vaughan, D. G.; Comiso, J. C.; Allison, I. et al. Observations: Cryosphere. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T. F.; Qin, D.; Plattner, G.-K. et al, Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2013. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter04_FINAL.pdf. See also Intergovernmental Panel on Climate Change (IPCC). *Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.-O.; Roberts, D. C.; Masson-Delmotte, V. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2019. https://www.ipcc.ch/srocc/. See also Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al., Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2021. https://www.ipcc.ch/report/ar6/wg1/.

15 A mass change of –1.0 m water equivalent per year is equivalent to an ice thickness loss of about 1.1 m per year, and corresponds to a mass loss of one tonne per square metre.

16 Akademie der Naturwissenschaften Schweiz (SCNAT). *Schlimmer als 2003: Schweizer Gletscher Schmolzen Wie Noch Nie* [Press release]. 28 September 2022. https://scnat.ch/de/uuid/i/2e076759-0234-567e-9bfb-2cdfebd6ff34-Schlimmer_als_2003_Schweizer_Gletscher_schmolzen_wie_noch_nie.

17 As the Greenland Ice Sheet covers a vast area of 1.7 million km^2 (Morlighem, M.; Williams, C. N.; Rignot, E. et al. BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation. *Geophysical Research Letters* **2017**, *44* (21), 11 051–11 061. https://doi.org/10.1002/2017GL074954), only satellite observations can provide ice-sheet-wide monitoring of its mass changes. The estimate of Greenland Ice Sheet mass balance used here is the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) estimate updated to 2021. The IMBIE estimate is the result of the combination of 27 satellite-based ice sheet

mass balance estimates, derived from satellite observations of ice sheet volume change from satellite altimetry, changes in the ice sheet's gravitational field from satellite gravimetry, and changes in ice velocity, combined with a model estimate of surface mass balance from the input–output method (Otosaka, I. N.; Shepherd, A.; Ivins, E. R. et al. Mass Balance of the Greenland and Antarctic Ice Sheets from 1992 to 2020. *Earth System Science Data* **2022**, *15* (4), 1 597–1 616. https://doi.org/10.5194/essd-15-1597-2023).

18 The 2022 mass balance year runs from 1 September 2021 to 31 August 2022. See data sources and more detailed information, p. 15, *State of the Global Climate 2022* (WMONo. 1316).

19 The European Arctic sector is here defined as the ocean area within 44°W–50°E, 63°–85°N (excluding the Baltic Sea).

20 More details about sea-ice condition in the Baltic Sea can be found at https://www.bsis-ice.de/Beschreibung_Eiswinter2022/Eiswinter2022en.html.

21 The data record of maximum sea-ice extent in the Baltic Sea in winter from the Finnish Meteorological Institute used here goes back more than 300 years to the winter of 1719/1720.

22 Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al. Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2021. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

23 von Schuckmann, K.; Cheng, L.; Palmer, M. D. et al. Heat Stored in the Earth System: Where Does the Energy Go? *Earth System Science Data* **2020**, *12* (3), 2013–2041. https://doi.org/10.5194/essd-12-2013-2020.

24 Cheng, L.; Trenberth, K. E.; Fasullo, J. T. et al. Evolution of Ocean Heat Content Related to ENSO. *Journal of Climate* **2019**, *32* (12), 3 529–3 556. https://doi.org/10.1175/JCLI-D-18-0607.1.

25 Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al. Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2021. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

26 Josey, S. A.; Sinha, B. Subpolar Atlantic Ocean Mixed Layer Heat Content Variability is Increasingly Driven by an Active Ocean. *Communications Earth Environment* **2022**, *3*. https://doi.org/10.1038/s43247-022-00433-6.

27 Keil, P.; Mauritsen, T.; Jungclaus, J. et al. Multiple Drivers of the North Atlantic Warming Hole. *Nature Climate Change* **2020**, *10*, 667–671. https://doi.org/10.1038/s41558-020-0819-8.

28 Holliday, N. P.; Bersch, M.; Berx, B. et al. Ocean Circulation Causes the Largest Freshening Event for 120 Years in Eastern Subpolar North Atlantic. *Nature Communications* **2020**, *11*. https://doi.org/10.1038/s41467-020-14474-y.

29 Overviews of the change in sea level in a warming climate can be found in Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al., Eds.; Cambridge University Press: Cambridge, UK, and New York, USA, 2021. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

30 Nicholls, R. J.; Lincke, D.; Hinkel, J. et al. A Global Analysis of Subsidence, Relative Sea-Level Change and Coastal Flood Exposure. *Nature Climate Change* **2021**, *11*, 338–342. doi.org/10.1038/s41558-021-00993-z.

31 World Meteorological Organization (WMO). *State of the Global Climate 2022* (WMO-No. 1316). Geneva: 2023.

32 The uncertainty in the global mean sea-level trend since 1993 is estimated to be ±0.3 mm/year and up to 0.9 mm/year in the European area. For more details see https://climate.copernicus.eu/climate-indicators/about-data#Sealevelindicator, under "Uncertainty estimates".

33 Near the coast, the altimeter-based sea-level variations and associated trends are more uncertain than in the open ocean. This is due to local factors, such as the distortion of the altimeter radar echo by coastal features, the higher uncertainties of some altimeter corrections (such as ocean tides), other local processes that are not captured by satellites (such as how far waves wash up the shore), and the spatial resolution of the satellite data.

34 Centre for Research on the Epidemiology of Disasters (CRED) Emergency Events Database (EM-DAT): https://www.emdat.be/

35 *2022 State of Climate Services: Energy* (WMO-No. 1301)

36 https://erccportal.jrc.ec.europa.eu/ECHO-Products/Echo-Flash#/daily-flash-archive/4637

37 Centre for Research on the Epidemiology of Disasters (CRED) Emergency Events Database (EM-DAT): https://www.emdat.be/

38 Robert Koch Institut, Germany: *Hitzebedingte Mortalität in Deutschland 2022*

39 Office for National Statistics (ONS) and UK Health Security Agency (UKHSA): *Excess Mortality During Heat-periods: 1 June to 31 August 2022*

40 Santé Publique, France: *Bilan Canicule et Santé: Un Eté Marqué par des Phénomènes Climatiques Multiples et un Impact Sanitaire Important*

41 Centre for Research on the Epidemiology of Disasters (CRED) Emergency Events Database (EM-DAT): https://www.emdat.be/

42 San-Miguel-Ayanz, J.; Durrant, T.; Boca, R. et al. *Advance Report on Forest Fires in Europe, Middle East and North Africa 2022*; Publications Office of the European Union: Luxembourg, 2023. doi:10.2760/091540, JRC133215.

43 A marine heatwave can be defined as a period of at least five days when sea-surface temperatures are higher than 90% of temperatures recorded over a 30-year comparison period for the same calendar days and region: Hobday, A. J.; Alexander, L. V.; Perkins, S. E. et al. A Hierarchical Approach to Defining Marine Heatwaves. *Progress in Oceanography* **2016**, *141*, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014.

44 Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In C*limate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al. Eds.; Cambridge University Press: Cambridge, UK and New York, USA, 2021. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

45 https://www.mercator-ocean.eu/actualites/marine-heatwaves-mediterranean-summer-2022/

46 Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: Synthesis Report of the IPCC Sixth Assessment Report (AR6)*. https://www.ipcc.ch/report/ar6/syr/.

47 https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en.

48 https://ember-climate.org/insights/research/european-electricity-review-2023/

49 https://climate.copernicus.eu/esotc/2022/wind-solar-energy-resources

50 https://www.dwd.de/DWD/klima/rcccm/int/rcc_eude_eur_sun_anos_2022_17.png

51 Map obtained from the Global Solar Atlas 2.0 is a free, web-based application, developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info.

52 Map obtained from the Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info. This Global Wind Atlas version 3.0 was developed by a team consisting of Jake Badger, J.; Bauwens, I.; Casso, P. et al.

53 Based on plant locations (for micro hydropower to large-sized plants) and on the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) break line data sets (elevation) and runoff data from the Global Runoff Data Centre. Hoes, O. A. C. *Global Potential Hydropower Locations*; Version 1. 4TU.ResearchData dataset, 2014. https://doi.org/10.4121/uuid:99b42e30-5a69-4a53-8e77-c954f11dbc76.

54 Based on time series since 1983 of surface irradiance from monthly mean SARAH-2.1 data, 100 m wind speed and total precipitation, based on monthly mean ERA5 data: https://cds.climate.copernicus.eu/#!/home.

55 https://climate.copernicus.eu/esotc/2022/wind-solar-energy-resources

56 Based on International Renewable Energy Agency (IRENA); Food and Agriculture Organization of the United Nations (FAO). *Renewable Energy for Agri-food Systems – Towards the Sustainable Development Goals and the Paris Agreement*; IRENA and FAO: Abu Dhabi and Rome, 2021. https://doi.org/10.4060/cb7433en.

57 https://gcos.wmo.int/en/publications/gcos-implementation-plan2022

58 https://www.ocean-ops.org/

59 The WMO Regional Association Region VI area can be accessed in interactive format at https://www.arcgis.com/apps/mapviewer/index.html?layers=2848c7bbd9bf479f9d810d8f1c32e2f5.

60 https://public.wmo.int/en/about-us/members

61 https://european-union.europa.eu/principles-countries-history/country-profiles_en

62 https://www.euro.who.int/__data/assets/pdf_file/0020/215660/The-World-Health-Organization-in-the-European-Region-Eng.pdf

63 https://unece.org/geographical-scope

For more information, please contact:

World Meteorological Organization

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Strategic Communications Office

Tel.: +41 (0) 22 730 83 14 – Fax: +41 (0) 22 730 80 27

Email: cpa@wmo.int

public.wmo.int

JN 23654