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State of the UK Climate 2022

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Left: Damage to the O2 Arena, Greenwich Peninsula, East London following high winds from storm Eunice on 18 February 2022. This was the first time a red warning has been issued for wind covering south-east England, including London. Image: Travers Lewis, Shutterstock.com

Right: The interior of the Stevenson Screen at Coningsby, Lincolnshire on 20 July 2022 showing the automatic instruments, the day after it recorded the UK's highest temperature on record of 40.3°C. The instruments on the right are the primary and check temperature sensors, the instrument on the left is the humidity sensor. Image: Gill Allbones, Met Office

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SPECIAL ISSUE ARTICLE

International Journal of Climatology RMetS

State of the UK Climate 2022

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Futile it were to heave the fretful sigh
When facile mirth is free to such as I:
Should cheerless rain from high
Olympus fall,
I choose wet weather, and record it all.

A poem in the preface to British Rainfall, 1916 (British Rainfall Organization, 1917)

INTRODUCTION

This report provides a summary of the UK's weather and climate through the calendar year 2022, alongside the historical context for a number of essential climate variables. This is the ninth in a series of annual 'State of the UK Climate' publications and an update to the 2021 report (Kendon et al., 2022). It provides an accessible, authoritative and up-to-date assessment of UK climate trends, variations and extremes based on the most up-to-date observational datasets of climate quality.

The majority of this report is based on observations of temperature, precipitation, sunshine and wind speed from the UK land weather station network as managed by the Met Office and a number of key partners and co-operating volunteers. The observations are carefully managed so that they conform to current best-practice observational standards as defined by the World Meteorological Organization (WMO). The observations also pass through a range of quality assurance procedures at the Met Office before application for climate monitoring. Time series of near-coast sea-surface temperature (SST) and sea-level are also presented, and in addition there is a short section on phenology which provides dates of 'first leaf' and 'bare tree' indicators for four common shrub or tree species plus several other indicators. The reliance of this report on these observations highlights the ongoing need to adequately maintain the observation networks, in particular the UK land weather station network, into the future, to ensure that this UK climate monitoring capability is continued.

National and regional statistics in this report are from the HadUK-Grid dataset which is the principal source of data (Hollis et al., 2019). Temperature and rainfall series from this dataset extend back to 1884 and 1836 respectively. Details of the datasets used throughout this report and how the various series which are presented are derived are provided in the appendices. This version of the dataset includes two significant additions compared to last year: firstly, an updated version of the digitized historical monthly rainfall data between 1836 and 1960, further improving the geographical representation of rainfall through this period (Hawkins et al., 2022); secondly, the addition of digitized historical monthly sunshine data from Met Office Monthly Weather Reports (MWRs) before 1919, allowing for the extension of the national sunshine series back to 1910.

The report presents summary statistics for the most recent year 2022 and the most recent decade 2013–2022 against the 30-year standard climate normal period 1991–2020 and the baseline period 1961–1990, following WMO climatological best practice (WMO, 2017). These two 30-year reference periods do not overlap. The baseline reference period 1961–1990 provides a consistent reference period used throughout the series of State of UK Climate reports and more widely for historical comparison, climate change monitoring and climate modelling. The full series provides longer-term context, while a comparison is also made to centennial averages for the Central England temperature (CET) series.

The decade 2013–2022 provides a 10-year 'snapshot' of the most recent experience of the UK's climate and how that compares to historical records. Differences between 2013–2022 and the 30-year reference periods may reflect shorter-term decadal variations as well as long-term trends. For this annual publication, the most recent decade (currently 2013–2022) changes every year, while the most recent 30-year reference period (currently 1991–2020) changes every decade.

Throughout the report's text the terms 'above normal' and 'above average' etc. refer to the 1991–2020 reference period unless otherwise stated. The majority of maps in this report show the year 2022 relative to 1991–2020 – that is, they are anomaly maps which show the spatial variation in this difference from average. Some anomaly maps relative to 1961–1990 are also included, and the report also contains a number of anomaly maps for the most recent decade 2013–2022 against both 1991–2020 and 1961–1990. Maps of actual values are in most cases not displayed because these are dominated by the underlying climatology, which for this report is of a lesser interest than the year-to-year variability.

These data are presented to show what has happened in recent years, not necessarily what is expected to happen in a changing climate. However, two figures showing UK Climate Projections (UKCP) for annual mean temperature and rainfall are included to provide future context to 2100.

Values quoted in tables throughout this report are rounded, but where the difference between two such values is quoted in the text (e.g. comparing the most recent decade with 1991–2020), this difference is calculated from the original unrounded values.

Updates compared to State of UK Climate 2021

- Anomaly maps and summary tables for the most recent decade (2013–2022) have been added for temperature, rainfall and sunshine.
- UKCP plots to year 2100 have been added for temperature and rainfall.
- Panels of daily maps have been added to provide visualization of conditions through the calendar year.
- Analyses of observed trends in daily temperature and daily rainfall have been added to show changes in percentiles and extremes.
- UK annual temperature extremes plots have been added.
- The dataset used for UK near-coast SST has been changed.
- The UK sea-level index has been reintroduced together with storm surge data.
- Phenology indicators for four flower species, four invertebrate species and four vertebrate species have been added.

Feedback

We welcome any suggestions for future publications of this report. Please send any feedback to the Met Office at ncic@metoffice.gov.uk.

This State of the UK Climate report was supported by the Met Office Hadley Centre Climate Programme funded by DSIT.

EXECUTIVE SUMMARY

- The UK's climate continues to change. Recent decades have been warmer, wetter and sunnier than the 20th century.
- The observations show that in the UK extremes of temperature are changing much faster than the average temperature.
- The UK has warmed at a broadly consistent but slightly higher rate than the observed change in global mean temperature.

- The UK's record warm year of 2022 and unprecedented July heatwave were both made more likely by climate change.

Land temperature

- 2022 was the warmest year in the UK series from 1884, 0.9°C above the 1991–2020 average. It was the first year to record a UK annual mean temperature above 10°C.
- 40°C was recorded in the UK for the first time during a heatwave which exceeded previous records by a large margin.
- Winter, spring, summer and autumn 2022 were all ranked in the top 10 warmest seasons for the UK in series from 1884 (winter from 1885).
- All the top-10 warmest years for the UK in the series from 1884 have occurred in the 21st century.
- The most recent decade (2013–2022) has been on average 0.3°C warmer than the 1991–2020 average and 1.1°C warmer than 1961–1990. This is the warmest 10-year period in both the UK series from 1884 and CET series from 1659.
- Half of the years, more than one in three of the constituent seasons, and almost one in four of the constituent months within the most recent decade (2013–2022) have been within the top 10 warmest in the UK series from 1884 (winter from 1885).

Air and ground frost

- The numbers of air and ground frosts in 2022 were below the 1991–2020 average although neither were exceptionally low.
- The most recent decade (2013–2022) has had 4%/7% fewer days of air and ground frost than the 1991–2020 average, and 15%/23% fewer than 1961–1990.

Energy demand indices for heating, cooling and plant growth

- Heating and cooling degree days (CDD) in 2022 were second-lowest and third-highest in series from 1960. Growing degree days (GDD) were the highest in the series.
- The most recent decade (2013–2022) has had 3% fewer heating degree days (HDD) per year on average than 1991–2020 and 12% fewer than 1961–1990.
- CDD are dominated by annual variability, however, for England, the most recent decade (2013–2022) has had 7 more CDD than 1991–2020 and 15 more than 1961–1990 – the latter representing a doubling over this period.
- The most recent decade (2013–2022) has had 5% more GDD per year on average compared to 1991–2020 and 19% more than 1961–1990.

Near-coast SST

- 2022 was the warmest year for UK near-coast SST in a series from 1870.
- The most recent decade (2013–2022) has been on average 0.2°C warmer than the 1991–2020 average and 0.8°C warmer than 1961–1990 for UK near-coast SST.
- All the top 10 warmest years for UK near-coast SST for the UK have occurred in the 21st century.

Precipitation

- 2022 rainfall was 94% of the 1991–2020 average.
- 2022 included the UK's eighth wettest February on record but January, March, April, July and August were all notably dry, particularly across England and Wales, and the UK had its driest summer since 1995.
- Five of the 10 wettest years for the UK in a series from 1836 have occurred in the 21st century.
- Since 2009, the UK has had its wettest February, April, June, November and December on record in monthly series from 1836 – 5 of 12 months – as well as its two wettest winters.
- The most recent decade (2013–2022) has been on average as wet as 1991–2020 (i.e. anomaly 0%) and 8% wetter than 1961–1990 for the UK overall.
- For the most recent decade (2013–2022) UK winters have been 10% wetter than 1991–2020 and 25% wetter than 1961–1990, with much smaller changes for spring, summer and autumn overall.
- There has been a slight increase in heavy rainfall across the UK in recent decades.

Snow

- 2022 was one of the least snowy years on record when compared to the last 60 years. It was similar to several other recent years (2020, 2019, 2016 and 2014).
- In recent years, widespread and substantial snow events have occurred in 2021, 2018, 2013, 2010 and 2009, but their number and severity have generally declined since the 1960s.

Sunshine

- 2022 was the seventh sunniest year in the UK series from 1910, with 110% of the 1991–2020 average. England had its equal-sunniest year.

- January 2022 was the sunniest January for England, and March the sunniest March for Scotland and Northern Ireland in the series.
- The most recent decade (2013–2022) has had for the UK on average 3% more hours of bright sunshine than the 1991–2020 average and 9% more than 1961–1990. 2013–2022 is the sunniest 10-year period in the UK series.
- For the most recent decade (2013–2022) UK winters have been 3% sunnier than 1991–2020 and 14% sunnier than 1961–1990. UK springs have been 6%/16% sunnier.

Wind

- 2022 was comparable in storminess with other years in recent decades, although, unusually, all five named storms occurred in January and February.
- There have been fewer occurrences of max gust speeds exceeding 40/50/60 Kt in the last two decades compared to the 1980s and 1990s.
- The UK annual mean wind speed for 2022 was close to the 1991–2020 average.
- The UK annual mean wind speed from 1969 to 2022 shows a downward trend, consistent with that observed globally.

Sea-level rise

- Since the 1900s, the sea level around the UK has risen by about 18.5 cm. Over the past 30 years (1993–2022) the sea level has risen by 11.4 cm.
- The rate of sea-level rise is increasing, with rates over the past 30 years in several locations around the UK range from 3.0 to 5.2 mm·year^{-1} corrected for vertical land movement.
- Over the past 30 years the rate of sea-level rise around the UK is close to the estimate of the global sea-level rise.
- The most widespread storm surges of 2022 came with storm Eunice on 18 February, with the northern Irish Sea witnessing over 1 m skew surges. Severe coastal flooding in the Bristol Channel and Severn Estuary was avoided as defences held.
- Despite occurring during a neap tide, Storm Malik on 29 January caused the highest water levels of the year at Cromer, Norfolk (skew surge 1.4 m) and Lowestoft, Suffolk (skew surge 1.3 m).

Significant weather

- Storm Eunice on 18 February 2022 was the most severe storm to affect England and Wales since 12 February 2014.
- An unprecedented heatwave from 18 to 19 July 2022 set a new UK all-time temperature record of 40.3°C at Coningsby, Lincolnshire.
- The period January–August was the driest across England and Wales since 1976, with drought status declared across parts of England and all of Wales.
- In December 2022, the UK experienced one of the most significant spells of low winter temperatures since December 2010. However, the observations show a clear downward trend in events of this type.

Phenology

- Indicators for spring 2022 were early by 1–10 days compared to the 1999–2020/2021 baseline for all species except the Swallow. Hazel had its second earliest flowering date in a series from 1999. February 2022 was notably warm and helped to advance the early stages of spring.
- Bare tree dates were 1–10 days later than the 1999–2021 baseline due to a warm October. Pedunculate Oak had its second latest bare tree date in a series from 1999.
- Overall, the 2022 leaf-on season was 7–16 days longer than the 1999–2021 baseline because of the extended seasons in both spring and autumn.

1 | SYNOPTIC SITUATION

1.1 | Atmospheric circulation

Figure 1 shows seasonal mean sea-level pressure anomalies for the four seasons of 2022 relative to the 1991–2020 average, using the ERA5 reanalysis (Hersbach et al., 2020). This provides an indication of atmospheric circulation patterns for each season overall.

A high pressure anomaly extended from north of the Azores eastwards to the Bay of Biscay during the winter, with a low pressure anomaly across Russia and eastern Scandinavia, consistent with a fairly weak positive WNAO (Section 1.2). In December 2021 pressure was slightly below normal across the southern half of the UK. In January, a large high pressure anomaly dominated the UK with a dry, settled spell of weather for much of the month. In contrast, in February the UK was between a high pressure anomaly over the Azores and a deep low pressure anomaly to the north. The month was very westerly – mild and wet – with a succession of low pressure systems; around mid-month a powerful jet stream drove three named storms across the country.

Pressure was higher than normal across the UK during spring, particularly in the east, with a large high

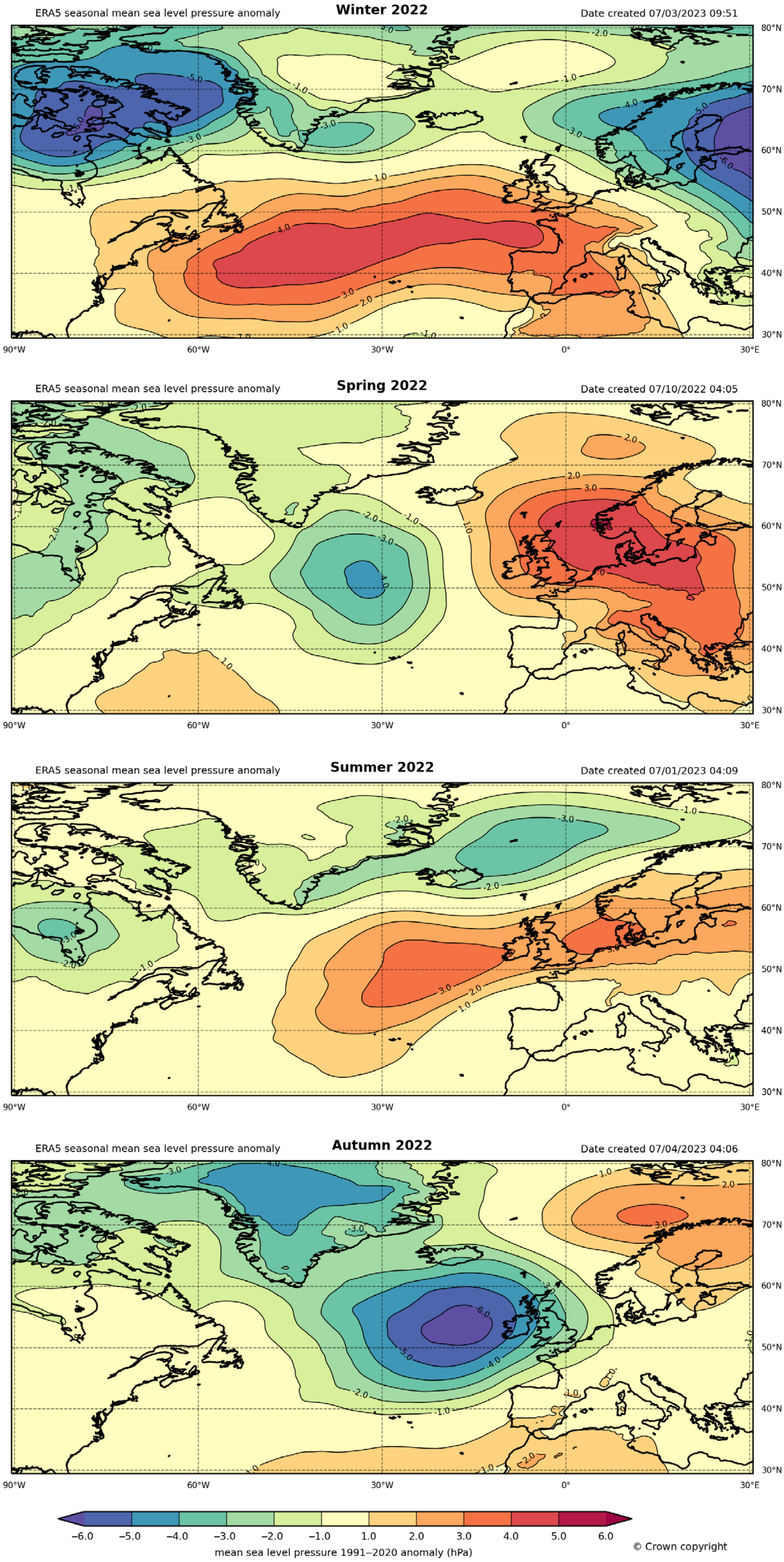


FIGURE 1 2022 seasonal mean sea-level pressure anomalies relative to 1991–2020 using the ERA5 reanalysis (Hersbach et al., 2020). Winter refers to the period December 2021 to February 2022. Pressure anomalies are scaled equally across all four seasons for consistency; however, winter months typically have larger pressure anomalies than summer months.

pressure anomaly over the North Sea. In March this high pressure anomaly was centred over the Baltic, whereas in April it was to the north over Iceland. Both months saw significant spells of high pressure with dry, settled weather in the second half. May was rather more unsettled generally with pressure below normal in the north-west.

A shallow high pressure anomaly was located across the UK during summer, and overall it was a warm, dry and sunny summer, especially in the south. Pressure was near normal in June across much of the UK, but slightly below normal in the north and the weather was mostly fairly quiet and uneventful. Pressure was much higher than normal in July, with plenty of fine, settled weather, including an exceptional heatwave. Pressure was also higher than normal in August, although to a lesser extent. High pressure dominated the weather for the first half of the month and included a further significant heatwave but after this the weather was more variable.

A low pressure anomaly was located to the west of the UK for autumn overall. September and October saw a fairly typical mix of weather types, whereas this pattern was particularly pronounced in November with a deep low pressure anomaly dominating the north Atlantic and a high pressure anomaly across northern Scandinavia, resulting in a very mild and rather wet westerly month.

In December, a low pressure anomaly was located near the Azores and high pressure to the north, with the jet stream displaced to the south of the UK. The first half of the month saw northerly then easterly winds across the UK, bringing cold and at times snowy conditions with Atlantic weather systems blocked. However, from mid-month the normal mild westerly influence resumed.

In summary, the year saw significant spells of dry, settled weather associated with high pressure particularly in January, March, April, July, August and December and unsettled weather in February and November.

1.2 | NAO index

Figure 2 shows the winter North Atlantic Oscillation (WNAO) index from 1850 to 2022 inclusive (Appendix A1 provides details of the WNAO index). (Note here and throughout the report winter refers to the year in which January and February fall.) This index is a measure of the large-scale surface pressure gradient in the North Atlantic between the Azores and Iceland, which determines the strength of westerly winds across the Atlantic, and is the principal mode of spatial variability of atmospheric patterns in this region. When the pressure difference is large, the WNAO is positive and westerly winds dominate with stronger and more frequent storms. When the pressure difference is small, the WNAO is negative with an increased tendency for blocked weather patterns, reducing the influence of Atlantic weather systems.

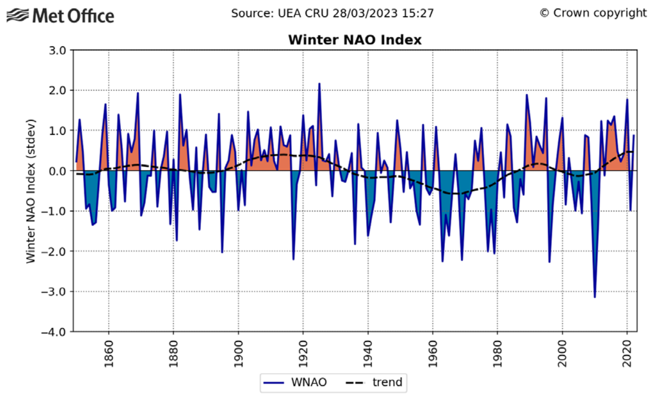


FIGURE 2 Winter NAO index based on the standardized monthly mean pressure difference between stations in Gibraltar and south-west Iceland. Winter 2022 refers to the period December 2021 to February 2022.

The WNAO index for 2022 was positive (+0.9), similar to the majority of winters for the most recent decade, and in contrast to the previous winter (−1.0). A WNAO positive winter would tend to be associated with a mild, wet, westerly winter. For the UK this was a mild winter (anomaly +1.1°C); dull in the west but sunny in the east, although the rainfall pattern overall was variable. February was particularly dominated by westerly conditions, being mild, very wet and exhibiting a strong dull (west) to sunny (east) sunshine contrast. However, in January the UK was much more under the influence of high pressure.

The UK has experienced a run of mild, wet winters in the most recent decade, consistent with this current positive phase of the WNAO, including the very wet winters of 2014, 2016 and 2020 (Figure 33). Overall, the WNAO index shows a large annual variability but also decadal variability with periods of mainly positive phase (e.g. the 1910s to 1920s, 1990s and 2010s) and negative phase (e.g. the 1960s) which are also represented by the smoothed trend line in Figure 2. Hanna et al. (2015) discuss changes in the NAO index and note an increase in variability of WNAO since 1990.

Figure 3 shows the summer North Atlantic Oscillation (SNAO) index from 1850 to 2022 inclusive (Appendix A1 provides details of the SNAO index). Similar to the WNAO index, this is a measure of large-scale climate variability in the North Atlantic based on the surface pressure gradient, but based on a more northerly location and smaller spatial scale than the winter counterpart, reflecting the more northerly location of the Atlantic storm track in summer.

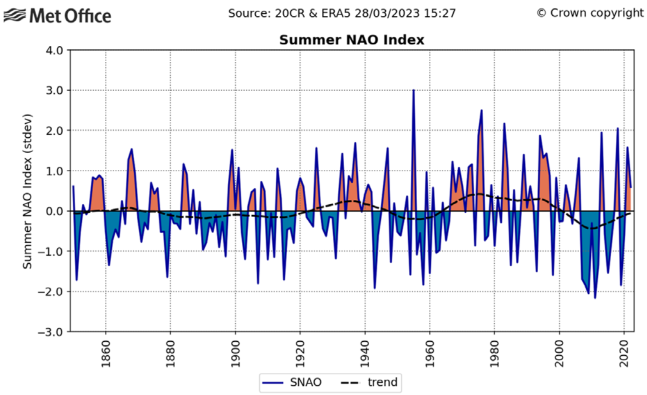
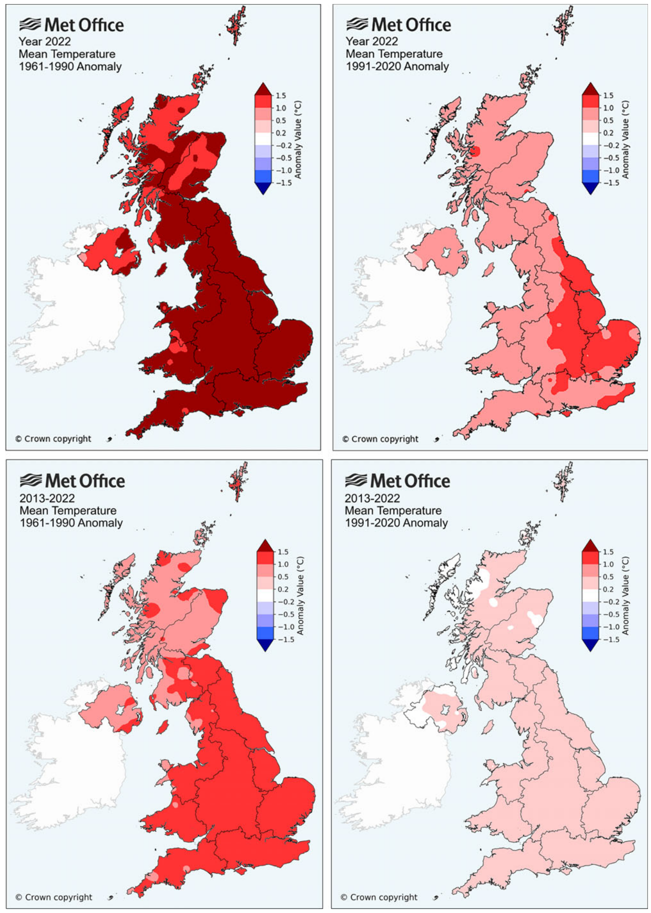


FIGURE 3 Summer NAO index based on the standardized monthly mean pressure difference using the 20th-century reanalysis (Slivinski et al., 2019) and extended to the present day using the ERA5 reanalysis (Hersbach et al., 2020). Summer refers to the period June–August.

The 2022 SNAO index was positive (+0.6). Summers with a positive SNAO index tend to be associated with higher temperatures and lower rainfall, and for the UK overall, the summer was warm (anomaly 1.1°C) and drier than average (anomaly 64%). Other recent summers with a higher SNAO index include 2013, 2018 and 2021 and these too were warmer and drier than average (the latter excluding the south-east).

As with its winter counterpart, the SNAO shows periods of mainly positive phase (e.g. the 1970s to 1990s) and negative phase (e.g. the 1880s and 1890s), with Hanna et al. (2015) noting a decrease in the SNAO since the 1990s, which includes the run of wet summers from 2007 to 2012. The large fluctuations in the SNAO in the most recent decade reflect some markedly contrasting summers – illustrating the UK's large annual variability in the weather and atmospheric circulation patterns across this relatively small spatial scale.



2022	1961–1990	1991–2020
UK	1.7	0.9
England	1.9	1.0
Wales	1.6	0.8
Scotland	1.5	0.8
Northern Ireland	1.4	0.7

2013-2022	1961–1990	1991–2020
UK	1.1	0.3
England	1.3	0.3
Wales	1.1	0.3
Scotland	0.9	0.2
Northern Ireland	0.9	0.2

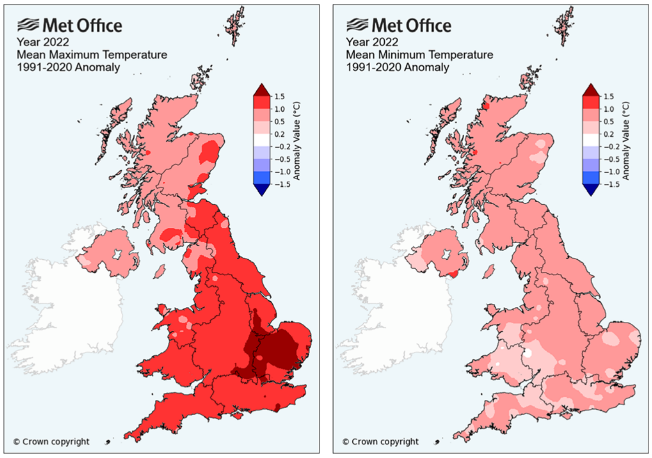
FIGURE 4 Mean temperature anomalies relative to 1961–1990 and 1991–2020 for year 2022 and the decade 2013–2022. The tables show anomaly values for the UK and countries (°C).

2 | TEMPERATURE

2.1 | Annual, seasonal and monthly temperature

The UK mean temperature (T_{mean}) for 2022 was 10.0°C, which is 0.9°C above the 1991–2020 long-term average. 2022 was the warmest year on record in the UK series from 1884 and also the first year with an annual mean temperature reaching 10°C (exceeding 9.9°C in 2014). The highest anomalies relative to 1991–2020 were across central and eastern England (+1.0°C) and lowest across Northern Ireland (+0.7°C). The UK mean temperature was 1.7°C above the 1961–1990 baseline long-term average (Figure 4).

The most recent decade 2013–2022 has been 0.3°C warmer than 1991–2020 and 1.1°C warmer than 1961–1990, with slightly more warming across England and Wales and slightly less across Scotland and Northern Ireland (Figure 4). Five of the 10 years 2013–2022 have been within the top 10 warmest for the UK overall, and this is the warmest 10-year period in the UK series.



	Tmax	Tmin
UK	1.1	0.6
England	1.3	0.6
Wales	1.1	0.5
Scotland	0.9	0.7
Northern Ireland	0.7	0.7

FIGURE 5 2022 temperature anomalies relative to 1991–2020 for (a) mean maximum and (b) mean minimum temperature. The table shows anomaly values for the UK and countries relative to 1991–2020 (°C).

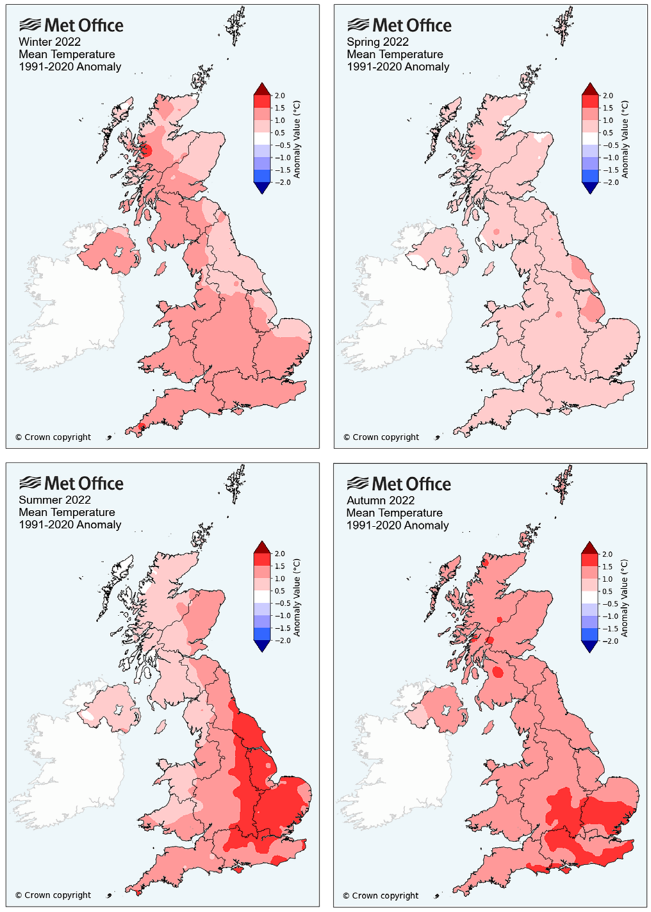


FIGURE 6 2022 seasonal mean temperature anomalies relative to 1991–2020. Winter refers to the period December 2021 to February 2022.

The UK annual mean daily maximum temperature (T_{max}) for 2022 was 13.9°C, 1.1°C above the 1991–2020 long-term average and the warmest year in the UK's T_{max} series from 1884 by a considerable margin (next warmest 13.5°C in 2014). The warmest areas were across eastern England with anomalies particularly high across counties such as Cambridgeshire, Bedfordshire and Hertfordshire (+1.5°C). The UK annual mean daily minimum temperature (T_{min}) for 2022 was 6.2°C, which is 0.6°C above average, with anomalies generally lowest in the south. In contrast to the T_{mean} and T_{max} series, for T_{min} this was not the UK's warmest year on record, with 2014 warmer (6.3°C) (Figure 5).

Figures 6 and 7 show seasonal and monthly T_{mean} anomalies for the UK for 2022. Table 1 shows monthly, seasonal and annual actual and anomaly values and ranks for the UK and countries for 2022.

A key feature of the year was the persistent warmth throughout. All months of the year except December were warmer than the 1991–2020 average. Anomalies were +1.0°C or higher in 7 months (February, March, May, July, August, October and November), with the highest anomalies in the latter 2 months, +1.8°C and +1.7°C respectively. Although no month was record-breaking for the UK overall (for T_{mean}), 6 of the 12 months of the year were in the top 10 warmest in series from 1884. August 2022 was the equal-third warmest August for T_{max}, November 2022 the third warmest November for T_{mean} and T_{min}, and May 2022 the warmest May on record for T_{min}. For the UK overall, there have been only two calendar months warmer than August 2022 in the last 10 years (July 2018 and July 2013). In contrast, December was colder than average (anomaly −1.3°C) and ranked in the coldest third of the series for the UK and across all four countries. It was the UK's coldest December since 2010, although that exceptional month was very much colder (anomaly −5.1°C). Even so, only four previous months in the most recent decade (from 2013 to 2022) have been colder than December 2022; February and March 2013, February 2018 and January 2021.

As a result of the persistent warmth, for the UK all four seasons were in the top 10 warmest in series from 1884 (winter from 1885): winter (anomaly +1.1°C, ranked eighth warmest), spring (+0.8°C, ranked fifth warmest), summer (+1.1°C, ranked fourth warmest) and autumn

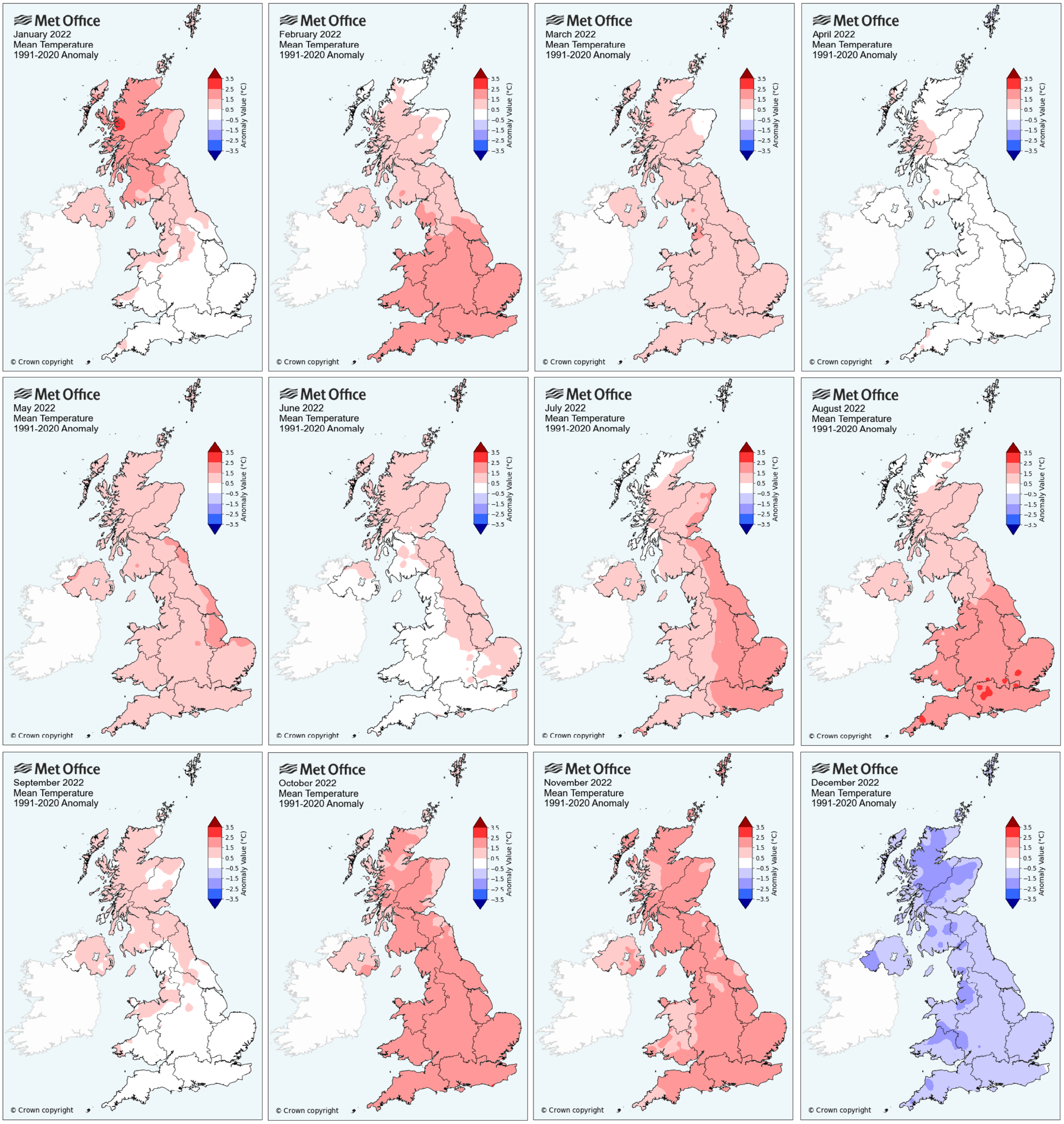


FIGURE 7 2022 monthly mean temperature anomalies relative to 1991–2020. The legend scale ranges from −3.5 to +3.5°C.

(+1.3°C, ranked third warmest). England had its equal warmest summer on record, with 2018. Remarkably, there were no locations in the UK with the seasonal mean temperature below the 1991–2020 average for winter, spring, summer or autumn 2022. The year 2022 overall was the warmest year on record for the UK and across all four nations.

Table 2 shows monthly, seasonal and annual T_{mean} anomaly values for the UK and countries for the most recent decade 2013–2022 against both 1961–1990 and 1991–2020. The most recent decade has been 0.3°C warmer than 1991–2020 and 1.1°C warmer than 1961–1990. Warming has been relatively consistent across all countries, months and seasons comparing the most

TABLE 1 Monthly, seasonal and annual mean temperature actual and anomaly values (°C) relative to 1991–2020 for the UK and countries for year 2022.

	UK		England		Wales		Scotland		Northern Ireland	
	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly
January	4.7	0.8	4.6	0.2	4.8	0.4	4.7	1.8	5.5	1.1
February	5.6	1.5	6.5	1.9	6.4	1.9	3.9	0.8	5.7	1.0
March	6.7	1.0	7.5	1.1	7.0	1.1	5.2	0.9	6.6	0.7
April	8.1	0.2	8.8	0.2	8.2	0.1	6.7	0.2	8.0	0.1
May	11.8	1.2	12.8	1.2	11.8	0.9	10.2	1.1	11.8	1.3
June	13.9	0.5	14.8	0.5	13.5	0.0	12.5	0.9	13.3	0.3
July	16.5	1.3	18.1	1.6	16.4	1.1	14.2	0.8	15.5	0.8
August	16.6	1.5	18.3	2.0	16.9	1.8	13.9	0.7	15.5	1.0
September	13.4	0.5	14.3	0.3	13.5	0.4	11.9	0.6	13.1	0.6
October	11.6	1.8	12.7	2.0	12.0	1.9	9.7	1.5	11.0	1.3
November	8.2	1.7	8.9	1.8	8.5	1.5	6.9	1.7	8.0	1.3
December	2.9	−1.3	3.5	−1.2	3.4	−1.4	1.6	−1.4	3.4	−1.3
Winter	5.2	1.1	5.7	1.1	5.9	1.3	4.0	1.0	5.8	1.2
Spring	8.9	0.8	9.7	0.8	9.0	0.7	7.4	0.7	8.8	0.7
Summer	15.7	1.1	17.1	1.4	15.6	1.0	13.6	0.8	14.8	0.7
Autumn	11.1	1.3	12.0	1.4	11.3	1.3	9.5	1.3	10.7	1.1
Annual	10.0	0.9	10.9	1.0	10.2	0.8	8.5	0.8	9.8	0.7

Key						
Coldest on record	Top 10 cold	Cool: ranked in lower third of all years	Middle: ranked in middle third of all years	Warm: ranked in upper third of all years	Top 10 warm	Warmest on record

Note: Colour coding corresponds to the rank as given in the key. The series lengths are 1884–2022 (139 years) except winter which is 1885–2022 (138 years).

recent decade 2013–2022 to 1961–1990, with UK decadal anomalies between +0.9°C (for March and October) to +1.5°C (for July) for the UK overall, and the greatest warming of +1.7°C in July for England. Comparing 2013–2022 to 1991–2020, decadal anomalies are largest for June, July, October and December (between +0.5°C and +0.9°C), with winter, summer and autumn having all warmed by +0.4°C but no change in spring. These statistics reflect some annual and decadal variability in the UK's climate in addition to the ongoing warming due to climate change.

Figure 8 shows a time series of annual T_{mean} anomalies for the UK and countries from 1884 to 2022 inclusive, and shows that the main period of warming for the UK has been from the 1980s onward at a rate of approximately 0.25°C per decade (i.e. 1°C in the last 40 years). All top 10 warmest years in the UK T_{mean} series have occurred in the 21st century; none of the top 10 coldest years have occurred in this century. The coldest year this century (2010) is ranked 22nd coldest in the UK series; every other year this century falls in the top third warmest years in the series. Half of the years in the most recent decade 2013–2022 have been in the top 10 warmest, including the two warmest years in the series, 2014 and 2022.

Figure 9 shows annual mean maximum and minimum temperatures for the UK from 1884 to 2022 as anomalies relative to 1991–2020. These series are highly correlated (R^2 0.82). Warming is slightly higher for T_{max} than T_{min} with the most recent decade (2013–2022) warmer than 1961–1990 by 1.3°C for T_{max} and 1.0°C for T_{min}. The UK average diurnal temperature range (DTR, $T_{max} - T_{min}$) is approximately 7°C. There has been a small recent increase in the average DTR but to levels similar to those observed prior to the mid-20th century (Figure 10).

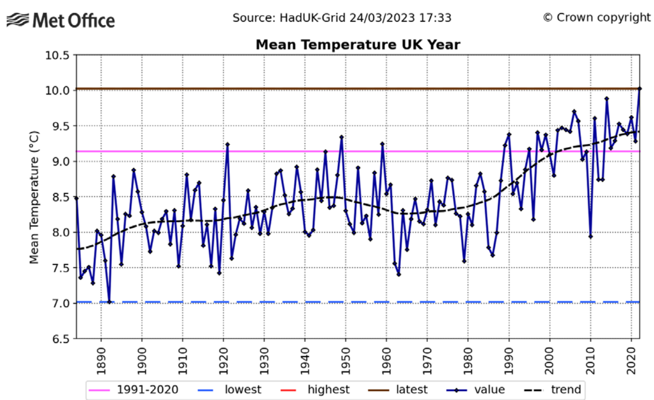
Figure 11 shows UK seasonal mean temperature for all four seasons. As with the annual series, the seasonal series show large inter-annual variability and some decadal variability, with a marked increase in temperature across all four seasons from the 1970s or 1980s onward. The most recent decade 2013–2022 has seen

TABLE 2 Monthly, seasonal and annual mean temperature anomaly values (°C) relative to 1961–1990 and 1991–2020 for the UK and countries for the decade 2013–2022.

	UK		England		Wales		Scotland		Northern Ireland	
	6190	9120	6190	9120	6190	9120	6190	9120	6190	9120
January	1.0	0.1	1.1	0.1	1.1	0.2	0.9	0.1	0.8	0.0
February	1.4	0.2	1.6	0.3	1.5	0.3	1.1	0.0	1.0	0.0
March	0.9	−0.1	1.1	−0.1	0.8	−0.2	0.8	−0.1	0.6	−0.2
April	1.0	−0.1	1.2	−0.1	1.2	0.0	0.8	−0.2	0.8	−0.1
May	1.0	0.1	1.1	0.1	1.0	0.0	0.9	0.2	1.1	0.2
June	1.1	0.5	1.2	0.5	1.2	0.4	1.0	0.5	1.1	0.5
July	1.5	0.6	1.7	0.7	1.3	0.6	1.3	0.5	1.2	0.5
August	1.0	0.2	1.2	0.2	0.9	0.2	0.8	0.0	0.8	0.1
September	1.0	0.3	1.0	0.3	0.9	0.3	1.1	0.3	0.8	0.2
October	0.9	0.6	1.1	0.7	0.9	0.6	0.6	0.5	0.6	0.4
November	1.2	0.2	1.3	0.3	1.1	0.2	1.1	0.2	1.0	0.1
December	1.3	0.9	1.5	1.0	1.5	1.0	1.0	0.8	0.9	0.7
Winter	1.3	0.4	1.4	0.5	1.4	0.6	1.0	0.3	0.9	0.3
Spring	1.0	0.0	1.1	0.0	1.0	−0.1	0.8	0.0	0.8	0.0
Summer	1.2	0.4	1.4	0.5	1.1	0.4	1.0	0.4	1.1	0.4
Autumn	1.0	0.4	1.1	0.4	1.0	0.4	0.9	0.3	0.8	0.2
Annual	1.1	0.3	1.3	0.3	1.1	0.3	0.9	0.2	0.9	0.2

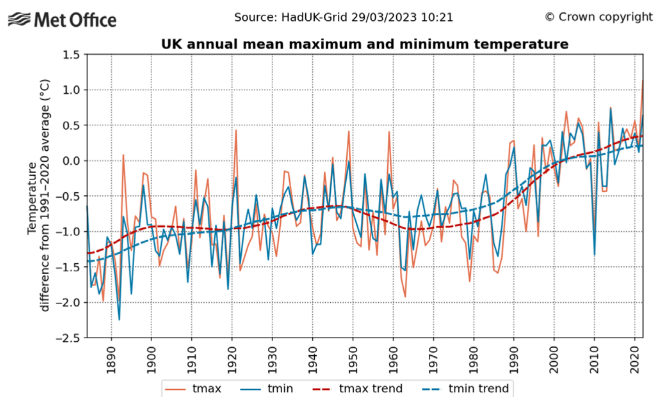
Key: <−0.95°C | −0.95 to −0.45°C | −0.45 to −0.25C | −0.25 to 0.25°C | 0.25 to 0.45°C | 0.45 to 0.95°C | >0.95°C

Note: Colour coding corresponds to the anomaly values as given in the key.



	1961–1990	1991–2020	2013–2022	2022
UK	8.3	9.1	9.4	10.0
England	9.0	10.0	10.3	10.9
Wales	8.6	9.4	9.7	10.2
Scotland	7.0	7.7	7.9	8.5
Northern Ireland	8.4	9.1	9.3	9.8

FIGURE 8 Annual mean temperature for the UK, 1884–2022. The table shows actual values for the UK and countries (°C).



	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
Tmax	11.9	12.8	13.1	13.9	1.3	0.4
Tmin	4.8	5.5	5.8	6.2	1.0	0.2

FIGURE 9 Annual mean maximum and minimum temperature for the UK, 1884–2022 as anomalies relative to 1991–2020. The table shows actual values for the UK (°C).

15 seasons out of 40 in the top 10 warmest in their corresponding seasonal series (more than one in three): five in winter (2014, 2016, 2019, 2020, 2022); four in spring (2014, 2017, 2020, 2022); three in summer (2018, 2021, 2022); three in autumn (2014, 2021, 2022) – whereas only one has fallen in the top 10 coldest (spring 2013). Nearly one in four of the constituent months in the most recent decade 2013–2022 have also been in the top 10 warmest in their corresponding monthly series. These statistics emphasize the fact that the UK's climate is changing; in a stationary climate, we might expect on average around three seasons in the top 10 warmest and three in the top 10 coldest within a 10-year period in a series of this length.

The uncertainty in these statistics is principally a function of the number and distribution of stations in the observing network which varies through time. For monthly, seasonal and annual averages the standard error is less than 0.1°C and consequently the uncertainty is much smaller than the year-to-year variability. For simplicity of presentation all the temperature data are presented in the tables to the nearest 0.1°C. More information relating to the uncertainties and how they are estimated is provided in Appendix B.

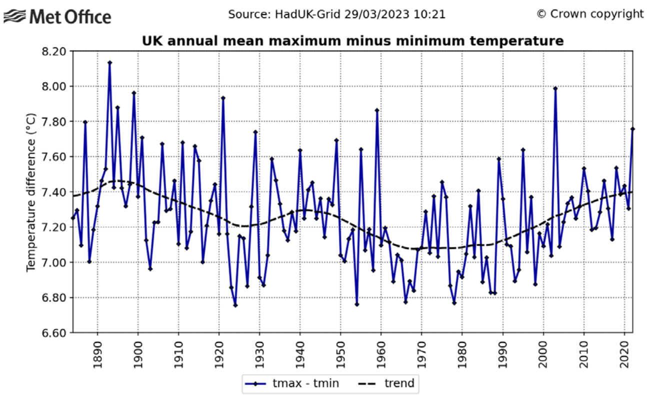


FIGURE 10 Annual mean maximum temperature minus mean minimum temperature (diurnal temperature range, DTR) for the UK, 1884–2022.

2.2 | Central England temperature

Figure 12 shows annual T_{mean} for the CET series from 1659 and for England from 1884 to 2022. Their close

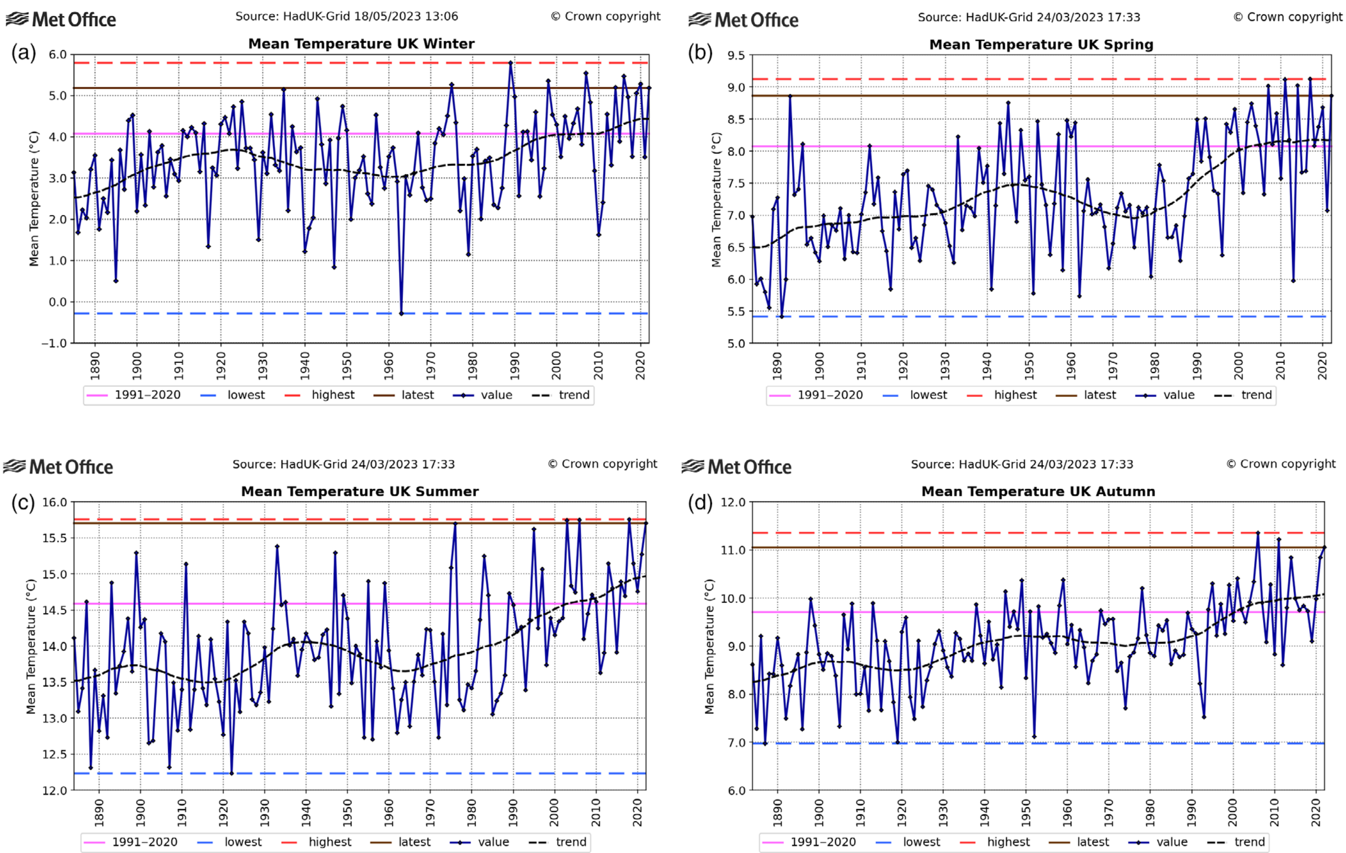
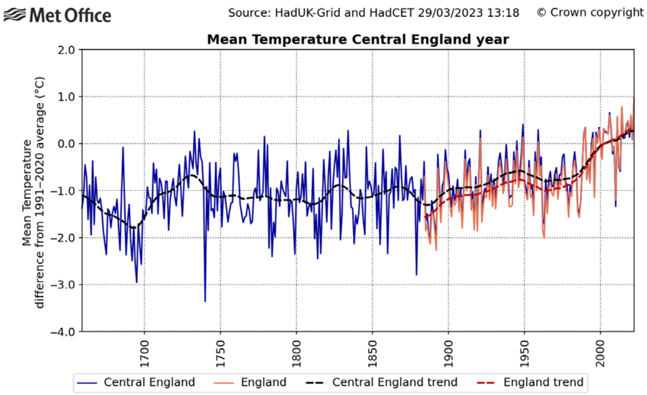


FIGURE 11 Seasonal mean temperature for the UK for (a) winter, (b) spring, (c) summer and (d) autumn, 1884–2022 (winter 1885–2022).



	1961–1990	1991–2020	2013–2022	2022
Central England	9.5	10.2	10.5	11.1
England	9.0	10.0	10.3	10.9

FIGURE 12 Annual mean temperature for Central England (CET), 1659–2022, and England, 1884–2022, as anomalies relative to 1991–2020. The table shows actual values (°C).

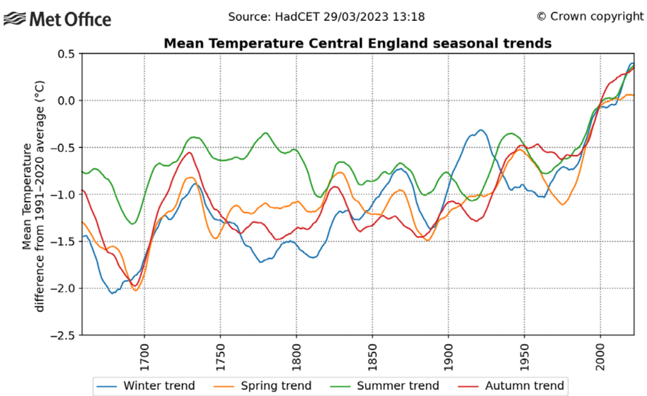


FIGURE 13 Seasonal mean CET trends 1659–2022 (winter 1660–2022), as anomalies relative to 1991–2020, showing the smoothed trends for each series using a weighted kernel filter described in Appendix B1.

consistency indicates that the CET series confirms the temperature trends in the HadUK-Grid dataset shown in Figure 8. 2022 was the warmest year in the CET series with an annual T_{mean} of 11.1°C, 0.9°C warmer than the 1991–2020 average and 0.1°C higher than the next warmest year, 2014. It was the warmest year in the CET T_{max} series from 1878 by a wide margin (15.3°C compared to 14.8°C in 2003 and 2014), but only the third-warmest year in the CET T_{min} series (2006 and 2014 both being warmer).

The CET series provides evidence that the 21st century so far has overall been warmer than any period of equivalent length in the previous three centuries, and that all seasons have also been warmer (Figure 13). When comparing the early 21st century (2001–2022) to previous centennial averages, the annual T_{mean} difference is +0.9°C compared to 1901–2000, +1.2°C compared to 1801–1900 and 1701–1800, and +1.7°C compared to 1659–1700 – with some seasonal variations (Table 3). The most recent decade (2013–2022) has been the warmest 10-year period in the CET series.

The CET and England series are highly correlated (based on an R^2 value of 0.98 for the period of overlap) and have a root-mean-square difference of 0.1°C which is comparable to the estimated series uncertainty as described in Appendix B. The CET series could effectively be considered a proxy for an England series from 1659, although because these are different datasets produced in different ways, some differences are inevitable. The England series has warmed slightly more than the CET series, which means that in Figure 12 the England series anomalies are slightly lower than the CET series before the 1991–2020 period.

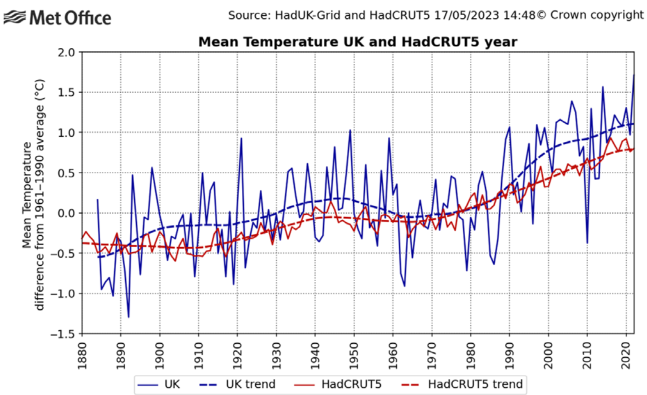
2.3 | Comparison with global mean surface temperature

Figure 14 plots annual T_{mean} for the UK from 1884 to 2022 alongside global mean surface temperature based on the 'best estimate' time series from the HadCRUT5 dataset (Morice et al., 2021). This figure therefore compares UK and global observations. Both series are plotted as anomalies relative to the baseline reference period 1961–1990. The table provides anomaly values relative to 1961–1990. The annual variability in UK T_{mean} is very much larger than HadCRUT5 as the UK covers only a small fraction (approximately 1/2000) of the Earth's surface, and comprises land surface, rather than a combination of land and sea.

The most recent decade 2013–2022 has been 1.1°C warmer than 1961–1990 for the UK, compared to 0.8°C for global mean surface temperature. Globally, warming is greater across high latitudes compared to the equator, and over land compared to the ocean (Blunden & Boyer, 2022). (Section 2.7 shows that the warming has been slightly greater over UK land than UK near-coastal waters). The UK's climate is also subject to natural multi-annual to multi-decadal modes of variability (the same being true for the global climate). This variability will super-impose on any longer term trend, so with these factors taken into consideration the underlying warming observed for the UK is broadly consistent with that observed globally. However, to some extent, the

Season	1659–1700	1701–1800	1801–1900	1901–2000	2001–2022
Year	8.7	9.2	9.1	9.5	10.4
Winter	3.0	3.5	3.7	4.2	4.9
Spring	7.5	8.1	8.1	8.4	9.3
Summer	14.9	15.5	15.2	15.3	16.2
Autumn	9.1	9.6	9.5	10.0	11.0

TABLE 3 Centennial averages for Central England temperature (°C) 1659–2022 (winter from 1660–2022).



	1991–2020	2013–2022	2022
UK	0.8	1.1	1.7
HadCRUT5	0.5	0.8	0.8

FIGURE 14 Annual mean temperature for the UK, 1884–2022, plotted alongside global annual mean temperature based on the HadCRUT5 dataset as anomalies relative to 1961–1990. The table shows anomaly values relative to 1961–1990 (°C).

comparison also depends on the choice of 1961–1990 as the baseline.

2.4 | Daily temperatures and extremes

Figure 15 shows daily maximum and minimum temperature anomaly maps relative to the 1991–2020 monthly averages for each day of 2022. In the UK's climate, daily maximum and minimum temperature anomalies are typically within ±8°C of the monthly average (encompassing the full colour scale of these charts) with anomalies generally only exceeding these values on a few days of the year – often across only a relatively small area. Figure 16a,b shows the UK area-average daily maximum and minimum temperatures through the year.

The consistent warmth of the year is clearly evident, with the number of days of above average temperature very much greater than the number of days below. Compared to the 1991–2020 UK daily average temperature for the time of year, 2022 comprised 254/111 days above/below for maximum and 224/141 days above/below for minimum temperature. There were several prolonged spells of above average temperature through the year, whereas the only lengthy spell below average occurred in the first half of December.

The year began with unusually mild conditions on New Year's Day, with daily maximum temperatures reaching 16.3°C at St James's Park, London, and daily minima widely 10–12°C across England and Wales. Temperatures reached 20°C during a spell of fine, settled weather with high pressure in late March, but by contrast there was a cold plunge of Arctic Maritime air at the start of April bringing some hard frosts as far as the south coast (−4.7°C at Hurn, Dorset on 3 April). By far the most exceptional feature of the year was the unprecedented heatwave of 18–19 July, where 40°C was recorded in the UK for the first time (described in the events Section 9.2). Temperatures also reached 30°C on one day in June (17th) and from 10 to 14 August (34.9°C at Charlwood, Surrey on 13th). There was a prolonged spell of generally mild conditions through October and November, and, for daily minimum temperatures, 11 November was exceptionally mild for the time of year, setting new November daily minimum temperature records for Scotland (14.9°C at Banff Golf Club, Banffshire) and Northern Ireland (14.5°C at Magilligan, County Londonderry).

After the mild autumn, the cold spell in early December was a dramatic transition to winter (described in the events Section 9.4). This was by far the most notable spell of wintry weather in 2022, with UK area-average daily maximum temperatures below 5°C and daily minimum temperatures below 0°C for 11 and 12 consecutive days respectively. The UK area-average daily maximum temperature then increased by over 10°C in only 3 days from 16 to 19 December, bringing this spell to an abrupt end.

Figures 17 and 18 show time series of the UK daily area-average mean maximum and minimum temperature distributions for each year as percentiles from 1960 to 2022, including summary statistics below. These provide insight into how these temperature distributions have changed over this period, with the extremes of the distribution of particular interest.

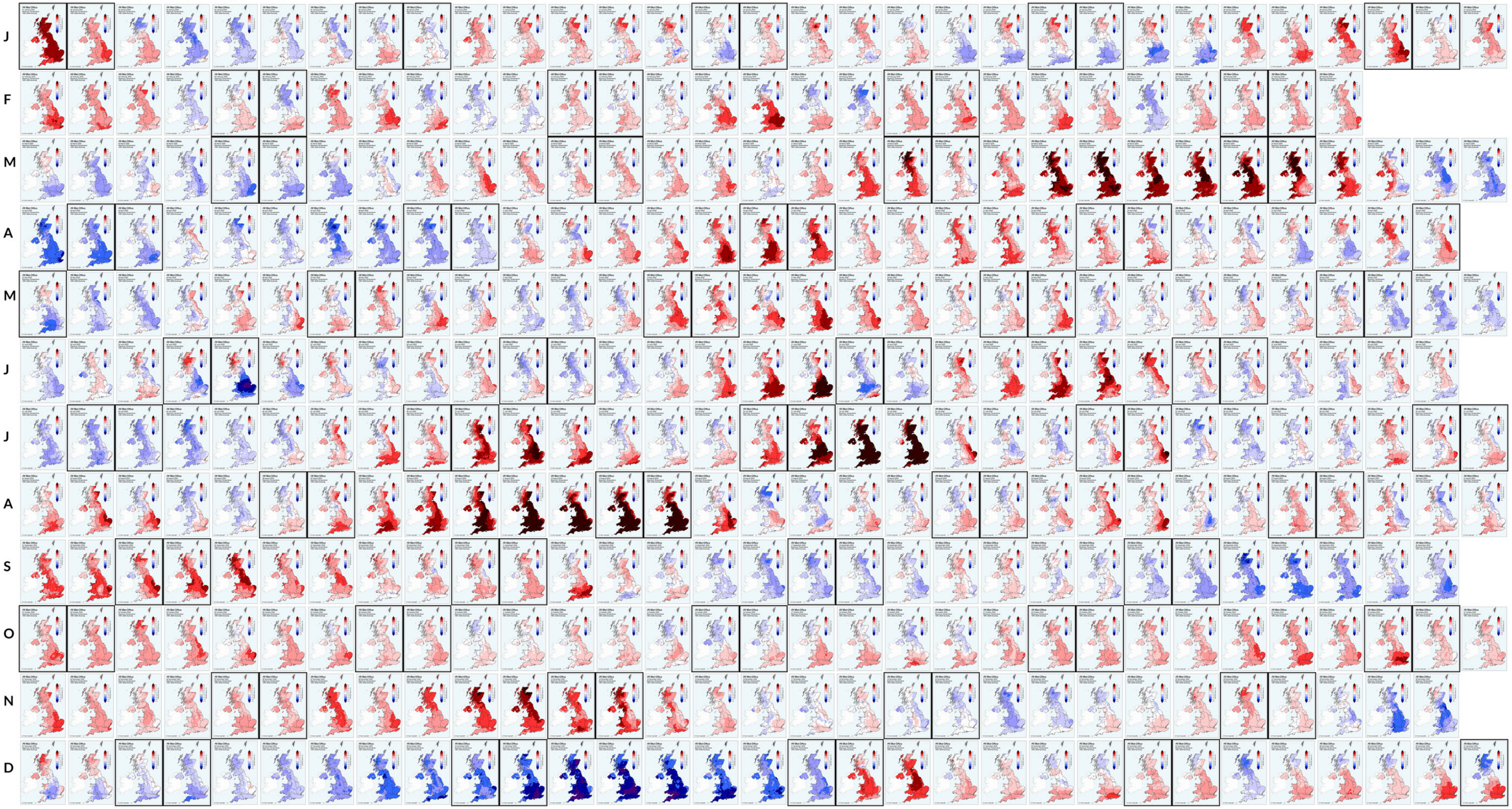


FIGURE 15 2022 daily anomalies relative to 1991–2020 by month (top to bottom) and day (left to right) for (a) maximum and (b) minimum temperature. Weekends are displayed with a black border. The anomaly shading covers +8 to −8°C as shown in (c).

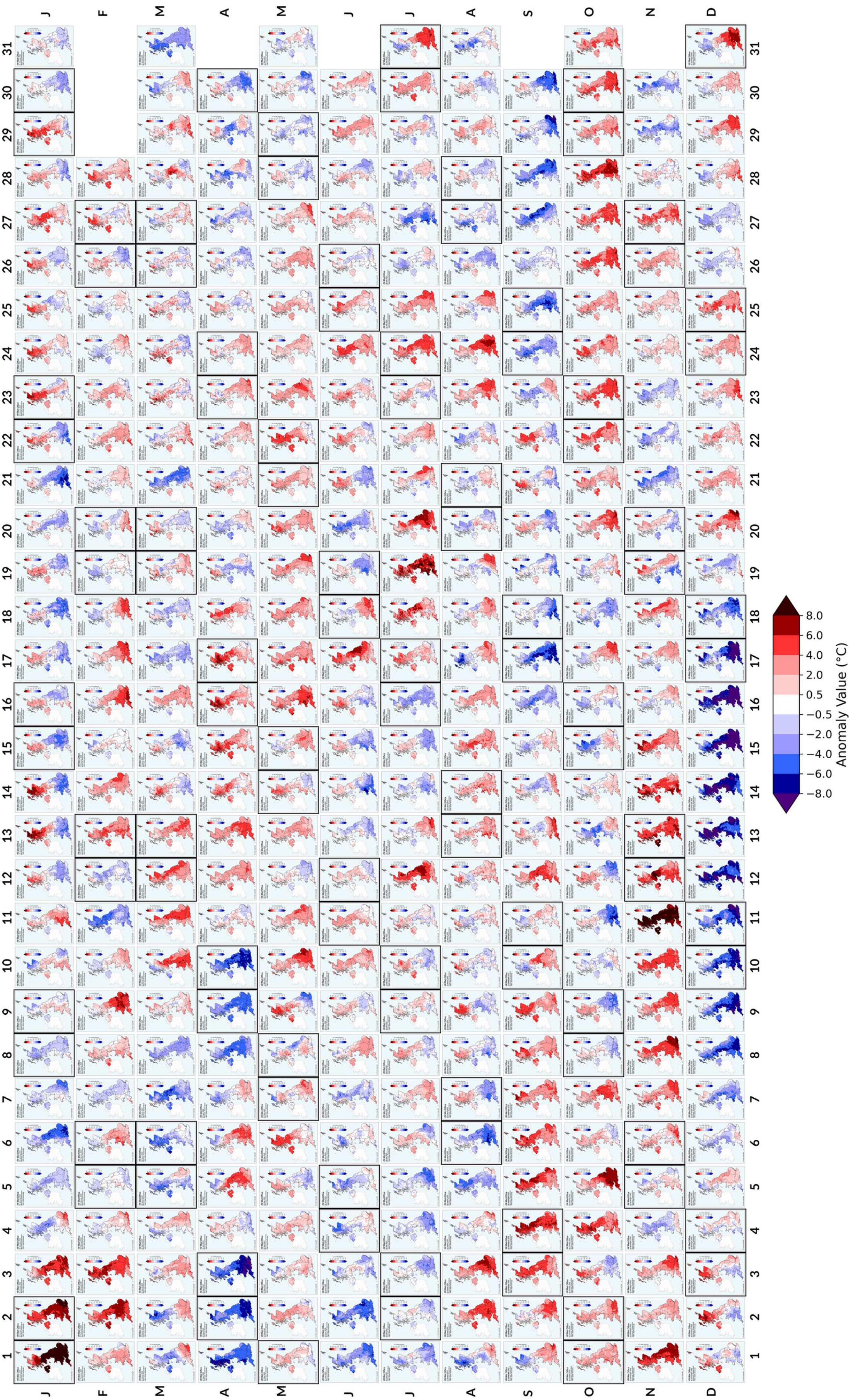
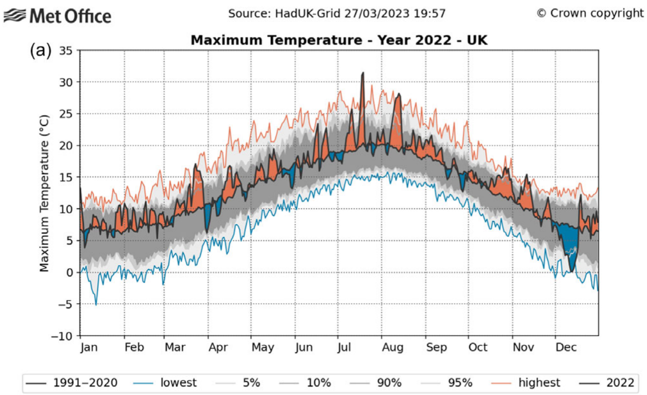


FIGURE 15 (Continued)



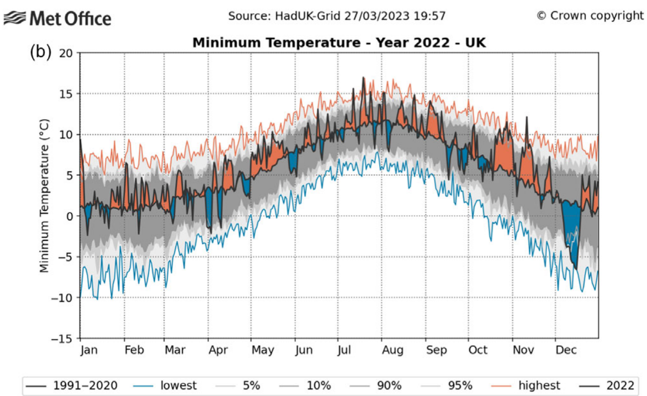
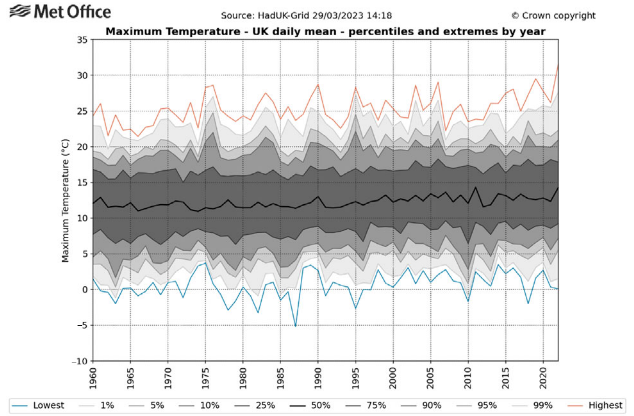


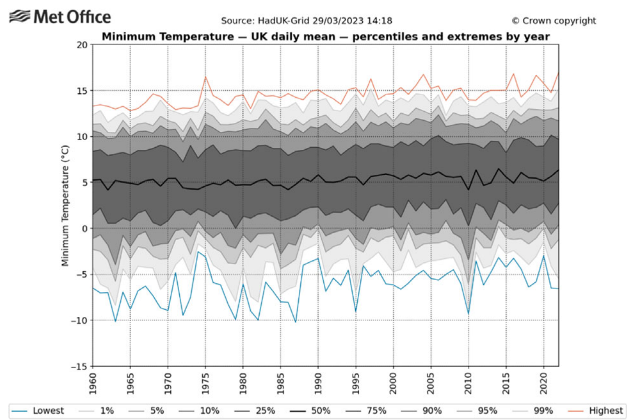
FIGURE 16 Daily anomalies for (a) UK mean maximum and (b) UK mean minimum temperature for each calendar day of the year 2022. The black line shows the 1991–2020 average for each calendar day; the red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1960–2022 inclusive.

Upward spikes in the 90th, 95th and 99th percentiles for T_{max} coincide with years where major summer heatwaves have occurred (e.g. 1976, 1995, 2003, 2006 and 2018), whereas downward spikes in the 1st, 5th and 10th percentiles for T_{min} coincide with particularly cold winter spells – with 2010 notably prominent in the 21st century. The most recent decade 2013–2022 has shown warming across all percentiles for both T_{max} and T_{min}, but this is not consistent across the distribution. For T_{max}, the 99th percentile warmest day (representing the warmest 3 or 4 days in the year) has warmed by 1.9°C relative to 1961–1990, much more than the 50th percentile (+1.1°C). The hottest day has warmed to an even greater extent (+2.8°C). In 2022, the UK area-average T_{max} exceeded 30°C for the first time on both 18 and 19 July (for more details see the events Section 9.2). For T_{min}, there is a similar difference at the lower end of the distribution with the 1st percentile day (representing the coldest 3 or 4 days in the year) warming by 1.7°C relative to 1961–1990



	1961–1990	1991–2020	2013–2022	2022	2013–2022 diff from 1961–1990	2013–2022 diff from 1991–2020
min	0.1	1.1	1.4	0.1	1.3	0.2
1%	1.5	2.3	2.6	1.5	1.0	0.2
5%	3.4	4.4	4.8	5.5	1.5	0.4
10%	4.7	6.0	6.3	7.1	1.6	0.4
25%	7.6	8.6	8.8	9.2	1.3	0.2
50%	11.8	12.6	12.9	14.3	1.1	0.3
75%	16.2	17.1	17.5	17.8	1.3	0.4
90%	18.9	19.7	20.0	20.9	1.1	0.3
95%	20.3	21.3	21.6	22.3	1.2	0.3
99%	22.8	23.7	24.7	27.6	1.9	1.0
max	24.7	25.6	27.5	31.5	2.8	1.9

FIGURE 17 Annual distributions of UK mean daily maximum temperature for each year 1960–2022 (°C).



	1961–1990	1991–2020	2013–2022	2022	2013–2022 diff from 1961–1990	2013–2022 diff from 1991–2020
min	−7.0	−5.4	−4.8	−6.6	2.2	0.6
1%	−4.9	−3.7	−3.2	−5.5	1.7	0.5
5%	−2.5	−1.6	−1.1	−1.2	1.3	0.5
10%	−1.0	−0.4	0.0	0.4	1.1	0.4
25%	1.4	2.1	2.2	2.7	0.8	0.1
50%	4.9	5.5	5.6	6.4	0.7	0.1
75%	8.5	9.1	9.4	9.7	0.9	0.3
90%	10.6	11.3	11.6	11.7	1.0	0.3
95%	11.5	12.3	12.7	13.1	1.1	0.3
99%	13.0	13.9	14.1	15.1	1.1	0.3
max	14.0	15.0	15.5	17.0	1.6	0.6

FIGURE 18 Annual distributions of UK mean daily minimum temperature for each year 1960–2022 (°C).

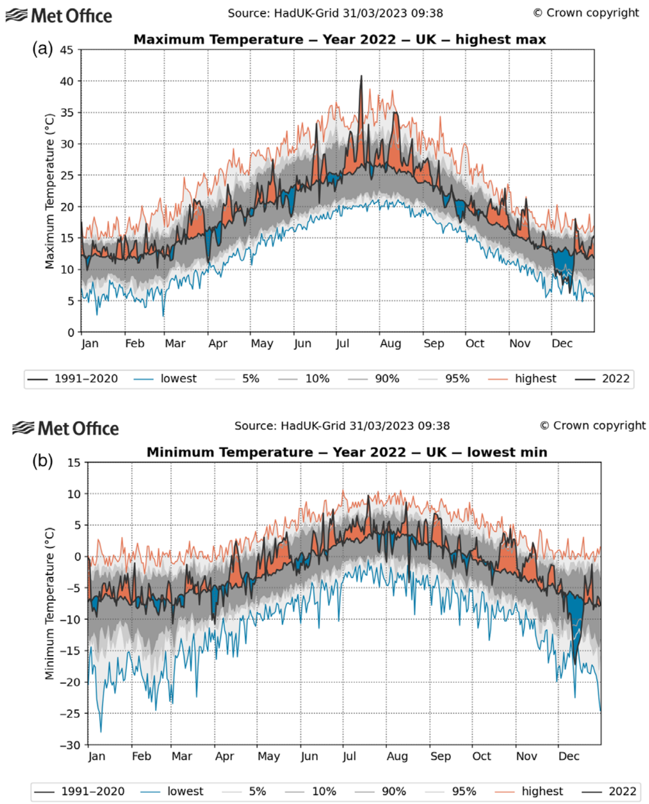
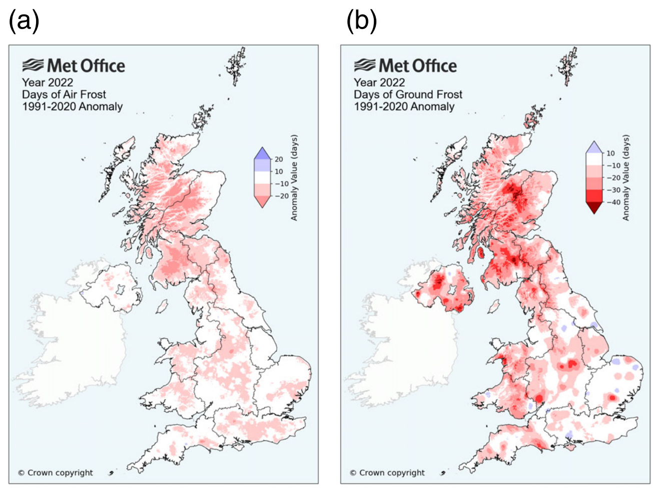


FIGURE 19 Daily anomalies for (a) UK highest maximum and (b) UK lowest minimum temperature for each calendar day of the year 2022. The black line shows the 1991–2020 average for each calendar day; the red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1960–2022 inclusive.



	Airfrost	Groundfrost
UK	−9	−13
England	−8	−9
Wales	−8	−15
Scotland	−13	−19
Northern Ireland	−5	−19

FIGURE 20 Days of (a) air frost and (b) ground frost for year 2022 relative to 1991–2020. The table shows anomaly values relative to 1991–2020 (days). The gridding process aims to strike a balance between a spatially smoothed field and the local characteristics of individual stations. Bulls-eye features in these maps are likely to be due to localized factors such as frost hollow effects at individual weather stations (present in either the actual or long-term average grids) which the gridding process is unable to fully represent, particularly for ground frost.

compared to +0.7°C for the 50th percentile and the coldest day by +2.2°C.

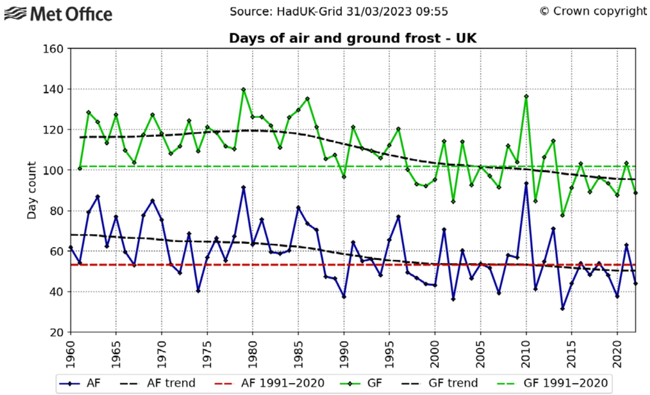
These time series display annual and decadal variability in the UK's climate in addition to the warming trend, and indicate an increased variability in the daily extremes series compared to the mean because sample size is smaller in each year. Nevertheless, these series show that the extremes of these distributions have changed faster than the means.

Figure 19a,b shows the UK's highest daily maximum and lowest daily minimum temperatures for each calendar day of year 2022 based on the HadUK-Grid dataset. These are point values – the location of which will vary on a daily basis depending where in the UK that daily extreme happens to be located – so differ from Figure 16a,b which are UK mean (i.e. area-average) daily maximum and minimum. The highest and lowest values therefore represent the absolute temperature ranges of point values across the UK through the calendar year from 1960 to 2022 – that is, defining the absolute envelope of UK climate observations – as they do not include spatial averaging. The dramatic spike in July 2022 shows the unprecedented July heatwave event in which UK temperatures exceeded 40°C for the first time. The UK's highest daily maximum exceeded 20°C in late March, 25°C in mid-May and 30°C in June, July and August, while the UK's lowest daily minimum fell below −15°C in early December.

2.5 | Days of air and ground frost

The UK experiences a very large spatial variation in the number of days of air and ground frost. The 1991–2020 annual average days of air frost ranges from more than 100 days across much of the high ground of Scotland to less than 10 days across parts of west Cornwall.

The average number of days of air frost for the UK for 2022 was 44 days, 9 days below average. The largest anomalies were across Scotland (13 days below average) (Figure 20). The number of air frosts was well below average in February and November, but above



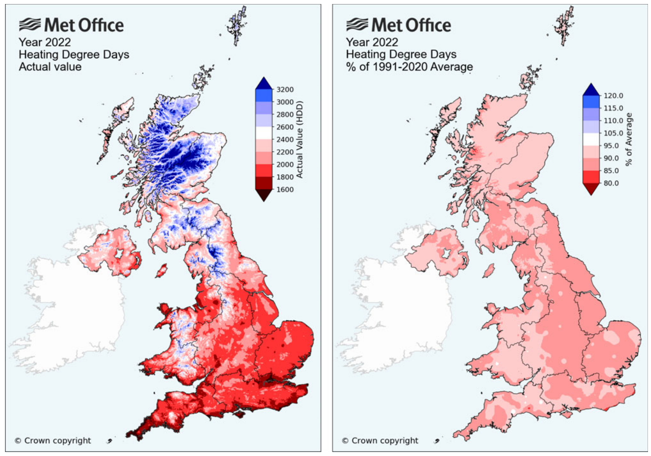
Air Frost	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
UK	64	53	50	44	−15	−4
England	56	45	41	37	−16	−5
Wales	54	45	41	37	−13	−4
Scotland	83	72	69	59	−14	−3
Northern Ireland	54	41	39	36	−15	−3

Ground Frost	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
UK	118	102	95	89	−23	−7
England	110	96	90	87	−19	−6
Wales	108	92	83	77	−25	−9
Scotland	135	116	106	97	−29	−10
Northern Ireland	110	93	87	74	−23	−6

FIGURE 21 Annual days of air and ground frosts for the UK, 1960–2022 and 1961–2022 respectively. The tables show actual values for the UK and countries (days), with anomaly values for 2013–2022 (days).

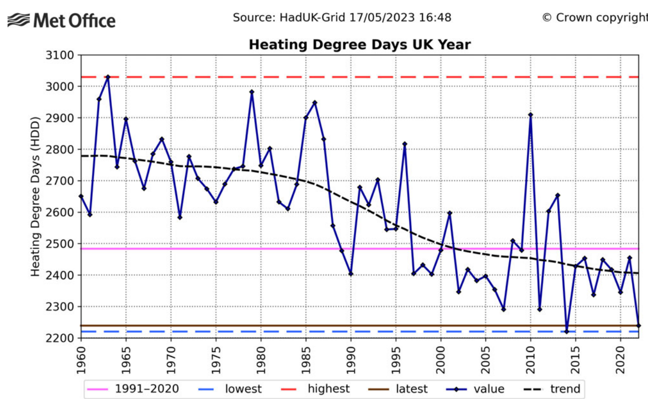
average in April and December. April saw some hard frosts early in the month – with −6.5°C at St Harmon, Powys as late as the 10th. By contrast, in November many stations in England were frost-free for the entire month, not just on the coast but inland – for example, 2.7°C as a November lowest minimum at Pitsford, Northamptonshire. By contrast, December had a run of widespread frosts from 8th to 18th – many of these hard. This was the frostiest December since 2010, although the cold snap was offset to some extent by milder conditions in the latter half of the month. The average number of days of ground frost for the UK for 2022 was 89 days, twice the number of days of air frost and 13 days below average.

The most recent decade 2013–2022 has had 4%/7% fewer days of air and ground frost per year compared to 1991–2020 and 15%/23% fewer than 1961–1990; these representing substantial changes in the UK's climate with the number of ground frosts across Wales, Scotland and Northern Ireland decreasing by a quarter or more (Figure 21).



2022	1961–1990	1991–2020
UK	82	90
England	80	89
Wales	82	91
Scotland	84	91
Northern Ireland	83	91

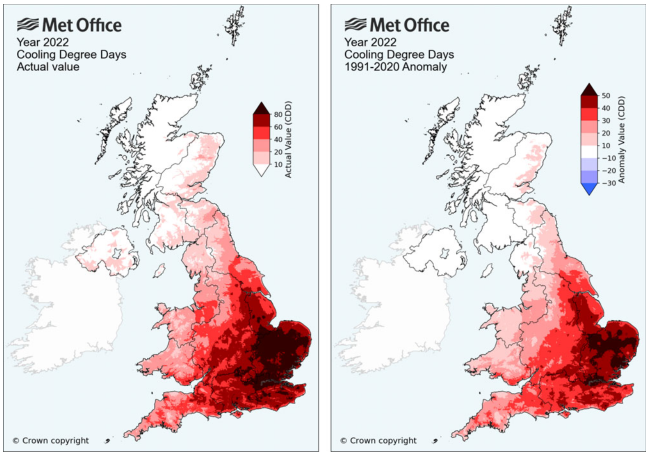
FIGURE 22 Heating degree days for 2022, actual and anomalies relative to 1991–2020. The table shows anomaly values for the UK and countries for year 2022 relative to 1961–1990 and 1991–2020 (%).



	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
UK	2739	2484	2399	2239	88	97
England	2521	2247	2156	2011	85	96
Wales	2620	2362	2277	2144	87	96
Scotland	3149	2923	2846	2653	90	97
Northern Ireland	2655	2425	2367	2199	89	98

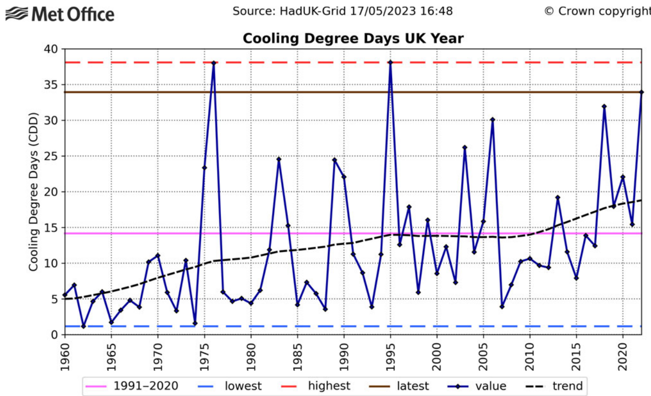
FIGURE 23 Annual heating degree days for the UK, 1960–2022. The table shows actual values for the UK and countries (HDD) with anomaly values for 2013–2022 (%).

Appendix A8 explains how these areal series are calculated. Note that air frosts are derived from daily minimum temperature grids which extend back to 1960 and



2022	1961–1990	1991–2020
UK	25	20
England	40	32
Wales	21	19
Scotland	3	3
Northern Ireland	5	4

FIGURE 24 Cooling degree days for 2022, actual and anomalies relative to 1991–2020. The table shows anomaly values for the UK and countries for year 2022 relative to 1961–1990 and 1991–2020 (CDD). Anomalies are presented as difference from, rather than percentage of, average. This is because CDD are close to zero over much of Highland Scotland.



	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
UK	9	14	19	34	9	4
England	14	22	29	54	15	7
Wales	8	10	14	29	6	4
Scotland	3	3	4	6	1	1
Northern Ireland	3	4	6	8	3	2

FIGURE 25 Annual cooling degree days for the UK, 1960–2022. The table shows actual values for the UK and countries (CDD) with anomaly values for 2013–2022 (CDD).

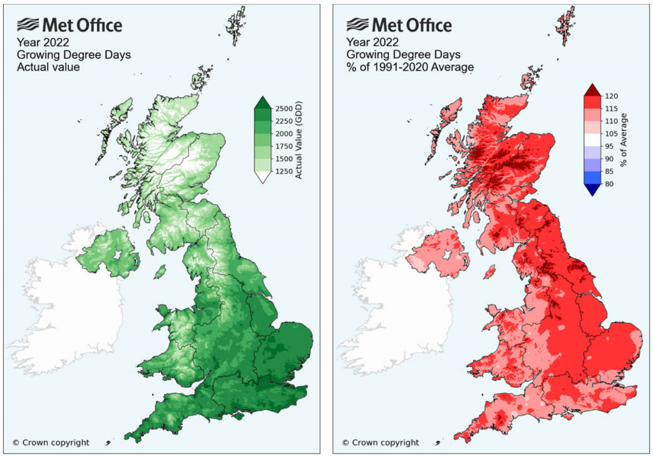
ground frosts are derived from monthly ground frost grids which extend back to 1961, so both of these series are less than half the length of the monthly, seasonal and annual temperature series which are derived from monthly temperature grids from 1884.

2.6 | Degree days

A degree day is an integration of temperature over time and is commonly used to relate temperature to particular impacts. It is typically estimated as the sum of degrees above or below a defined threshold each day over a fixed period of time. The standard degree days monitored by the Met Office are heating, cooling and GDD. These relate to the requirement for heating or cooling of buildings to maintain comfortable temperatures (i.e. relating to energy demand), and the conditions suitable for plant growth respectively. These indices are useful metrics, but as they are derived from temperature only, users should be aware that other relevant factors such as solar gain, day length, wind and rain will also influence the actual responses of, for example, plant growth. The thresholds used for HDD, CDD and GDD are 15.5, 22 and 5.5°C respectively and the formulae used are described in Appendix A5.

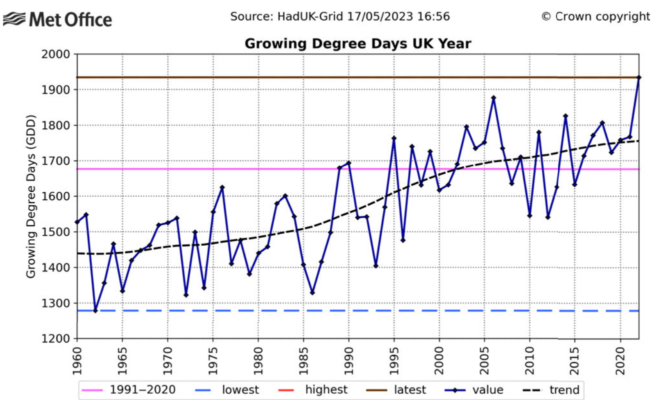
Note that degree days are derived from daily temperature grids which extend back to 1960. HDD relate to heating requirements of buildings – that is, milder conditions result in lower HDD – so are greatest in the winter months. HDD presented here are for the calendar year, so these are split across two winters. In this report HDD and GDD anomalies are presented as percentage of average, whereas CDD anomalies are presented as difference from average. This is because CDD average values for Scotland and Northern Ireland are very small and there is a very large annual variability in these series with many years having near-zero CDD values for these regions.

HDD for 2022 were below the 1991–2020 average for the UK (90%) and the second-lowest in a series from 1960, with only 2014 lower (Figure 22). 2022 and 2014 both saw only one significant spell of well below average temperatures for the time of year, but whereas in 2022 this occurred in early December, in 2014 it was in August. HDD anomalies for 2022 were slightly larger across England (89%) than the other countries (all 91%). The lowest 10 HDD years for the UK in this series from 1960 have all occurred in the 21st century (Figure 23). For the UK, the most recent decade 2013–2022 has had an annual average HDD 3% lower than 1991–2020 and 12% lower than 1961–1990, with 2013 the only year of this decade having above average HDD. Years such as 2010 and 2013 demonstrate it is still possible for UK



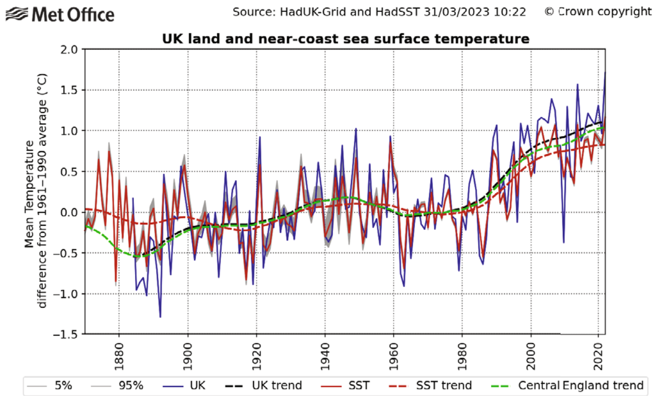
2022	1961–1990	1991–2020
UK	131	115
England	132	116
Wales	130	114
Scotland	131	116
Northern Ireland	127	113

FIGURE 26 Growing degree days for 2022, actual and anomalies relative to 1991–2020. The table shows anomaly values for the UK and countries for year 2022 relative to 1961–1990 and 1991–2020 (%).



	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
UK	1471	1676	1756	1934	119	105
England	1677	1920	2012	2221	120	105
Wales	1517	1723	1802	1970	119	105
Scotland	1124	1269	1331	1467	118	105
Northern Ireland	1424	1606	1663	1809	117	104

FIGURE 27 Annual growing degree days for the UK, 1960–2022. The table shows actual values for the UK and countries (GDD) with anomaly values for 2013–2022 (%).



Area	1991–2020	2013–2022	2022
SST	0.6	0.8	1.2
UK	0.8	1.1	1.7

FIGURE 28 UK annual mean temperature over land 1884–2022, Central England temperature trend and UK annual mean sea surface temperature across near-coastal waters around the UK 1870–2022 as anomalies relative to 1961–1990. The figure shows the SST uncertainty range (5%–95%). The table shows anomaly values relative to 1961–1990 (°C).

climate to experience well above average HDD values resulting from cold winters.

CDD were between two and three times the 1991–2020 average for England (54 CDD compared to 22 CDD) and Wales (29 CDD compared to 10 CDD) and also twice the average for both Scotland and Northern Ireland (Figure 24). Temperatures exceeded 40°C during the unprecedented heatwave in July, and 35°C very widely across England and Wales. However, this heatwave was brief, with the exceptional heat lasting only 2 days (18 and 19 July) – while CDD is a measure of accumulated heat above a threshold. There was also a spell of 5 days in early August (10th–14th) during which temperatures exceeded 30°C widely across England and parts of Wales.

The UK CDD series (Figure 25) is dominated by annual variability, to a much greater extent than either the HDD series (Figure 23) or GDD series (Figure 27). HDD and GDD are very highly correlated with the UK annual T_{mean} series (Figure 8) (R^2 values 0.98 and 0.89 respectively). In contrast, the CDD correlation is much weaker (R^2 value 0.32). Significant peaks in CDD coincide with significant summer heat-waves (including 1976, 1995, 2003, 2006, 2018 and 2022) and to emphasize this point, 1976 and 1995 still have, by a wide margin the highest CDD values in the UK series despite the underlying warming of the UK's climate. CDD for 2022 were third-highest in the series from 1960, higher than 2018 but substantially lower than either 1976 or 1995. In 1976, temperatures peaked at 35.6°C, relatively modest in the context of the last two decades, but this summer was exceptional in large part due to the persistence of the high temperatures. In common with 1976, summer 1995 also saw prolonged periods of fine, warm weather but no extreme temperatures, with the peak again a relatively modest 35.2°C. It is this persistence of warmth that makes 1976 and 1995 the highest in the CDD series for the UK.

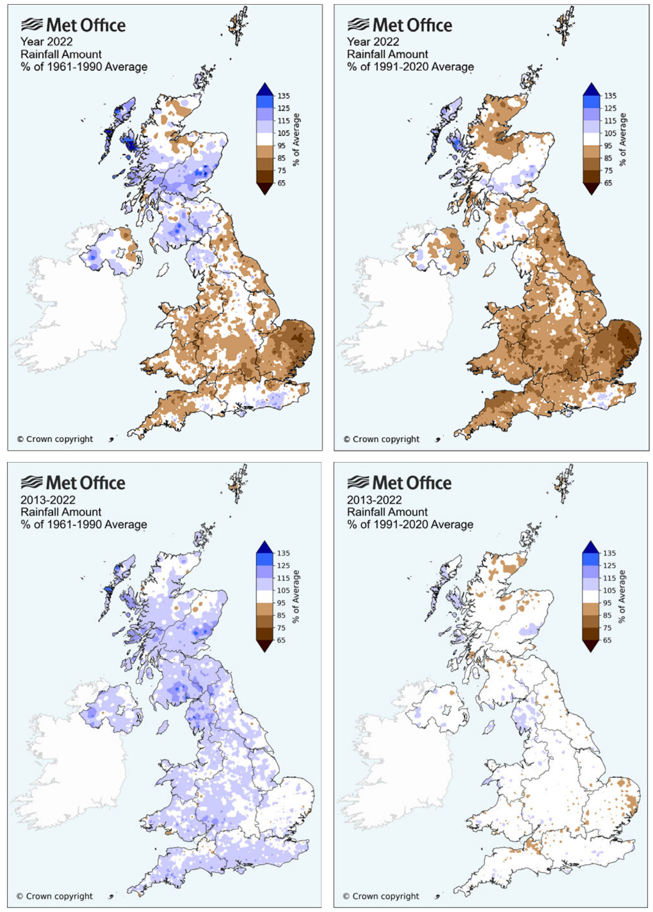
Nevertheless, despite this large annual variability in the series and much weaker correlation, there is still an underlying rising trend. For England, the most recent decade has had 7 CDD more than 1991–2020 and 15 more than 1961–1990 – representing a doubling of CDD over this period. The last 5 years have all had CDD higher than the 1991–2020 average. The cooler climates of Scotland and Northern Ireland mean that CDD are much lower, each with long-term averages of less than 5 CDD (Figure 25).

GDD for 2022 were around 115% of average across the UK (Figure 26). UK GDD overall were, by a fairly wide margin, the highest in the UK series from 1960. Although the summer heatwaves of July and August 2022 will have contributed significantly to the annual GDD value, the combination of very hot, dry conditions was often not beneficial to plant growth and brought challenging conditions for many farmers, gardeners and growers.

The highest 10 GDD years for the UK in this series from 1960 have all occurred since 1995. In contrast with CDD (Figure 25), 2022 saw over 300 more GDD compared to 1976. The most recent decade has had an annual GDD 5% higher than 1991–2020 and 19% higher than 1961–1990 (Figure 27). The similar (downward) trend in HDD and (upward) trend in CDD and GDD from 1960 to date each reflect the underlying warming of the UK's climate, coupled with fewer frosts resulting in an extended growing season. Phenology data for 'first leaf' and 'bare tree' dates of four common shrub or tree species are presented in Section 10.

2.7 | Coastal waters

The annual mean SST for 2022 for near-coast waters around the UK was 1.2°C above the 1961–1990 long-term average making this the UK's warmest year for near-coast SST in a series from 1870 (Figure 28). For UK near-coast SST, the most recent decade 2013–2022 has been 0.2°C warmer than the 1991–2020 long-term average and 0.8°C warmer than 1961–1990. Six of the 10 years 2013–2022 are within the top 10 warmest in the series, and all top 10 warmest years in the series have occurred in the 21st century.



2022	1961–1990	1991–2020
UK	101	94
England	95	89
Wales	94	89
Scotland	107	99
Northern Ireland	102	96

2013–2022	1961–1990	1991–2020
UK	108	100
England	106	100
Wales	107	101
Scotland	109	100
Northern Ireland	107	101

FIGURE 29 Rainfall anomalies relative to 1961–1990 and 1991–2020 for year 2022 and the decade 2013–2022. The tables show anomaly values for the UK and countries (%).

Near-coast SST is highly correlated with the land observations (R^2 value 0.85, see Appendix B5) with a root mean square difference of less than 0.3°C. The SST series is entirely independent from observations from the UK land network. Some differences between historical trends in these series are apparent, notably in the period pre-

1900. However, these differences are also apparent in the CET series, also shown in Figure 28, which closely follows the UK series. Uncertainties in the SST dataset will generally be larger at smaller scales (such as UK near-coast) and can include uncertainty in the bias adjustments applied to minimize the effect of instrumentation changes. See Appendix A11 for details of the UK near-coast SST series.

3 | PRECIPITATION

3.1 | Annual, seasonal and monthly rainfall

The UK rainfall total for 2022 was 1090 mm, 94% of the 1991–2020 average. Rainfall totals were below average across most of the UK except for parts of Scotland and the west of Northern Ireland. East Anglia had a particularly dry year with less than two-thirds of normal rainfall in some locations (Figure 29). Norfolk and Suffolk each recorded around three-quarters of normal rainfall. The wettest locations in Cumbria and the West Highlands received over 3000 mm of rain, whereas the driest locations in parts of Essex received less than 400 mm.

The most recent decade 2013–2022 has been exactly as wet as 1991–2020 for the UK (anomaly 0%), and 8% wetter than 1961–1990, with relatively little regional variation (Figure 29). Two of the 10 years 2013–2022 have been within the top 10 wettest for the UK overall (2014 and 2020).

Figures 30 and 31 and Table 4 show seasonal and monthly rainfall anomalies across the UK for 2022. The UK rainfall total for winter was 328 mm, 95% of the 1991–2020 long-term average. The rainfall pattern was variable across much of the UK; the season was notably dry for southern counties of England but rather wet in the north-west. January was a dry month with 52% of normal rainfall for the UK and only a third of normal widely across southern England and parts of eastern Scotland. In contrast, February was a wet month in many areas (157% for the UK and eighth wettest in the UK series from 1836). It was particularly wet across north-west England with more than twice the monthly average across Manchester, Leeds and the south Pennines, although not as wet as the exceptional February of 2020 (the UK's wettest February on record).

For the UK the spring and summer were both dry, with rainfall well below average for March (60%), April (69%), June (80%), July (59%) and August (55%). May was the only wetter than average month (109%); it was very wet locally in the West Highlands and Hebrides with 448 mm of rain recorded as a monthly total at Alltdearg House, Isle of Skye. July was especially dry across southern England with only 18% of normal rainfall for this

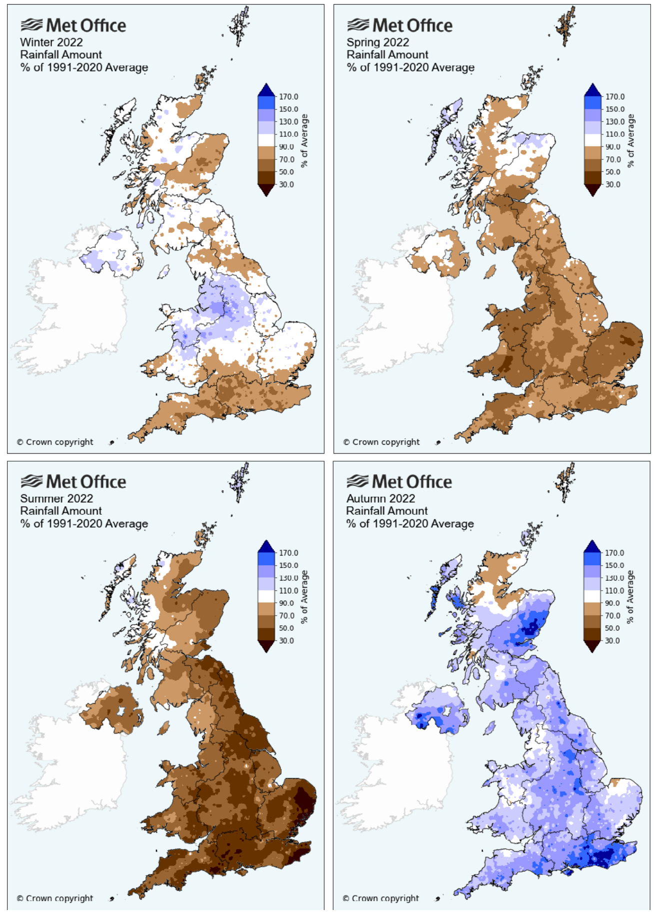


FIGURE 30 2022 seasonal rainfall anomalies relative to 1991–2020. Winter refers to the period December 2021 to February 2022.

region; England had its driest July since 1977 and the eighth driest July in the series from 1836, while Wales and Northern Ireland each had their tenth driest July (see also Figure 77). The UK had its driest summer since 1995. The persistent dryness over the 8-month period January–August across southern England and Wales led to drought conditions being declared in some areas; this is described further in the events Section 9.3.

In contrast to spring and summer, the autumn was wetter than average for the UK (125%). The UK had its wettest autumn since 2000 and eighth wettest in the series. All three constituent months were wetter than average, although not exceptional. November was particularly wet for parts of south-east England, eastern Scotland and, once again, the Isle of Skye (885 mm at Alltdearg House). Northern Ireland received more than 150% of normal in both September and October. December totals were slightly below normal overall.

In summary, as is always the case, monthly and seasonal rainfall patterns showed some very large variations over the course of the year, but with the most notable

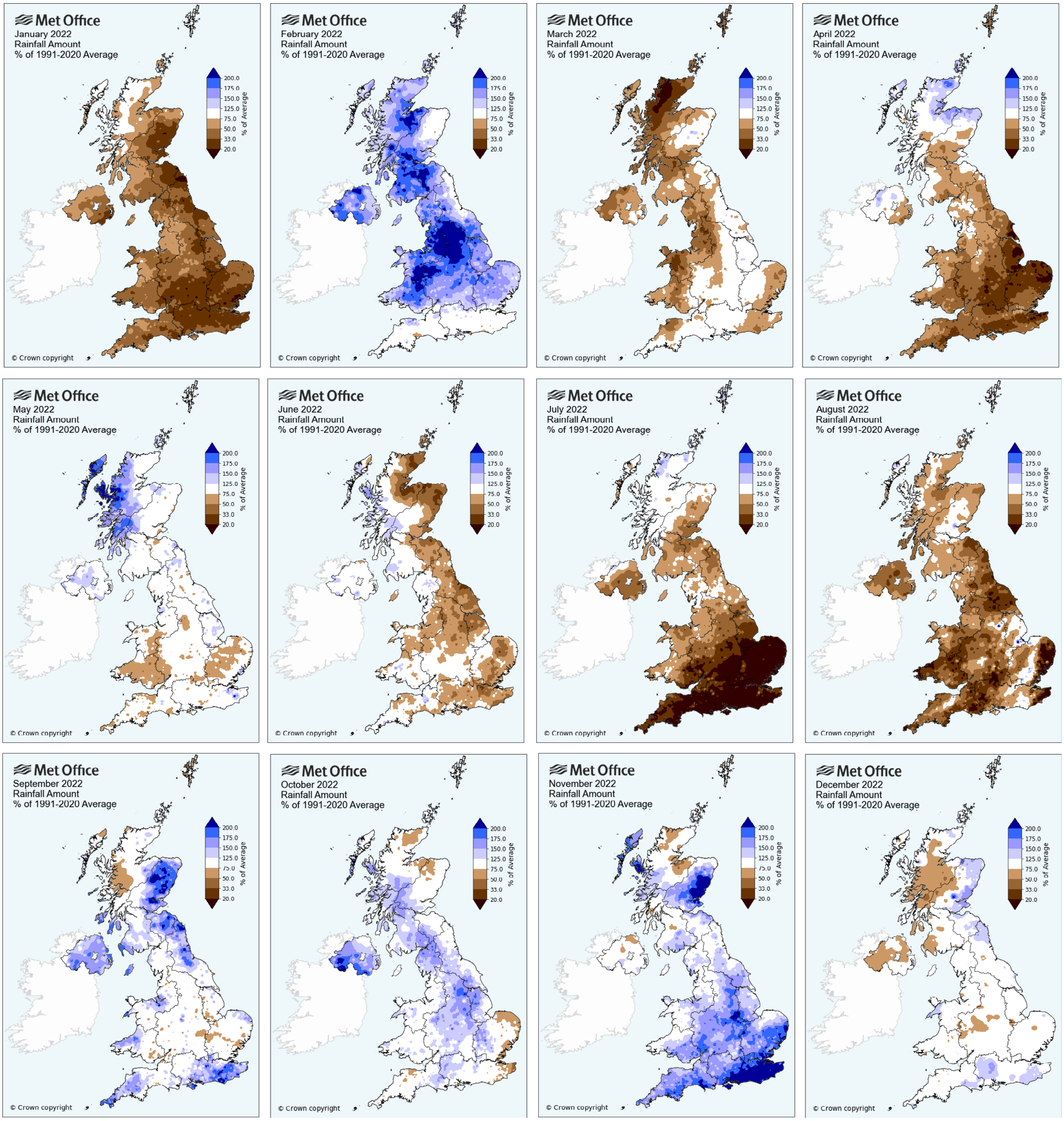


FIGURE 31 2022 monthly rainfall anomalies relative to 1991–2020. The legend scale ranges from 20% to 200%.

feature being the persistent dryness for the January–August period, especially across England and Wales.

Table 5 shows monthly, seasonal and annual rainfall anomaly values for the UK and countries for the most recent decade 2013–2022 against both 1961–1990 and 1991–2020. For the most recent decade (2013–2022), UK winters have been 10% wetter than 1991–2020 and 25% wetter than 1961–1990. UK summers have been 3% drier than 1991–2020 and 6% wetter than 1961–1990. February has seen the largest increase, with the most recent decade 17% wetter than 1991–2020 and 45% wetter than 1961–1990 (and 52% wetter than 1961–1990 for Scotland). April has seen the largest decrease, with the most recent decade 28% drier than 1991–2020 and 21% drier than 1961–1990 (and a 34% decrease for England against both reference periods).

TABLE 4 Monthly, seasonal and annual rainfall actual values (mm) and anomaly values (%) relative to 1991–2020 for the UK and countries for year 2022.

	UK		England		Wales		Scotland		Northern Ireland	
	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly
January	63	52	32	39	71	46	113	64	57	50
February	151	157	100	151	205	170	223	158	152	166
March	51	60	43	74	53	51	63	51	49	57
April	50	69	25	45	48	54	88	95	70	95
May	77	109	52	91	64	73	121	136	90	122
June	62	80	46	71	76	83	81	87	83	102
July	48	59	24	35	53	54	88	85	48	54
August	52	55	36	48	43	38	82	69	44	44
September	105	116	79	115	123	110	140	113	134	153
October	148	120	107	119	180	114	200	119	179	157
November	167	136	143	155	209	129	205	124	117	96
December	116	91	91	99	172	98	148	85	88	72
Winter	328	95	223	93	468	104	464	94	343	105
Spring	178	78	120	70	164	59	272	89	210	89
Summer	162	64	106	51	173	57	251	79	176	65
Autumn	420	125	329	131	512	118	545	119	431	133
Annual	1090	94	778	89	1296	89	1552	99	1112	96

Key						
Driest on record	Top 10 driest	Dry: ranked in lower third of all years	Middle: ranked in middle third of all years	Wet: ranked in upper third of all years	Top 10 wettest	Wettest on record

Note: Colour coding corresponds to the rank as given in the key. The series lengths are 1836–2022 (187 years) except winter which is 1837–2022 (186 years).

Although the UK's climate is getting wetter, there is large annual and decadal variability in the UK's precipitation, so caution is advised for interpreting trends over relatively short time periods, and decadal averages can be strongly influenced by extreme years. For example, the summer precipitation anomaly for the most recent decade has changed markedly from last year's report as a result of inclusion of the dry summer of 2022 (64% of average for the UK) and the omission of the exceptionally wet summer 2012 (149%, i.e. with more than twice as much rain as for summer 2022).

The UK annual precipitation time series from 1836 to 2022 shows the large annual variability inherent in the UK's climate. There has been an increase from the 1970s and 1980s onwards (Figure 32). The wettest year for the UK overall is 1872 (124% of average) and the driest 1855 (68%). Five of the 10 wettest years in the UK series from 1836 have occurred in the 21st century (in descending order, 2000, 2020, 2012, 2008 and 2014); but none of the 10 driest years. This version of the dataset uses a second version of Rainfall Rescue data back to 1836; the first version of Rainfall Rescue data was used in the 2021 report. Further details are provided in Appendix A2.

Figure 33 shows seasonal rainfall series for the UK from 1836 to 2022 (for winter 1837–2022). Similar to the annual series, the seasonal series are dominated by large annual variability with some decadal variability about a relatively stable long-term mean. There has been a marked increase in winter rainfall in the most recent decade with 2014, 2016 and 2020 all in the top five wettest (the other winters being 1995 and 1990). Summer rainfall has also increased but from a drier period through the 1970s, 1980s and 1990s which included the record dry summers of 1976 and 1995. Spring rainfall has decreased slightly and there has been little change in autumn rainfall (see also Table 5).

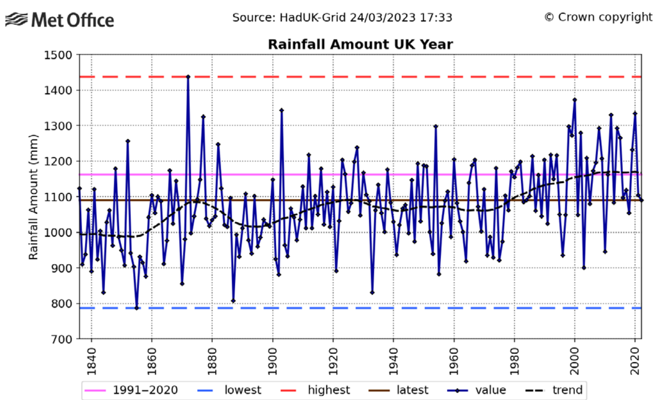
Since 2000, nine seasons have been in the top 10 wettest in UK seasonal series (winter 2014, 2016, 2020 and 2007, spring 2006, summer 2012 and 2007, autumn 2000 and 2022) but only one in the top 10 driest (spring 2020). Since 2009, the UK has recorded its wettest February (2020), April (2012), June (2012), November (2009) and

TABLE 5 Monthly, seasonal and annual rainfall anomaly values (%) relative to 1961–1990 and 1991–2020 for the UK and countries for the decade 2013–2022.

	UK		England		Wales		Scotland		Northern Ireland	
	6190	9120	6190	9120	6190	9120	6190	9120	6190	9120
January	110	101	110	106	107	103	112	96	103	102
February	145	117	136	119	145	124	152	112	144	127
March	96	102	98	111	97	106	93	94	99	103
April	79	72	66	66	71	68	95	80	84	75
May	108	107	104	108	109	107	113	107	106	105
June	103	94	101	93	104	93	104	95	107	96
July	108	94	102	89	101	83	114	103	123	95
August	107	102	105	100	107	102	108	104	112	107
September	86	94	90	92	93	101	81	93	83	95
October	116	105	126	107	111	100	112	104	101	101
November	106	97	112	99	103	95	101	95	114	98
December	121	109	117	107	122	112	126	110	117	106
Winter	125	110	122	112	125	114	129	107	120	112
Spring	95	94	90	95	93	95	99	94	97	95
Summer	106	97	103	94	104	93	109	101	114	100
Autumn	103	99	110	100	103	98	99	98	99	98
Annual	108	100	106	100	107	101	109	100	107	101

Key						
<80%	80%–90%	90%–95%	95%–105%	105%–110%	110%–120%	>120%

Note: Colour coding corresponds to the anomaly values as given in the key.



	1961–1990	1991–2020	2013–2022	2022
UK	1084	1163	1163	1051
England	820	870	870	747
Wales	1379	1465	1470	1246
Scotland	1444	1573	1569	1498
Northern Ireland	1091	1157	1171	1105

FIGURE 32 Annual rainfall for the UK, 1836–2022. The table shows actual values for the UK and countries (mm).

December (2015) – 5 out of 12 months – in monthly series from 1836; and its wettest and second-wettest winters (2014 and 2016), and the driest September (2014).

3.2 | England and Wales precipitation

The annual rainfall total for 2022 in the long-running England and Wales precipitation (EWP) series was 857 mm, which is 88% of the 1991–2020 average (Figure 34). This series shows there are some notable decadal fluctuations in the series such as a wet period through the 1870s, and the 'Long Drought' from 1890 to 1910 (Marsh et al., 2007), which highlight the value of rainfall series before the 20th century for understanding the full historical context of UK rainfall. The most recent decade 2013–2022 is 1% wetter than 1991–2020 and 8% wetter than 1961–1990. Importantly, the England and Wales areal rainfall series based on 1 km resolution gridded data is highly correlated to EWP for the period of overlap, with an R^2 value of 0.98 and root mean square difference of 1.8%. Minor differences between the series are inevitable due to the more limited

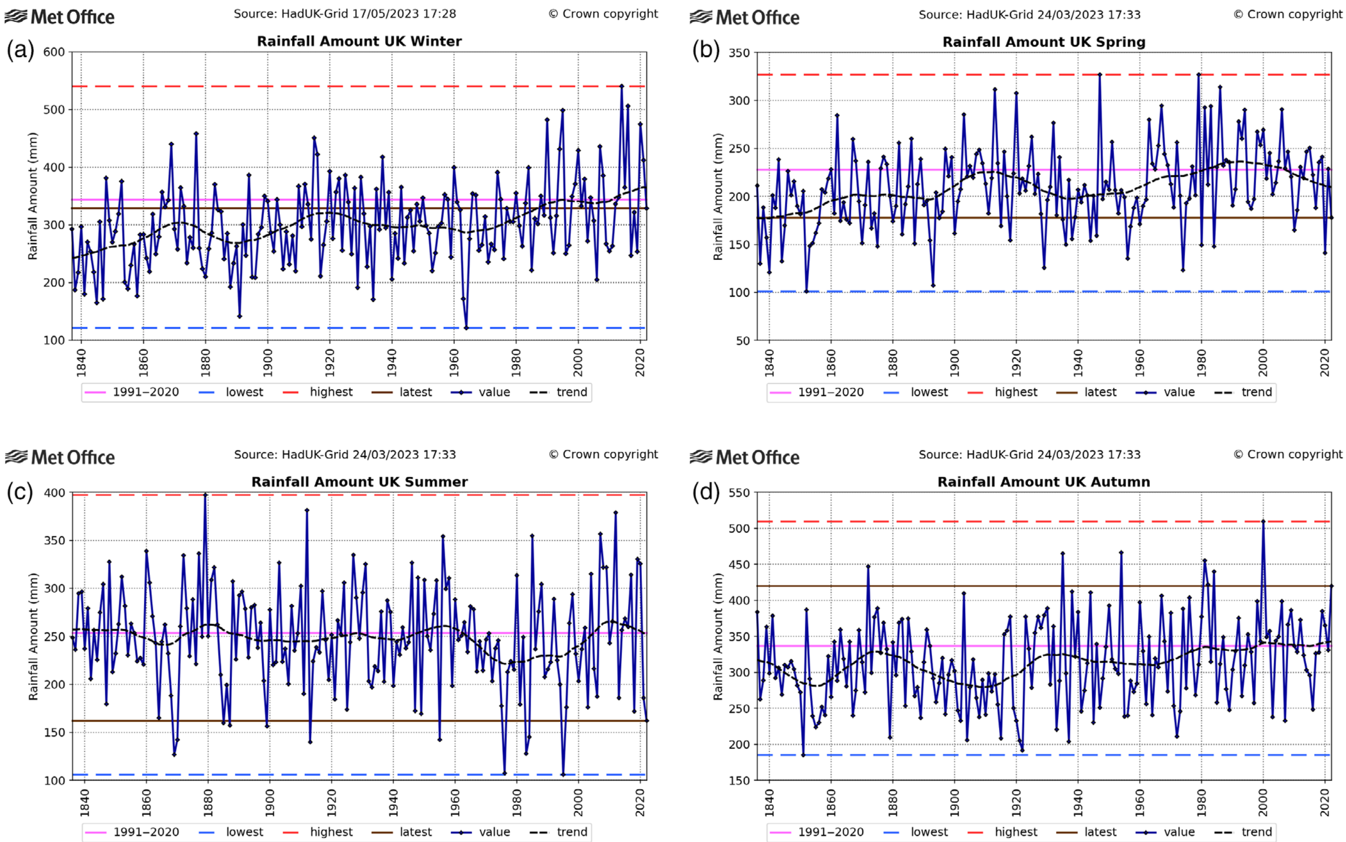


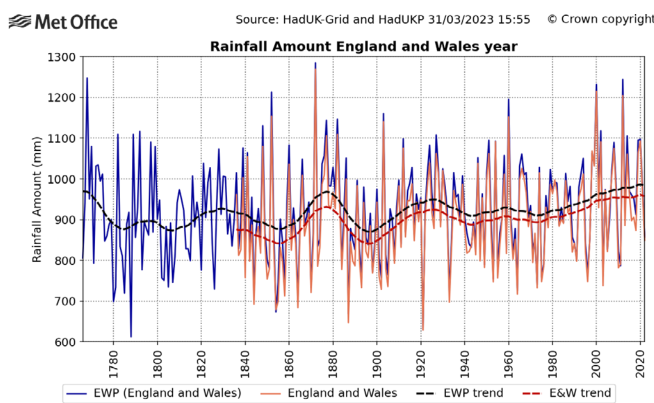
FIGURE 33 Seasonal rainfall for the UK for (a) winter, (b) spring, (c) summer and (d) autumn, 1836–2022 (winter 1837–2022).

sampling of stations used for the EWP series and the gridding method used for the England and Wales areal series.

Figure 35 shows trends in seasonal EWP rainfall amounts from 1766 to date, together with the England and Wales series from the HadUK-Grid dataset. The long-term mean for the annual EWP series is comparatively stable, but this is not the case for the seasonal series. Some caution is needed interpreting these seasonal trends, however, the datasets show good agreement.

EWP shows a marked increase in winter rainfall (winter 2014 is the wettest winter in this series, 2021 ranked seventh wettest, 2016 ranked ninth wettest and 2020 ranked 12th wettest). Prior to 1900, EWP winter rainfall was substantially lower than autumn rainfall, but the increase in winter rainfall has meant that during the 20th-century autumn and winter rainfall were roughly equal on average. The increasing winter rainfall has been offset by a slightly smaller reduction in summer rainfall, while spring/autumn rainfall have each remained fairly steady with only a slight increase/decrease respectively.

These seasonal trends are very sensitive to the choice of start and end dates. There are also potential issues with the estimation of winter rainfall early in the series



	1961–1990	1991–2020	2013–2022	2022
EWP (England and Wales)	915	971	984	857
England and Wales	897	951	955	849

FIGURE 34 Annual rainfall for England and Wales (EWP) 1766–2022, and England and Wales from HadUK-Grid dataset, 1836–2022. The table shows actual values (mm).

relating to the treatment of snow before systematic meteorological observing networks were established which could be associated with an underestimation (Murphy

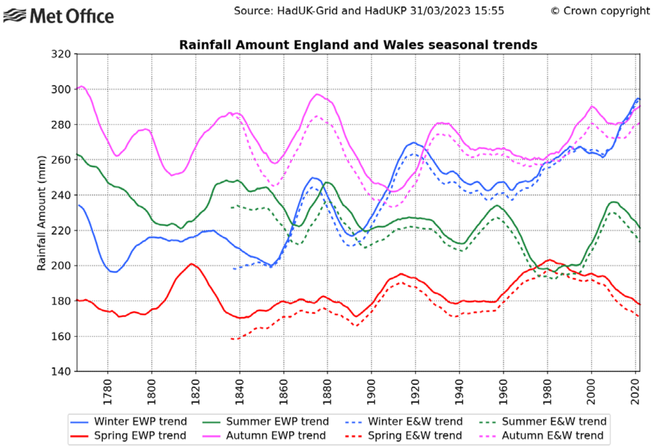


FIGURE 35 Seasonal EWP trends 1766–2022 (winter 1767–2022) showing the smoothed trends for each series using a weighted kernel filter described in Appendix B1. The equivalent England and Wales (E&W) series from the HadUK-Grid dataset are also shown dashed.

et al., 2020). The lower number of rain-gauges earlier in the series used to construct EWP and how well they represent the wetter upland parts of western Britain (where winter rainfall is likely to be higher) could also be a factor. Summer rainfall trends in the 18th and early 19th century are also subject to some uncertainty and possibly overestimated (Murphy et al., 2020).

The rainfall statistics throughout this report are presented to the nearest whole mm, but the uncertainties of the areal statistics relating to changes in the observing network change over time. The standard error can approach 1% or less when the network comprises several thousand rain gauges but approaches 4% in early decades where this number reduces. The uncertainties are therefore generally much smaller than the year-to-year variability, and more detail on this can be found in Appendix B. However it is non-trivial to determine the robustness or significance of observed trends in rainfall as they are quite sensitive to region, season and choice of start and end dates.

3.3 | Daily rainfall and extremes

Figure 36 shows UK daily rainfall totals for each day of the calendar year 2022, and Figure 37 the time series of UK area-average daily rainfall. Figure 38 shows UK area-average daily rainfall as an accumulation through the year. Spells of dry weather (generally associated with high pressure bringing settled conditions) occurred mainly in mid-to-late January, the second half of both March and April, much of July and early August, mid-September and the first half of December. More prolonged spells of unsettled weather associated with low pressure and rain-bearing fronts occurred most notably in February, from late September through the autumn, and in the second half of December, but with other shorter spells throughout the year. For the UK overall, rainfall deficits built up from March to September and by the end of the year had only partially recovered with deficit at the end of December equivalent to approximately 1 month's average rainfall (Figure 38).

As occurs every year in the UK, there were various flood events during 2022. These are described below, although this is not a comprehensive list of all flood events to affect the UK, and attempting to summarize the large number of widespread events which typically happen is always challenging. In terms of the overall scale of impacts, these events were generally less significant than flooding from preceding years such as from storms Ciara and Dennis in February 2020, the South Yorkshire floods of November 2019, or the Cumbria floods from storm Desmond in December 2015.

The sequence of storm in mid-February, including Dudley (16th), Eunice (18th) and Franklin (20th–21st) resulted in a very wet succession of days and caused some flooding problems (see the wind event Section 5 describing these named storms). From 12th to 20th, more than 100 mm of rain fell widely across upland areas, and over 200 mm across parts of Wales and the Pennines. Much of Wales and northern England received the whole-month February 1991–2020 average rainfall, with some locations more than 150% of average in just these 10 days. Flows in major rivers responded, with three sites on the Rivers Severn, Mersey and Derwent recorded their highest ever levels. Around 400 properties were flooded, with severe flood warnings issued for several major rivers including the Severn and flood defences deployed at Ironbridge, Shropshire. In Yorkshire, the River Wharfe flooded the railway lines at Rotherham Central station, disrupting transport. In West Yorkshire, one of the wettest areas, 185 mm of rain fell in February, 248% of average, although this was still well short of the February 2020 total (242 mm, 325%). This part of the south Pennines has recently experienced a number of severe flood events, notably in November 2019 and February 2020. River catchments in this area (such as the River Calder in West Yorkshire) tend to be characterized by steep valley sides, with urban areas located in the valleys, contributing to flood risk, and as a consequence may suffer repeated flooding.

There were very few impacts from heavy rain events through the spring, with the weather often quiet and benign. A plume of warm, unstable air moved in from France to bring several outbreaks of

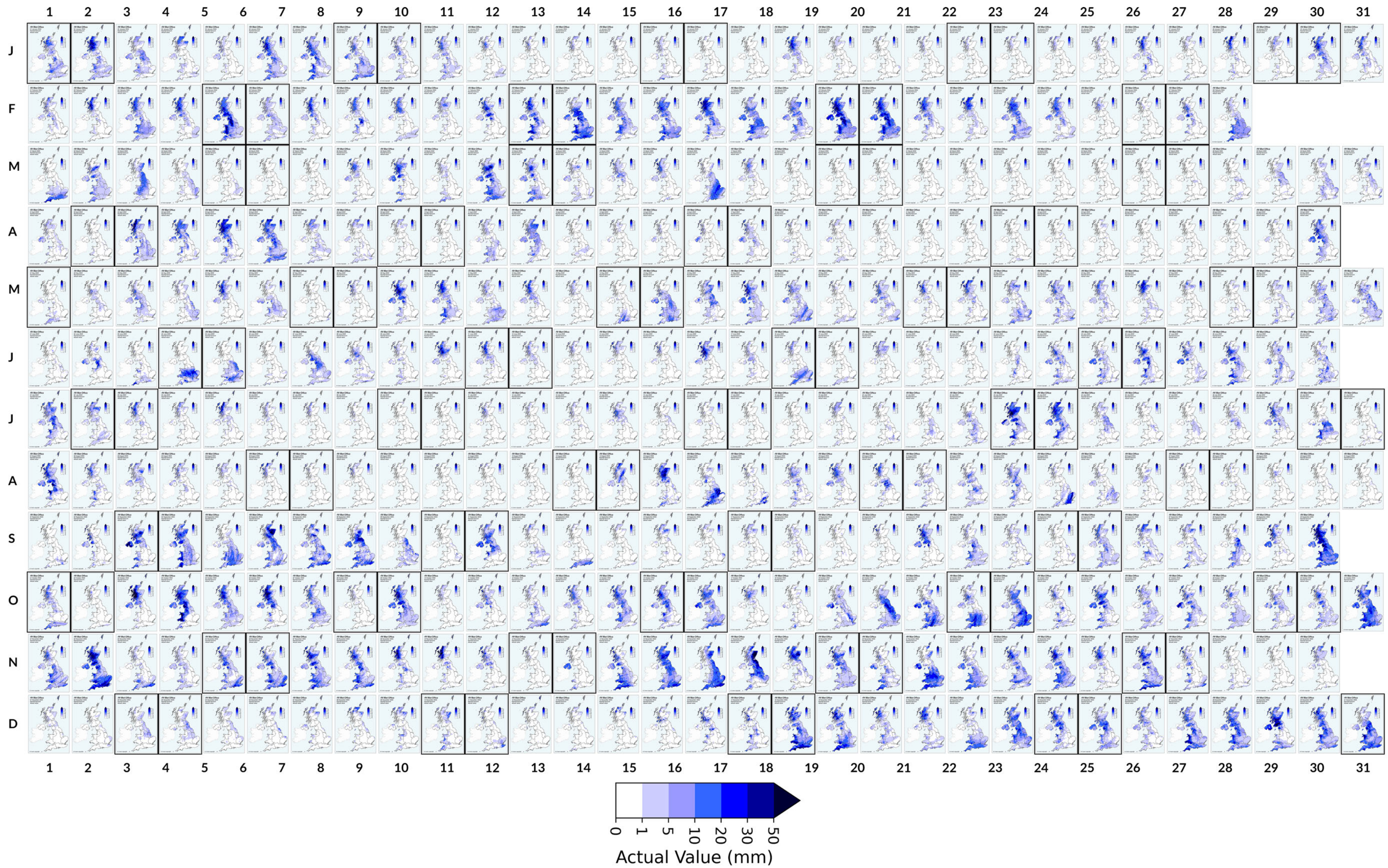


FIGURE 36 (a) 2022 daily actual rainfall by month (top to bottom) and day (left to right). Weekends are displayed with a black border. The actual shading covers 0–50 mm as shown in (b).

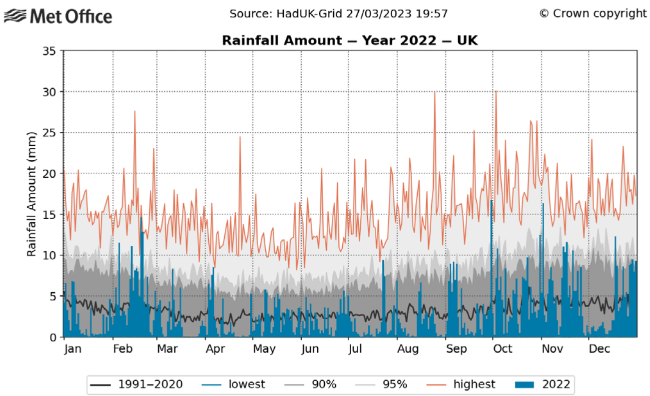


FIGURE 37 UK mean daily rainfall for each calendar day of the year 2022. The black line shows the 1991–2020 average for each calendar day; the red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1891–2022 inclusive.

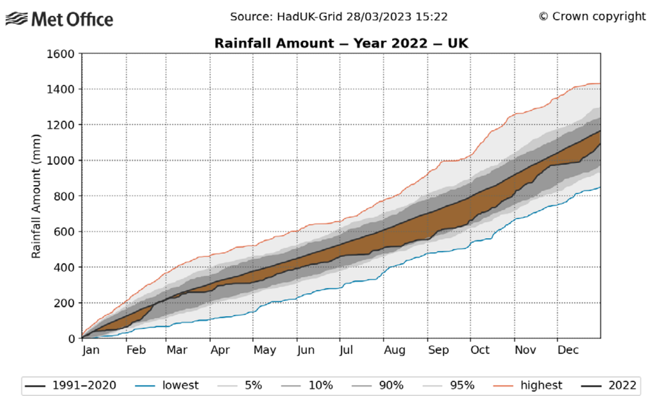


FIGURE 38 Rolling UK mean daily rainfall accumulation for the year so far, for each calendar day of the year 2022. The black line shows the 1991–2020 average for each calendar day; the red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1891–2022 inclusive. The light brown shaded area shows the accumulated rainfall deficit relative to normal for the year so far from the start of January (assuming no rainfall deficit or surplus at the start of the year).

heavy rain and thunderstorms from 16 to 19 May. The evening/night of 18th to 19th brought widespread thunderstorm activity to south-east England with significant lightning activity.

Thunderstorms and torrential downpours continued to cause occasional flooding issues through June, July and August, as is fairly typical for a UK summer. Thunderstorms affected parts of Wales and southern England during the Platinum Jubilee weekend of 2–5 June and there were further thunderstorms later in the month and towards the end of July, the latter affecting parts of Northern Ireland, Scotland and north-east England.

Atlantic weather fronts brought high rainfall across Eryri (Snowdonia) and the Lake District during the first 2 days of August (106.8 mm at Blaenau Ffestiniog, Gwynedd and 149.8 mm at Ennerdale, Black Sail, Cumbria on 1st). The Conwy river in North Wales overtopped, leading to flooding in and around the town of Llanrwst. There was a thundery break-down following the spell of hot weather from 10 to 14 August. On 14th, torrential rain in parts of Scotland led to some flooding and transport disruption and in Inverness the roof of a Tesco store partially collapsed due to heavy rain. Thunderstorms affected Cornwall on 15th and parts of South Wales and the East Midlands on 16th, with road and property flooding in Worksop (Nottinghamshire) and Market Rasen (Lincolnshire). Parts of southern England then experienced surface water flooding on 17th, with numerous roads in Greater London awash and several tube stations closed (24.8 mm in 1 h at Kew Gardens). Thunderstorms and torrential downpours developed in a belt from Hampshire through London into Norfolk and Suffolk on 24 August again causing localized flooding problems.

The weather was very unsettled and cyclonic from 3 to 9 September with low pressure just to the west of the UK bringing outbreaks of heavy rain. Flood impacts affected County Tyrone and Somerset and caused the overnight closure of the M25 in Surrey. On 6th, lightning damaged trackside equipment on the Dundee to Carnoustie rail line (daily total of 75.6 mm at Balmoral, Aberdeenshire) and the 7th and 8th saw further flooding, mainly affecting eastern Scotland, particularly Perth. On the last day of the month, an active Atlantic weather system brought some very wet weather across western upland areas; numerous sheep were reported lost in swollen rivers in Borrowdale, Cumbria.

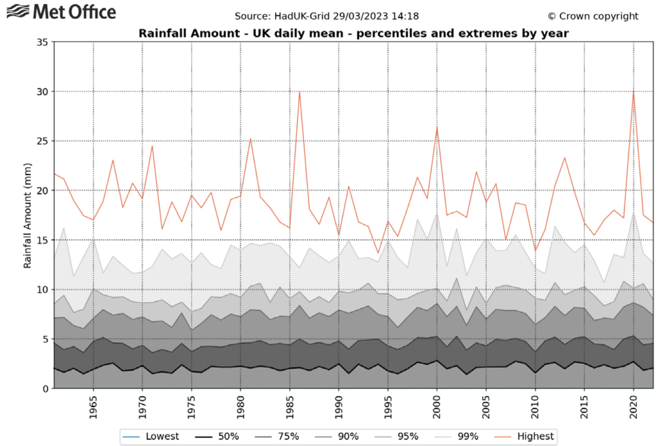
October and November saw further intermittent flooding problems; these were mostly localized and with fairly typical impacts – surface water flooding and some disruption to transport. The period 3–6 October was very wet across the West Highlands with a succession of Atlantic fronts. 182.6 mm was recorded at Alltdearg House, Isle of Skye on 3 October, the highest daily total of the year (see Section 7). On 3 November, after heavy overnight rain, flooding impacted roads and rail services across parts of Essex, London, Sussex and Kent, including some London Underground stations. Heavy rain caused disruption to parts of eastern England and eastern Scotland between 15 and 18 November; there was significant disruption to train services on 17th (daily total of 128.8 mm at Stonyford, Aberdeenshire) with reports of flooding on roads and railways as far apart as Edinburgh and Inverness.

Locally intense rain affected south Wales and south-west England on 21 November.

The weather was very unsettled during the closing days of December. Many parts of southern and eastern Scotland received the whole-month average rainfall from 18 to 31. The cumulative effect of several days' successive rainfall resulted in rising river levels. Landslips closed the West Coast Main Line between Lockerbie and Carstairs, and the Edinburgh to Aberdeen line was similarly disrupted in Fife. The River Nith in Dumfries overtopped its banks on the afternoon of the 30th, with flooding affecting the centre of Dumfries, including some properties. Sections of both the M9 and M74 were also closed due to flooding.

Figure 39 shows time series of UK daily area-average mean rainfall as percentiles for each year from 1961 to 2022, including summary statistics below. These figures are similar to those for temperature (Figure 16) and provide insight as to how these rainfall distributions have changed over this period, with the extremes of particular interest.

UK daily mean rainfall has generally increased across the distribution comparing the most recent decade 2013–2020 to 1961–1990, but the increase is greatest for the 50th percentile (13%), reducing to 3% for the 99th percentile, with very little change for maximum (Figure 39). The latter includes 30.1 mm for 2020; this was the UK's wettest day on record on 3 October (see Kendon & McCarthy, 2021). The spike in 1986 of 29.9 mm on 25 August (a late-summer bank holiday) was due to ex-hurricane Charley. The increases in the 50th to 95th percentiles when comparing 2013–2022 to 1961–1990 are consistent with the UK's climate becoming wetter (UK annual average rainfall increasing by 7% over this period). The smaller change in the 99th percentile and lack of change in the maximum reflect the fact that these extremes will tend to be dominated by the annual variability in the UK's climate.



	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
min	0.0	0.0	0.0	0.0	–	–
50%	2.0	2.2	2.3	2.1	113	102
75%	4.4	4.7	4.7	4.6	107	100
90%	7.2	7.6	7.7	7.4	107	101
95%	9.1	9.7	9.7	9.0	107	100
99%	13.3	14.0	13.7	12.6	103	98
max	19.3	18.6	19.2	16.8	99	103

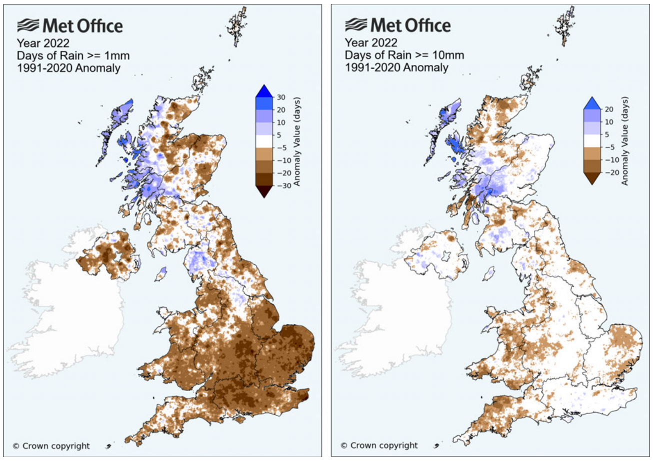
FIGURE 39 Annual distributions of UK mean daily rainfall for each year 1961–2022 (mm/%).

3.4 | Days of rain and rainfall intensity

The number of days of rain greater than or equal to 1 mm (RR1) for the UK during 2022 was 152 days, 7 days fewer than the 1991–2020 long-term average. There were fewer days of rain across England, Wales and Northern Ireland; central, southern and south-east England saw 20 days fewer fairly widely – approximately 15% (Figure 40). As is typically the case, the monthly variation was very similar to the rainfall anomaly pattern, with fewer days of rain in January, March, April, June and July and more in February, May, October and November; other months being fairly near-normal overall. The number of days of rain greater than or equal to 10 mm (RR10) was also below average, particularly across Wales and the south-west, with a variable pattern across Scotland (Figure 40).

Figure 41a,b shows the annual area-average RR1 and RR10 for the UK for 1961–2022. Overall, 2022 was below the 1991–2020 average for both RR1 and RR10, although not exceptional. For both RR1 and RR10 the year with the most days was 2000, and this year was also the second-wettest in the UK series from 1836, with only 1872 wetter. Most of the peaks in the RR1 series in the last three decades (1998, 2000, 2008, 2012, 2014 and 2020) are within the top 10 wettest years for the UK in the series from 1836. The RR1 series shows an increase from 154 days for 1961–1990 to 160 days for the most recent decade 2013–2022, and RR10 a similar increase from 31 to 35 days. This suggests an increase in the number of days of widespread heavy rain across the UK in the last few decades, although caution is needed in the interpretation of the observed trend because both time series are relatively short given the large annual and decadal variability in UK rainfall.

Figure 42 shows an estimate of the areal-average rainfall intensity across the UK for each year from 1961 to 2022 (see Appendix A2, Table A1 for definition). The figure is indicative of trends in rainfall intensity across the UK on wet days although, as with



	RR1	RR10
UK	−7	−2
England	−11	−3
Wales	−10	−5
Scotland	−1	0
Northern Ireland	−9	0

FIGURE 40 Days of rain (a) ≥1 mm (RR1) and (b) ≥10 mm (RR10) (b) for year 2022 relative to 1991–2020. The table shows anomaly values relative to 1991–2020 (days).

RR1 and RR10, it neither provides a seasonal breakdown, nor distinguishes between upland and lowland areas.

2022 was well below average for this metric. The 3 years with highest rainfall intensity in the series (2000, 2012 and 2020) also correspond to wet years for the UK, as noted for RR1. There is a slight upward increase of 0.2 mm (approximately 4%) when comparing the 1961–1990 and 1991–2020 averages, although the series is fairly flat from 1980 onwards. Again, this is a relatively short time series dominated by year-to-year variability. The rainfall intensity series is fairly well correlated with the RR10 series (R^2 value 0.71), as would be expected because in years with a large number of very wet days the average rainfall intensity on wet days is higher. In contrast, there is low correlation between the rainfall intensity series and the RR1 series (R^2 value 0.21) because in years with a large number of days exceeding 1 mm (a much lower threshold) we would not necessarily expect the rainfall intensity on wet days to be higher.

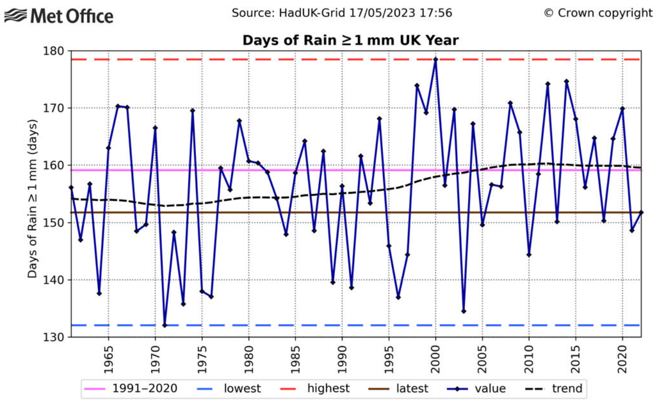
3.5 | Heavy rainfall

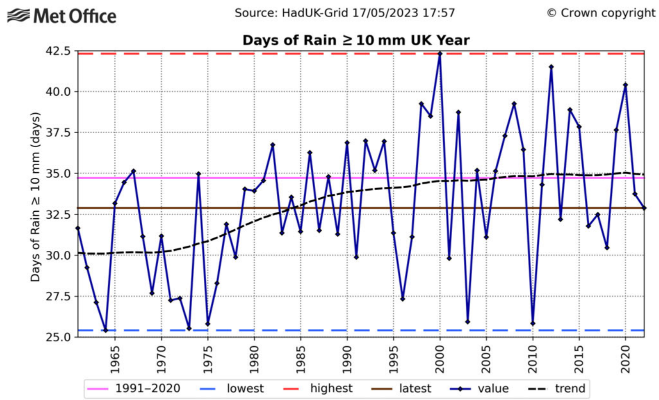
Alternative metrics for heavy rain are presented here. Heavy rainfall is a complex variable to monitor due to its potential to be highly localized, while rainfall causing surface water flooding impacts is often of short duration. These metrics adopt two different methods: a percentile approach and an absolute threshold. The ranking of individual years is quite sensitive to the choice of definition used and the series are relatively short in the context of the variability of rainfall. However, there are some consistent features across these different metrics – most notably, more heavy rain events have been recorded in the most recent decade than in earlier decades in the series.

Figure 43a,b shows the number of days each year where the rainfall total has exceeded the 95th and 99th percentiles for wet days. The 95th and 99th percentiles are calculated based on the period 1961–1990 for 'wet days' – exceeding 1 mm; the UK value is the areal-average of the number of days calculated at each grid point. (Based on Figure 41a, we would therefore expect about 5% of 154 = 7.7 days per year for the 95th percentile for the period 1961–1990 – which is indeed the case.) The percentiles and daycounts are calculated for each grid point, with the UK value as the mean of the daycount values across all grid points. As with rainfall intensity, this neither includes a seasonal breakdown, nor does it distinguish between orographically enhanced frontal rain and convective rain. This metric is based on a percentile approach with thresholds that vary geographically so that all parts of the UK will have an equal influence (since the climatologically wetter parts of the UK in the north and west will have higher percentile values than the drier parts in the south and east). This contrasts with the UK annual rainfall series which has the limitation that the climatologically wetter parts of the UK will have a greater influence and drier parts a lesser influence on the UK annual totals (see Appendix B4).

Both percentile series show large annual variability with some decadal variability, but with a rising trend for the 95th/99th percentiles from 7.7/1.6 days for the period 1961–1990 to 8.8/1.8 days for the most recent decade 2013–2022. The 2022 values for the 95th and 99th percentiles were both well below the 1991–2020 averages. The 95th percentile for wet days is well correlated with the annual RR10 series (R^2 value 0.80).

Figure 44 provides a count of the number of times each year any rain gauge in the observing network below 500 m elevation has recorded a daily rainfall total greater than or equal to 50 mm. We refer to this type of metric as a count of station-days. This metric cannot distinguish between a small number of widespread events recorded at many stations, or more frequent but localized events, but is a useful gauge of the occurrence of extreme heavy rainfall overall. This series has been adjusted to take into account the changing size of the UK rain-gauge network, which reached over 5000 gauges in the 1970s and has reduced to fewer than 3000 since the 2010s (see Figure A3).

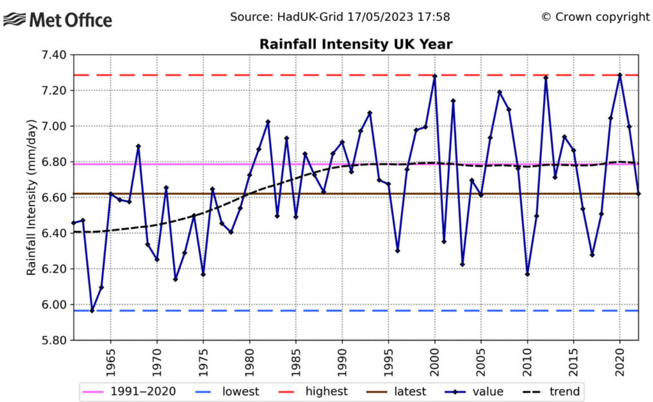




Raindays ≥1 mm	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
UK	154	159	160	152	6	1
England	131	135	136	124	4	1
Wales	167	173	175	163	9	2
Scotland	184	191	192	191	8	1
Northern Ireland	177	182	181	173	4	0

Raindays ≥ 10 mm	1961–1990	1991–2020	2013–2022	2022	2013–2022 anom wrt 1961–1990	2013–2022 anom wrt 1991–2020
UK	31	35	35	33	3	0
England	21	24	23	21	2	0
Wales	44	48	48	43	4	0
Scotland	45	50	51	50	5	0
Northern Ireland	29	32	33	31	4	1

FIGURE 41 Annual days of rain (a) ≥1 mm and (b) 10 mm for the UK, 1961–2022. The tables show actual values for the UK and countries (days), with anomaly values for 2013–2022 (days).



	1961–1990	1991–2020	2013–2022	2022
UK	6.6	6.8	6.8	6.6
England	5.9	6.0	6.0	5.9
Wales	8.0	8.1	8.1	7.6
Scotland	7.4	7.8	7.8	7.7
Northern Ireland	5.9	6.1	6.2	6.2

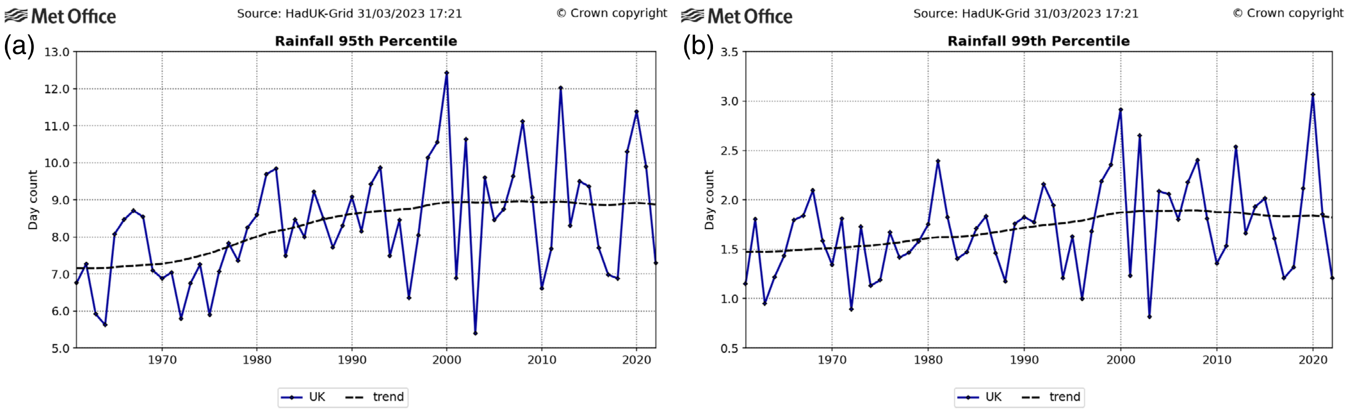
FIGURE 42 Annual rainfall intensity for the UK, 1961–2022. The table shows values for the UK and countries (mm·day^{-1}).

The dense network of several thousand rain gauges across the UK means that widespread heavy rain events will tend to be well captured, with a typical distance between individual rain gauges of approximately 10–20 km. Even so, highly localized convective events may still be missed. The series adjustment is made by applying a scaling factor (based on the number of stations in the UK rain-gauge network for each year) to the station-day counts for each year, so that earlier years are scaled down and later years scaled up, and the equivalent adjusted number of stations in the network remains constant throughout the series. However, note that this adjustment does not take into account the fact that the relative proportion of rain-gauges within different parts of the UK also changes with time. Therefore we cannot rule out the possibility that the present day network, while having fewer stations overall, may provide better sampling of regions that experience higher frequency of heavy rain days such as western Scotland.

By this metric, 2022 had a relatively low count of 945 station days, 68% of the 1991–2020 average, with the majority of this total accounted for by days with widespread frontal rainfall from Atlantic weather systems.

3.6 | Snow

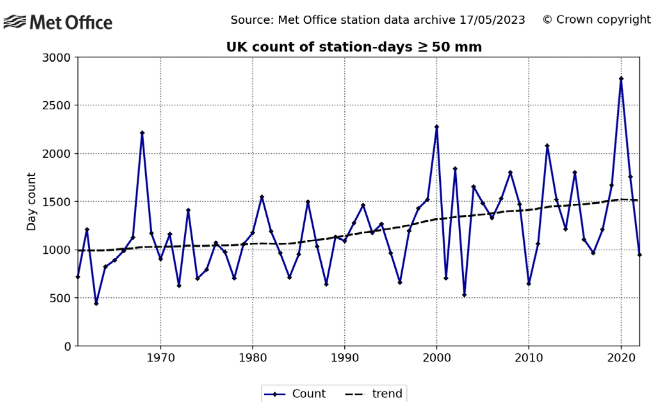
Parts of Scotland, Northern Ireland and northern England saw snow in early January, mainly across upland areas – although not unusual for the time of year. Snow depths reached 11 cm at Loch Glascarnoch, Highland on the 8th. There were some difficult driving conditions with a number of high level routes closed. There was further snow in February, mainly affecting Scotland, including some transport disruption in northern areas associated with storm Eunice on 18th. There were late snowfalls at the start



	1961–1990	1991–2020	2013–2022	2022
UK	7.7	8.9	8.8	7.3
England	6.6	7.4	7.3	6.1
Wales	8.3	8.9	8.5	5.9
Scotland	9.2	11.2	10.8	9.4
Northern Ireland	8.9	10.4	10.9	9.2

	1961–1990	1991–2020	2013–2022	2022
UK	1.6	1.9	1.8	1.2
England	1.3	1.5	1.5	0.9
Wales	1.7	1.8	1.8	0.7
Scotland	1.9	2.4	2.3	1.8
Northern Ireland	1.8	2.2	2.1	2.0

FIGURE 43 UK mean number of days each year where rainfall totals have exceeded (a) the 95th percentile and (b) the 99th percentile. The tables show values for the UK and countries (days).



	1961–1990	1991–2020	2013–2022	2022
UK	1031	1387	1496	945

FIGURE 44 Annual count of the number of UK station-days which have recorded daily rainfall totals greater than or equal to 50 mm from 1961 to 2022, adjusted for station network size and excluding stations above 500 m above sea level. The table provides average annual values (station-days). Note that the number of station-days for 1961–1990 and 1991–2020 have changed slightly from last year's report (1037, 1395). This is both because the adjustment for station network size has altered as a result of inclusion of year 2022, and also historical observations held within the climatological database may change over time as more digitized data are added or as a result of quality control; data for the full series have been re-extracted from this live database.

of March during a brief cold snap which extended into early April associated with a cold plunge. Copley (County Durham) and Redesdale Camp (Northumberland) recorded 10 cm on 31 March and 1 April respectively. A number of road traffic accidents were reported in Derbyshire, Lincolnshire and Norfolk on the morning of 31 March.

The most significant snow event of 2022 was from 8 to 18 December (described in Section 9.4), although this was neither as deep nor widespread as that of the previous February 2021. Significant and widespread lying snow might have been considered fairly typical for a UK winter of several decades ago. However, this type of event has become increasingly unusual in a warming climate over the last two or three decades. The last spells of significant and widespread lying snow across lowland parts of the UK were in February 2021, February–March 2018, January and March 2013 and January and December 2010 (with the February 2021 snow being general shorter in duration and less severe than these earlier spells). 2010 was the snowiest year by far for the UK in the last two decades, and was comparable to several snowy years in the 1970s and 1980s.

Figure 45 shows the count of station-days where snow depth sensors recorded greater than or equal to 10 or 20 cm of lying snow. The series has not been adjusted for network size, consequently it is indicative but not homogeneous (with the 2022 network size less than half that of the 1960s to 1990s, see Appendix A13).

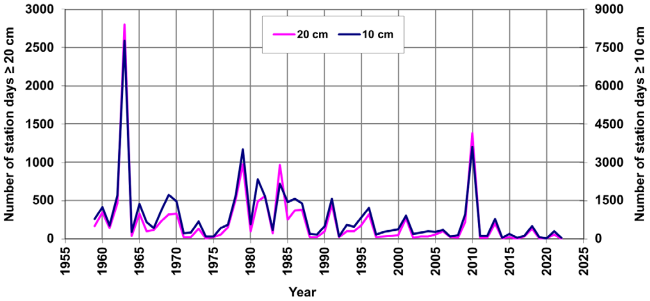


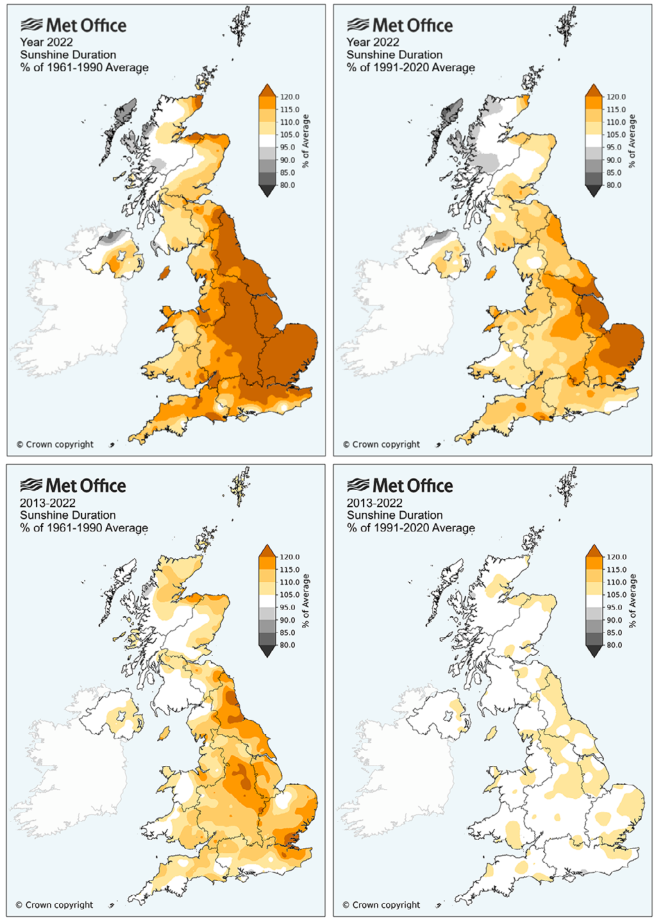
FIGURE 45 Count of number of station-days per year in the UK with recorded snow depths exceeding 20 cm (left-hand axis) and 10 cm (right-hand axis), excluding stations above 500 m above sea level. This series has not been adjusted for network size. The 2022 values are 39 (10 cm) and 0 (20 cm).

Despite the cold snap in December, 2022 was one of the least snowy years in this series, comparable with several other recent years in the most recent decade (2020, 2019, 2016 and 2014). Since the start of the 20th century, the UK's most severe spells of wintry weather (and the coldest UK months) occurred in January 1963 and February 1947. The 1960s had a greater frequency of snowfalls and blizzards than any decade since the 1860s and 1870s (Wild et al., 2000) and there were also some very substantial snow events through the 1970s and 1980s.

4 | SUNSHINE

The UK sunshine total for 2022 was 1538 h, 110% of the 1991–2020 average. Most areas were sunnier than average, with the exception of north-west Scotland and the west of Northern Ireland. Eastern England had a particularly sunny year (Figure 46). The sunniest locations in the south and east received more than twice the annual sunshine hours compared to the dullest in the north and west (over 2000 h compared to less than 1000). Preston Cove House, Dorset was the sunniest location with 2204 h, 118% of average. Tulloch Bridge, Highland was the dullest location with 902 h. A long-term average is not available for this station but this represents approximately 90% of normal in this area. For the UK, 2022 was the seventh sunniest year in the series from 1910. England had its equal-sunniest year on record (with 2003), while southern England had its sunniest year on record by margin of 14 h.

The most recent decade 2013–2022 has been 3% sunnier than 1991–2020 and 9% sunnier than 1961–1990 with slightly larger increases across England compared to the other countries (Figure 46, Table 7). Four years within the 21st century have been in the top 10 sunniest in the UK series, including most recently 2018, 2020 and 2022. The most recent decade 2013–2022 is the sunniest 10-year period in the UK series.



2022	1961–1990	1991–2020
UK	116	110
England	122	114
Wales	113	108
Scotland	106	103
Northern Ireland	105	103

2013–2022	1961–1990	1991–2020
UK	109	103
England	112	104
Wales	107	103
Scotland	105	102
Northern Ireland	104	102

FIGURE 46 Sunshine anomalies relative to 1961–1990 and 1991–2020 for year 2022 and the decade 2013–2022. The tables show anomaly values for the UK and countries (%). Due to missing sunshine observations for Lerwick the maps for Shetland for 2022 should be disregarded.

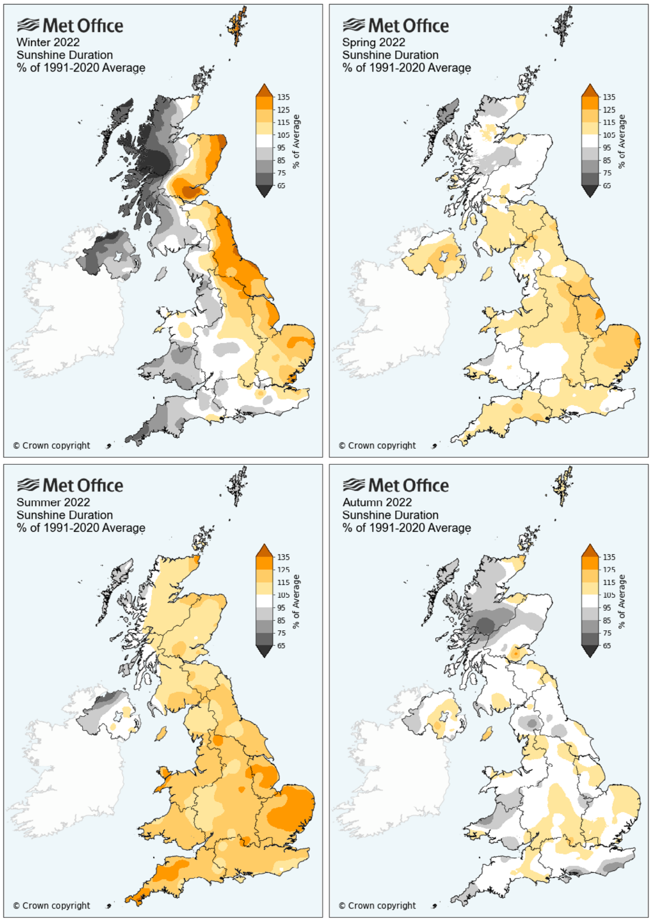


FIGURE 47 2022 seasonal sunshine anomalies relative to 1991–2020. Winter refers to the period December 2021 to February 2022. Due to missing sunshine observations for Lerwick the maps for Shetland for 2022 should be disregarded for winter, spring and autumn.

Figures 47 and 48 and Table 6 show seasonal and monthly sunshine anomalies across the UK for 2022. Winter 2022 saw a marked dull (west) to sunny (east) pattern in sunshine anomalies. December 2021 was a dull month across the UK (the dullest calendar month since January 1996, see Kendon et al., 2022). January was very sunny across eastern England and for England this was the sunniest January in the series with almost 50% more sunshine than average. The dull (west) to sunny (east) sunshine anomaly pattern was most prominent in February; this was a very westerly month dominated by Atlantic weather systems.

Spring sunshine totals were above average in most areas but the months were of very different character. March was the second-sunniest month in the series with 152% of average for the UK, April was slightly sunnier than average, and May was very dull. The UK March sunshine total of 166 h exceeded that of May (154 h); only the second time this has occurred in the UK series. Scotland and Northern Ireland each had their sunniest March on record. For Northern Ireland, the margin was 27 h, and remarkably, here, sunshine totals reduced each consecutive month from March to July, with the months of May to July all seeing around only three-quarters of normal sunshine or less.

The UK had a sunny summer (585 h, 115% of average), although not exceptional. It was the sunniest summer since 2018 and sunny across the UK except Northern Ireland and western and northern fringes of Scotland. June and August were the sunniest months (the UK had its fourth-sunniest August on record). High pressure was frequently established across the UK in August and overall this was the sunniest month of the year.

The UK autumn sunshine total was equal to the long-term average. Monthly sunshine totals were unremarkable; September and November were slightly duller than average whereas October was slightly sunnier, but all with a variable pattern across the UK. December was relatively sunny for most of the UK. In summary, the year was generally sunny, especially across England, with January, March and August the sunniest months and only May notably dull.

Table 7 shows monthly, seasonal and annual sunshine anomaly values for the UK and countries for the most recent decade 2013–2022 against both 1961–1990 and 1991–2020. The most recent decade has been 3% sunnier than 1991–2020 and 9% sunnier than 1961–1990 overall. UK sunshine totals have increased most in winter and spring compared to 1961–1990 (14% and 16% respectively), and for England by 21% and 18%. The months of January to April and July have seen the largest increases, with smaller increases in the other months and no change in June, October and November. Christidis et al. (2016) found evidence of human influence on winter sunshine extremes in the UK with the increase in winter sunshine most likely to be explained by changes in aerosol emissions. These decadal statistics will reflect annual and decadal variability in the UK's climate in addition to the overall increasing sunshine trend.

Figures 49 and 50 show annual and seasonal sunshine totals for the UK from 1910 to 2022 inclusive. The smoothed trend shows an increase in sunshine from a low during the 1960s to 1980s to a sunnier period from 2000 onwards. This increase is most apparent in the winter and spring series but largely absent in summer. The most recent decade 2013–2022 has seen seven seasons out of 40 in the top 10 sunniest: three in winter (2015, 2018 and 2019); two in spring (2015 and 2020); one in summer (2018); one in autumn (2018) – whereas none have fallen in the top 10 dullest. Only one season in the

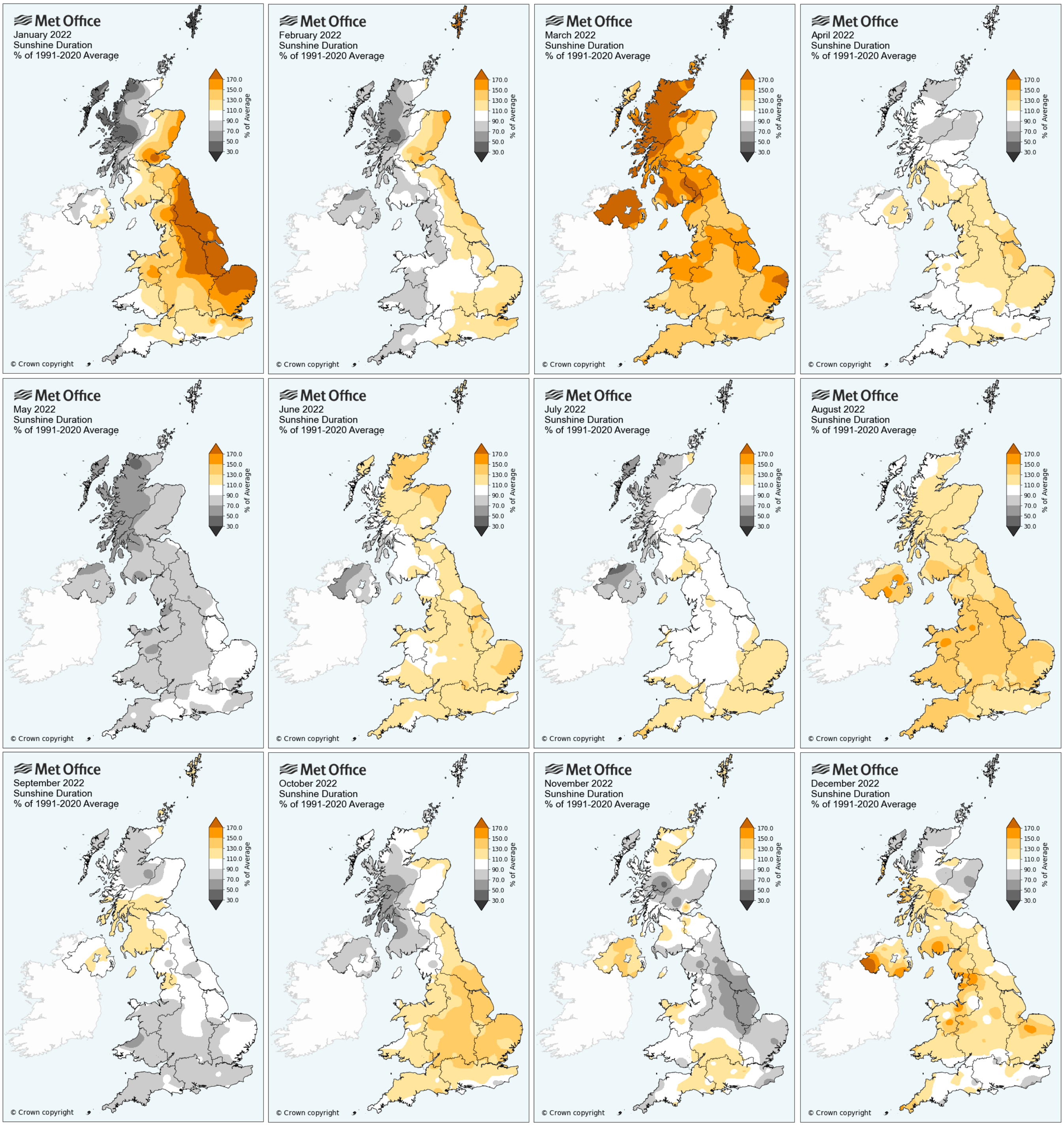


FIGURE 48 2022 monthly sunshine anomalies relative to 1991–2020. Due to missing sunshine observations for Lerwick, the maps for Shetland for 2022 should be disregarded for January, February, March and November. The legend scale ranges from 30% to 170%.

21st century has fallen in the top 10 dullest; the summer of 2012.

The addition of the years 1910–1918 in the sunshine series has resulted in the inclusion of the contrasting consecutive years of 1911 (UK annual anomaly 110%, the sixth-sunniest year in the series) and 1912 (80%, the dullest). Much of this is due to the markedly different summers of 1911 ('perfect' – warm, dry and sunny) and 1912 ('calamitous' – cold, wet and dull) – with the former summer having almost twice as many sunshine hours for the UK than the latter (for more details see Kendon & Prior, 2011).

TABLE 6 Monthly, seasonal and annual sunshine actual values (hours) and anomaly values (%) relative to 1991–2020 for the UK and countries for year 2022.

	UK		England		Wales		Scotland		Northern Ireland	
	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly
January	64	134	83	149	56	120	38	106	43	101
February	74	103	85	109	61	88	63	99	53	80
March	166	152	169	145	159	145	157	161	188	186
April	168	108	188	114	164	104	138	97	158	106
May	154	80	172	86	150	79	129	71	137	75
June	197	115	222	118	199	112	168	115	115	76
July	179	103	216	110	189	107	130	92	95	70
August	208	129	238	132	225	141	157	117	190	140
September	119	93	127	90	104	80	108	101	118	105
October	105	114	130	126	106	116	68	91	72	85
November	55	95	58	90	58	105	47	98	68	125
December	49	116	60	117	50	122	32	106	51	135
Winter	165	102	197	107	144	92	123	96	118	80
Spring	488	107	528	110	473	103	424	101	483	112
Summer	585	115	676	120	614	119	455	108	400	95
Autumn	278	100	315	102	268	97	223	97	259	102
Annual	1538	110	1747	114	1522	108	1234	103	1289	103

Key						
Dullest on record	Top 10 dullest	Dull: ranked in lower third of all years	Middle: ranked in middle third of all years	Sunny: ranked in upper third of all years	Top 10 sunniest	Sunniest on record

Note: Colour coding corresponds to the rank as given in the key. The series lengths are 1910–2022 (113 years) except winter which is 1911–2022 (112 years).

TABLE 7 Monthly, seasonal and annual sunshine anomaly values (%) relative to 1961–1990 and 1991–2020 for the UK and countries for the decade 2013–2022.

	UK		England		Wales		Scotland		Northern Ireland	
	6190	9120	6190	9120	6190	9120	6190	9120	6190	9120
January	111	101	116	103	98	91	105	101	98	101
February	121	108	130	109	114	105	110	109	109	104
March	117	107	118	106	117	107	115	109	111	107
April	125	113	129	112	120	111	120	115	112	109
May	108	100	110	103	108	103	105	95	106	99
June	100	103	103	103	107	105	94	101	96	101
July	113	108	116	108	114	112	106	107	104	105
August	103	100	106	101	97	98	100	98	98	97
September	107	100	107	101	106	100	107	97	101	95
October	100	96	100	95	98	94	99	96	108	104
November	100	100	100	99	94	100	104	102	101	104
December	106	96	113	99	90	86	94	90	106	96
Winter	114	103	121	104	102	95	105	102	104	101
Spring	116	106	118	107	114	107	113	105	109	105
Summer	105	104	108	104	106	105	100	102	99	101
Autumn	103	98	103	99	101	98	104	98	103	100
Annual	109	103	112	104	107	103	105	102	104	102

Key: <80% | 80%–90% | 90%–95% | 95%–105% | 105%–110% | 110%–120% | >120%

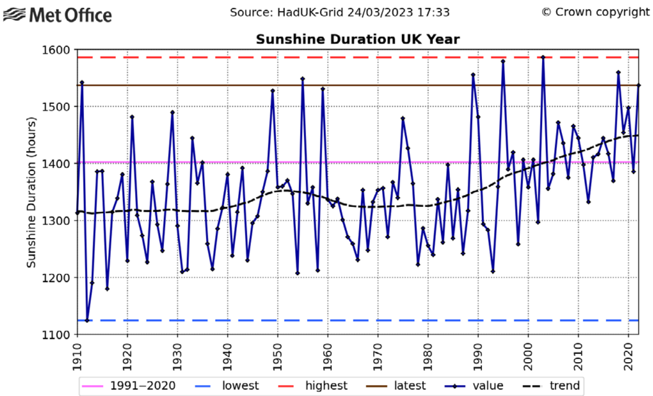
Note: Colour coding corresponds to the anomaly values as given in the key.

The sunshine network is relatively sparse, with the 2022 network comprising around 122 stations (Figure A5). Some parts of the UK such as Highland Scotland and central Wales have relatively few observations. Sunshine stations may be affected by exposure issues, particularly in the winter months when the sun is at a low elevation and topographic shading may be important. This, for example, is the case at Tulloch Bridge which has mountains exceeding 1000 m elevation within a distance of 5 km to the south and southwest. The sunshine statistics throughout are presented to the nearest whole hour, but the uncertainties of the areal statistics relating to changes in the observing network over time can approach 2% (equivalent to approximately 5 min per day, on average). More details can be found in Appendix B.

5 | WIND

The windiest days of 2022 are listed in Table 8, and named storms are listed in Table 9. (In this report, storms are grouped by calendar year, not by winter season.) As with previous years, storms in 2022 were named as part of an initiative between the Met Office, Met Éireann and KNMI (the Irish and Dutch national weather services). Other European national meteorological agencies also apply names to storms. Storm naming improves the communication of approaching severe weather through the media and government agencies by using a single authoritative system. Storms are named based on a combination of both the impact the weather may have, and the likelihood of those impacts occurring, taking into account wind, rain or snow. The number of named storms from year-to-year should not be used as a climate index in its own right because the criteria for naming storms have changed since the scheme was first introduced in autumn 2015. Five named storms occurred in 2022, these all occurring in January and February (Table 9).

Storms Malik and Corrie arrived in quick succession in late January and brought damaging north-westerly winds to northern Scotland and north-east England. Malik brought widespread gusts of over 60 Kt (69 mph) on 29 January across Scotland and north-east England, with a highest gust of 81 Kt (93 mph) at Brizlee Wood (Northumberland). Corrie arrived just 36 h later on



	1961–1990	1991–2020	2013–2022	2022
UK	1328	1403	1450	1538
England	1431	1538	1598	1747
Wales	1352	1407	1451	1522
Scotland	1166	1200	1229	1234
Northern Ireland	1234	1256	1282	1289

FIGURE 49 Annual sunshine for the UK, 1910–2022. The table shows actual values for the UK and countries (hours).

30 January and brought further damaging winds, with gusts reaching 80 Kt (92 mph) at Stornoway Airport (Western Isles) and 79 Kt (91 mph) at Inverbervie (Kincardineshire). Both storms brought some ferocious gusts across Scotland's mountain summits, well in excess of 100 Kt (115 mph). On 29 January, 128 Kt (147 mph) was recorded at Cairngorm Summit, the UK's highest gust since 129 Kt (148 mph) from storm Conor on 25 December 2016 – also at Cairngorm Summit. The UK record is 150 Kt (173 mph) at this same station on 20 March 1986.

Two people were killed by falling trees in Staffordshire and Aberdeen during storm Malik. There were widespread reports of structural damage with falling bricks and debris, and the roof of a house was blown off in Gateshead. Falling trees resulted in loss of power supplies to tens of thousands of homes in areas such as Aberdeenshire, Northumberland and County Durham, although the extent of the damage was not as significant as from storm Arwen in November 2021. Storms Malik and Corrie both caused transport disruption in Scotland and north-east England, and several schools were closed in Aberdeenshire, the Highlands and Moray.

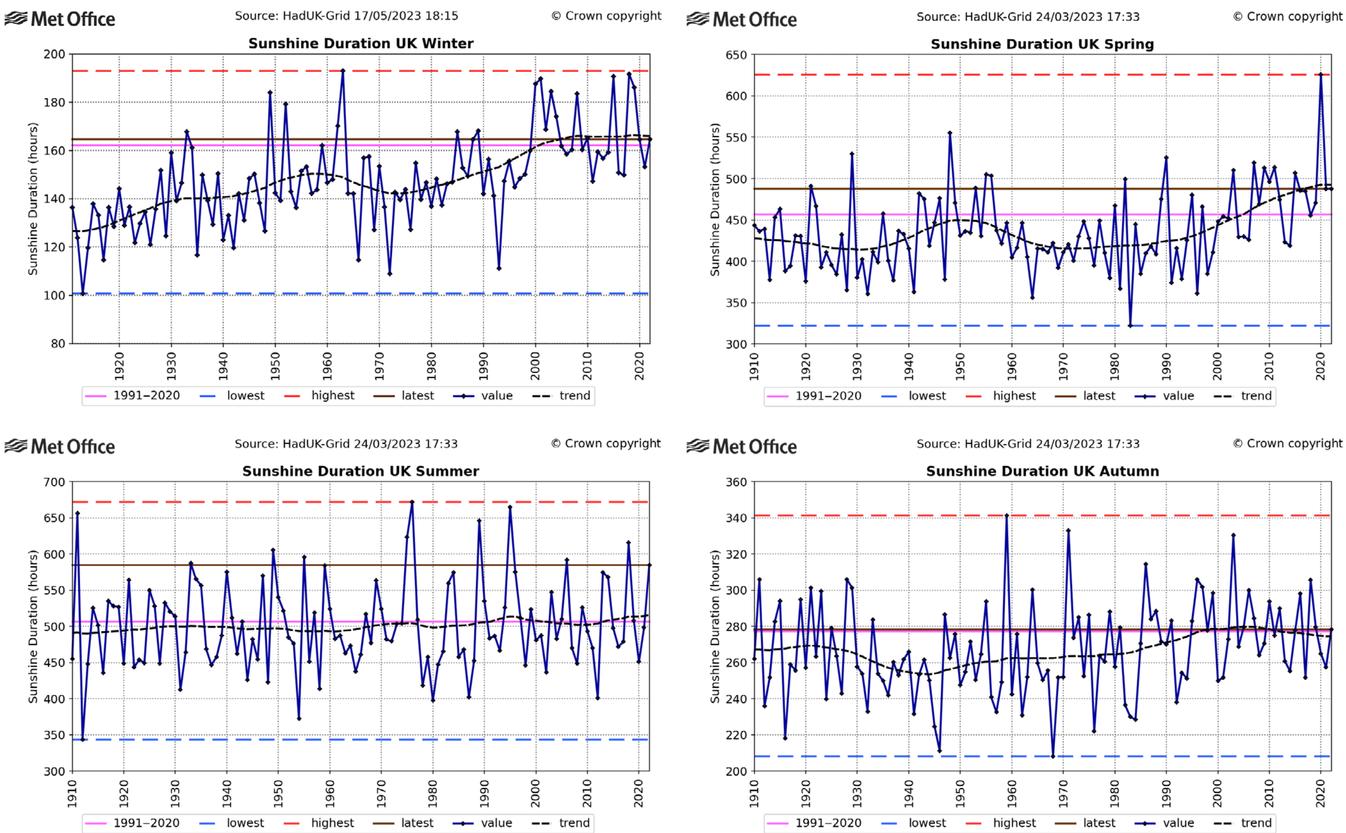


FIGURE 50 Seasonal sunshine for the UK for (a) winter, (b) spring, (c) summer and (d) autumn, 1910–2022 (winter 1911–2022).

TABLE 8 The windiest days of year 2022.

Date	England (95)	Wales (15)	Scotland (33)	Northern Ireland (12)	Total (155)	Named storm
29 January 2022	14	1	31	2	48	Malik
30 January 2022	4	1	15	1	21	Corrie
31 January 2022	7	1	7		15	Corrie
1 February 2022	3		13		16	
5 February 2022	5	3	9	1	18	
6 February 2022	8	6	9	3	26	
16 February 2022	26	5	8	4	43	Dudley
18 February 2022	76	12	1	2	91	Eunice
19 February 2022	7	3			10	
20 February 2022	42	9	7	5	63	Franklin
21 February 2022	33	9	9	8	59	Franklin
22 February 2022	3	2	6	1	12	
23 February 2022	4	2	11	1	18	
24 February 2022	5	1	5		11	
7 April 2022	7	4	2	1	14	
30 September 2022	4	3	11		18	
31 October 2022	11				11	
1 November 2022	12	2			14	
2 November 2022	7	11	8	3	29	
07 November 2022	8	7	2		17	
10 November 2022	3	3	6	1	13	
11 November 2022	4	1	6		11	
24 November 2022	4	8	4		16	
19 December 2022	6	8			14	
30 December 2022	5	4	5		14	

Note: The table lists dates where 10 or more stations across the UK recorded a maximum wind gust greater than or equal to 50 Knots (58 mph) on that day. The table also gives a count of affected stations by country. The number of wind observing sites in 2022 for each country (based on data availability) is also given in brackets.

TABLE 9 UK named storms of 2022.

Name	Date of impact on UK
Malik	29 January 2022 (named by Danish Meteorological Institute)
Corrie	30–31 January 2022
Dudley	16 February 2022
Eunice	18 February 2022
Franklin	20–21 February 2022

Just after mid-February, three named storms, Dudley, Eunice and Franklin affected the UK within the space of a week, the first time this has occurred since storm naming was introduced. These storms formed a turbulent spell of wet and windy weather associated with a powerful jet stream. Storm Eunice on 18 February was the most powerful and damaging storm of the year and is described in Section 9.1. Storm Dudley on 16 February was a fairly typical Atlantic winter storm for the UK, with the strongest winds in a swathe across northern parts, with gusts of 50–60 Kt (58–69 mph) in coastal locations and 40–50 Kt (46–58 mph) widely inland. Similar to Dudley, wind speeds from storm Franklin on 20–21 February were generally not quite as high as for storm Eunice. However, this was a particularly severe storm across Northern Ireland and parts of north-west England, with gusts of 68 Kt (78 mph) at Orlock Head (County Down), 66 Kt at Magilligan and Lough Fea (both County Londonderry), 67 Kt (77 mph) at Emley Moor, West Yorkshire and 65 Kt (75 mph) at St Bees Head, Cumbria. The strongest winds were very sustained for storm Franklin, with winds gusting at over 40 Kt for a 36-h period from midnight on 20 February to mid-day on 21 February.

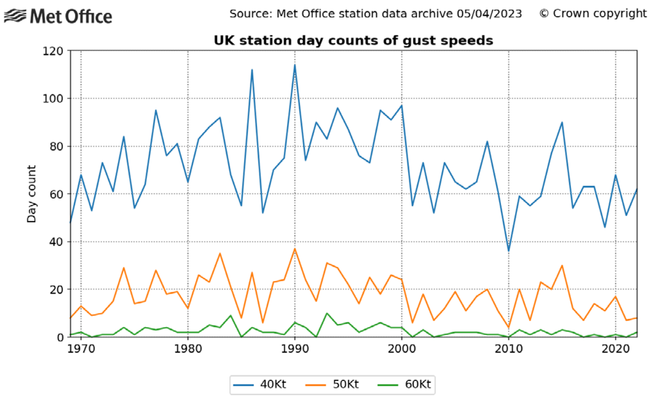
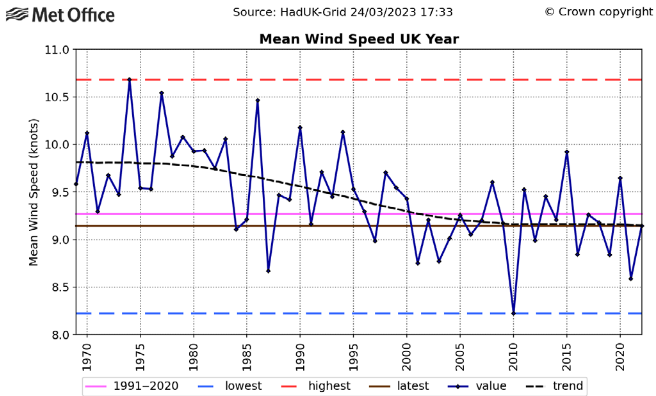


FIGURE 51 Count of the number of individual days each year during which max gust speeds ≥40, 50 and 60 Kt (46, 58, 69 mph; 74, 93, 111 kph) have been recorded by at least 20 or more UK stations, from 1969 to 2022. Stations above 500 m above sea level are excluded.



	1991–2020	2013–2022	2022
UK	9.3	9.2	9.1
England	8.3	8.2	7.9
Wales	9.7	9.8	9.4
Scotland	10.8	10.8	11.2
Northern Ireland	8.6	8.6	8.7

FIGURE 52 Annual mean windspeed for the UK, 1969–2022. The table shows actual values for the UK and countries (Kt).

Storm Dudley caused fairly typical impacts: loss of power for thousands of homes across parts of Cumbria, Yorkshire and Lancashire and disruption to rail services heading north to Glasgow and Edinburgh. The strong winds from Franklin hampered clean-up operations following Eunice. However, by this stage the main concern was flooding: the persistent heavy rain from the successive storms, together with snow at higher levels, brought significant problems in parts of England, Wales and Northern Ireland. Fortunately, severe coastal flooding in the Bristol Channel and Severn Estuary was avoided as defences held, and the storm surge did not coincide with high tide, in some places by only 90 min (see Section 6).

After this, there were no further named storms in 2022. There were none for the storm season 2022/2023 (which runs from early September to late August) before the end of the calendar year 2022; the first time this has occurred since storm naming was introduced in autumn 2015. (The first named storm of the season was not until 17 February 2023; storm Otto.) Any remaining wind impacts were generally fairly limited. On 7th April, a deepening Atlantic low pressure system tracked eastwards across southern Scotland. Fallen trees disrupted rail travel on Merseyside and the M48 Severn crossing was closed.

On 23 October, a band of locally severe thunderstorms moved north-eastwards into central southern and south-east England including London, these were the likely cause of one or two small tornadoes reported including one at Marwell Zoo near Winchester. Trees were brought down by the gusty winds in both central London and Brentwood, Essex. This system was named as storm Beatrice by the Spanish State Meteorological Agency (AEMET). The main weather impacts from strong winds and heavy rain were felt across Spain, and this was not a named storm for the UK.

On 1 November, an area of low pressure tracking rapidly north-eastwards across England brought wind gusts of 50–60 Kt (58–69 mph) along the south coasts of England and Wales. Needles Old Battery (Isle of Wight) recorded a gust of 100 Kt (115 mph) setting a new UK November gust speed record. On 2 November, another Atlantic low pressure system caused some transport disruption and the temporary closure of the Tay Bridge, Fife.

As a measure of storminess Figure 51 counts the number of days each year on which at least 20 stations recorded gusts exceeding 40/50/60 Kt (46/58/69 mph). Most winter storms have widespread effects, so this metric will reasonably capture fairly widespread strong wind events. The metric will consider large-scale storm systems rather than localized convective gusts.

The most recent two decades have seen fewer occurrences of max gust speeds above these thresholds than during the previous decades, particularly comparing the period before and after 2000. The number of station-days recording gusts exceeding 40/50/60 Kt in 2022 was broadly comparable to the period after 2000. However, there are considerable year-to-year and decadal variations in these series and they are relatively short.

Note that higher 40 Kt counts from the mid-1980s through the 1990s as shown in Figure 51 coincides with a similar period of positive phase of the winter NAO as shown in Figure 2. Since 2010, the winter NAO has been in a generally positive phase, yet this is not reflected in the gust count. This earlier period also included among the most severe storms experienced in the UK in the observational records including the 'Burns' Day Storm' of 25 January 1990, the 'Boxing Day Storm' of 26 December 1998 and the 'Great Storm' of 16 October 1987, while in the last decade the most significant major winter storms have been on 5 December 2013, 3 January 2012 and 8 December 2011 (for the latter three the strongest winds being across Scotland). Any comparison of storms is complex as it depends on severity, spatial extent and duration. Storm Eunice was the most severe storm to affect England and Wales since February 2014, but even so, these storms of the 1980s and 1990s were very much more severe.

Changes in instrument type, station network size, station exposure, and choice of metric used mean that interpreting trends in storminess from UK wind speed data is not straightforward due to the limitations of available data, and results should be treated with caution. The wind network on which Figure 51 is based comprises around 130 stations in the 1970s, 150 in the 1980s, 190 in the 1990s and 2000s and 160 in the 2010s and 2020s. Figure 51 has not been adjusted to take into account this changing network but this may partially account for the higher station counts in 40 Kt gusts through the 1980s and 1990s.

Figure 52 shows UK annual mean wind speed from 1969 to 2022 based on the HadUK-Grid dataset. This series shows a downward trend through the 1980s and 1990s. 2022 was close to the 1991–2020 average. In January, March, April, August, September and December, the UK was often influenced by high pressure and these months were less windy than average. In contrast, February 2022 was the UK's windiest month since February 2020. Both these Februarys were dominated by westerly Atlantic weather systems making them mild, windy and wet.

The 2021 BAMS state of the global climate report (Blunden & Boyer, 2022) shows that on a continental and global scale prior to around 2010 there was a widespread and general slowdown of near-surface winds termed 'global stilling'. More recently there are some indications of a reversal of this trend. Blunden & Boyer, 2022 and references within conclude that this is likely due to internal variability, which may be further influenced by anthropogenic greenhouse gas forcing, with regional influences from land use change, urbanization and instrumentation issues.

The UK mean speed series shown in Figure 52 broadly reflects the behaviours documented globally, although in the case of the UK the decline has stopped rather than reversed as reported for the global series. This series must be interpreted with some caution as it has not been rigorously assessed for long-term homogeneity of the series and observations of annual mean wind speed may be significantly affected by changes in the observing network and in the exposure of sites over time. However the broad-scale trend shares some consistency with global wind speed records.

6 | SEA LEVEL

Since 1900s sea-level rise in the UK is about 18.5 cm [15.6–21.4 cm, the 5th–95th percentiles], when excluding the effect of vertical land movement (Woodworth et al., 2009) and in good agreement with global sea-level rise estimate of 20 cm (likely range 15–25 cm) for the period 1901–2018 by the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Fox-Kemper et al., 2021).

However, UK sea-level change is not a simple linear increase, but also includes variations on seasonal to decadal timescales (Kendon et al., 2021). There is observational evidence that the rate of sea-level rise in the UK is increasing, for example, for the period since 1960s the rate of sea-level rise has increased to 2.4 ± 0.3 mm·year^{-1} (Hogarth et al., 2020), compared to the long-term estimate of 1.5 ± 0.1 mm·year^{-1} since the 1900s (Kendon et al., 2021). The rate for the period 1993–2022 has increased further to $3.8 \pm 0.9.0$ mm·year^{-1} which is comparable to the global estimate of sea-level rise of 3.3 ± 0.4 mm·year^{-1} for this same period based on satellite altimetry (updated from Johnson et al., 2022), meaning over the past 30 years, UK sea level has risen by 11.4 cm. However, the uncertainties are large due to gaps in the data: no value was able to be calculated for the UK sea-level index in 2020 and 2021 (Figure 53) as previously discussed in Kendon et al. (2022).

Sea-level rise is not uniform around the coastline of the UK. Over the past 30 years (1991–2020) the rates of sea-level rise in individual locations in the UK range from 3.0 to 5.2 mm·year^{-1} (Kendon et al., 2022), once tide gauge data have been corrected for vertical land movement in tide gauge locations associated with glacial isostatic adjustment (GIA) of the solid Earth (sometimes called post-glacial rebound). We have used GIA corrections from the ICE 5G model (Peltier, 2004; data are available from http://www.psmsl.org/train_and_info/geo_signals/gia/peltier/index.php).

The most widespread storm surges of 2022 came with storm Eunice on 18 February, with the northern Irish Sea witnessing over 1 m skew surges (see Appendix A16 for an explanation of this term). Smaller surges were also seen in most of the country through this week, with Dudley, Eunice and Franklin coming in quick succession. Fortunately, severe coastal flooding in the Bristol Channel and Severn Estuary was avoided as defences held.

Furthermore, the events fell on one of the smaller spring tides, so the astronomical contribution to the tides was lower (e.g. by 50 cm at Liverpool, 76 cm at Avonmouth) than would have occurred 2 weeks before. Storms Malik and Corrie (29–31 January) also brought surges above astronomical predictions, this time to the east coast.

Despite the neap tide Malik caused the highest water levels of the year at Cromer (skew surge 1.4 m) and Lowestoft (skew surge 1.3 m). Despite a stormy November bringing some further surges, in most locations the highest water levels of the year were just due to predictable tides (11 September). The Thames Barrier was closed six times, for storms Corrie and Franklin, and also for unnamed events on 4 and 5 January, 4 February, and 26 December.

Storm surges are caused by complex interaction between the position and speed of the low pressure system and the strength and direction of associated wind speeds, the shape of the UK coastline and water depths. The differences in the skew surge patterns in Figure 54a,b reflect the different storm tracks as illustrated by storms Malik and Eunice (Figure 55a,b). Storm Malik on 29 January took a northerly track, with northwesterly across the UK, whereas storm Eunice on 18 February crossed the UK on a much more southerly track with westerly winds.

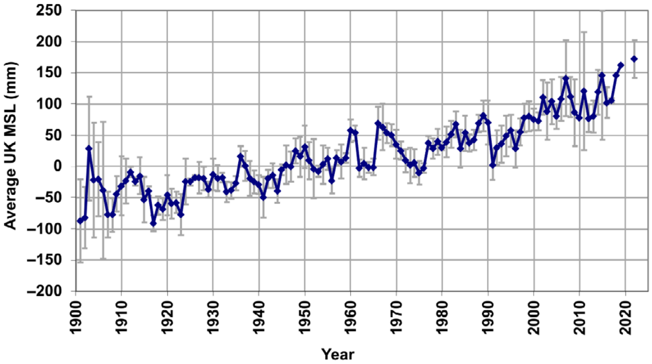


FIGURE 53 UK sea-level index for the period since 1901 calculated using sea-level data from five stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool) from Woodworth et al. (2009).

7 | EXTREMES FOR YEAR 2022

Table 10 shows the UK weather extremes for year 2022. The highest temperature of the year, 40.3°C at Coningsby, Lincolnshire on 19 July is described in the events Section 9.2. This event also set the UK's highest daily minimum temperature on record, 26.8°C at Shirburn Model Farm, Oxfordshire, exceeding the previous record, 23.9°C at Brighton, East Sussex on 3 August 1990 by a margin of almost 3°C. The lowest maximum, minimum and grass minimum temperatures and greatest snow depths all occurred in mid-December, with this event described in the events Section 9.4.

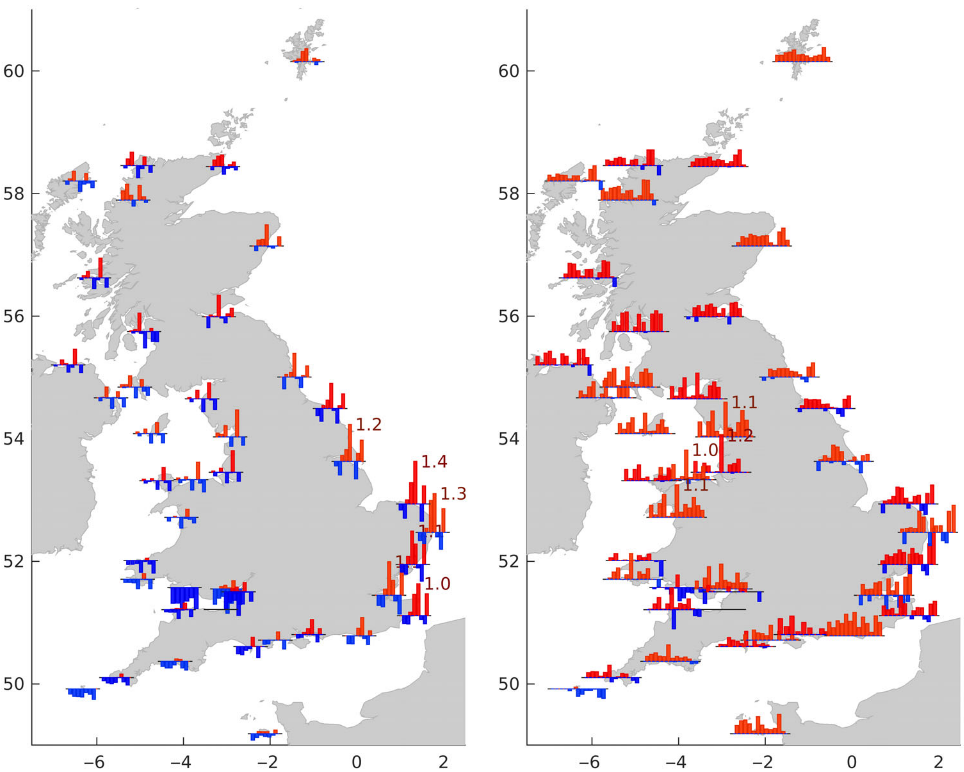


FIGURE 54 The additional height (skew surge) above each predicted High Water (red) or below predicted Low Water (blue) as measured at tide gauges during the named storms of 2022. Left storms Malik and Corrie 29 January to 31 January 2022 and right storms Dudley, Eunice and Franklin 16 February to 21 February 2022. A description of skew surge and associated diagram is included in Appendix A16.

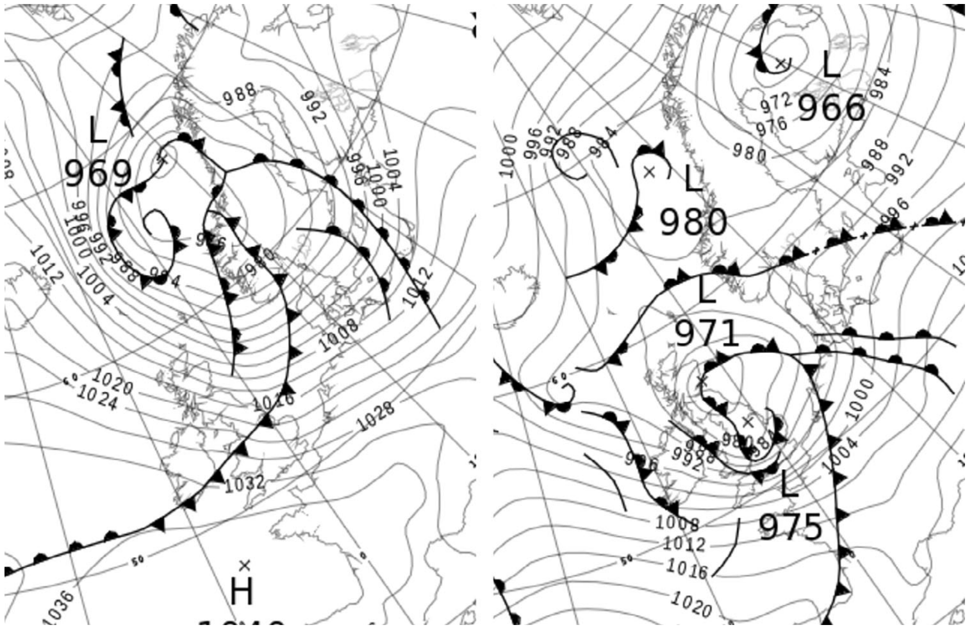


FIGURE 55 Analysis charts for storms Malik (1200 UTC 29 January 2022) and Eunice (1200 UTC 18 February 2022) compared.

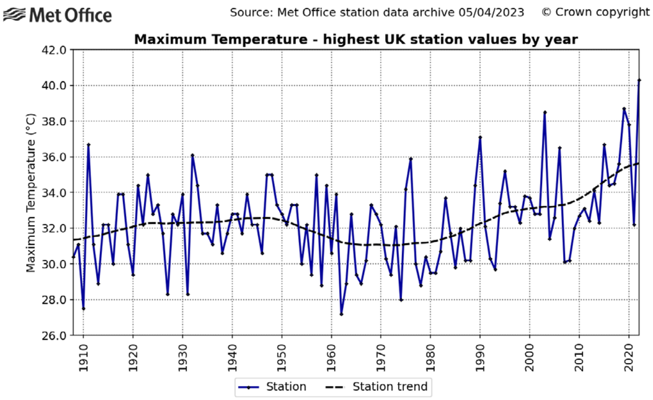
TABLE 10 Annual extremes for the UK for year 2022.

Extreme	Observation	Date	Station
Highest daily maximum temperature (0900–0900 GMT)	40.3°C	19 July	Coningsby, Lincolnshire, 6 masl
Lowest daily minimum temperature (0900–0900 GMT)	−17.3°C	13 December	Braemar, Aberdeenshire, 327 masl
Lowest daily maximum temperature (0900–0900 GMT)	−9.3°C	12 December	Braemar, Aberdeenshire, 327 masl
Highest daily minimum temperature (09–09 GMT)	26.8°C	19 July	Shirburn Model Farm, Oxfordshire, 108 masl
Lowest grass minimum temperature (0900–0900 GMT)	−17.2°C	13 December	Tulloch Bridge, Highland, 249 masl
Highest daily rainfall (0900–0900 GMT)	182.6 mm	3 October	Alltdearg House, Isle of Skye, 55 masl
Greatest snow depth (0900 GMT)	15 cm	15 December	Loch Glascarnoch, Ross & Cromarty, 269 masl
Highest daily sunshine	16.4 h	2 June	Stornoway Airport, Western Isles, 15 masl
Highest gust speed	106 Kt 122 mph	18 February	Needles Old Battery, Isle of Wight, 80 masl
Highest gust speed (mountain)	128 Kt 147 mph	29 January	Cairngorm Summit, Inverness-shire 1237 masl

Note: Stations above 500 m above mean sea level (masl) are considered as mountain stations and therefore not representative of low-level areas. They are excluded from the table with the exception of the highest mountain gust.

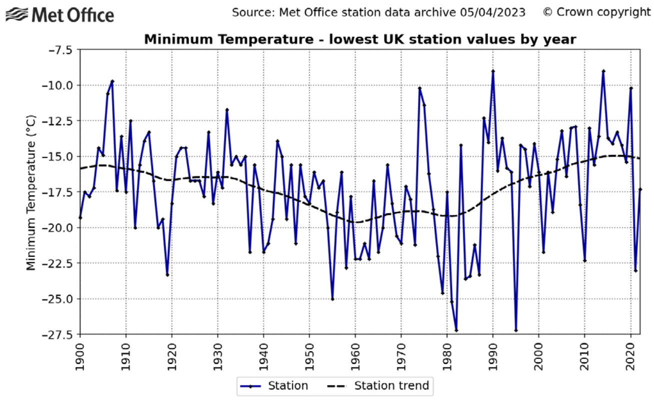
The highest daily rainfall total of 182.6 mm on 3 October 2022 occurred at Alltdearg House, Isle of Skye. This was a very wet day across the West Highlands with an autumn Atlantic low pressure system bringing prolonged heavy rainfall. Alltdeag House is located at the foot of the Cuillin Hills which are fully exposed to westerly weather systems as they lie west of the Scottish mainland. Despite being at low elevation, this station is climatologically one of the wettest in Scotland with a 1991–2020 long-term average of 3753 mm.

The highest gust speed of 106 Kt (122 mph) at Needles Old Battery occurred during storm Eunice and set a new England record. This station is located at the western end of the Isle of Wight, at 80 m above mean sea level at the top of a cliff and is fully exposed to westerly winds blowing up the English Channel. It is therefore often the windiest station in the UK – but not very representative. Storm Eunice is described in Section 9.1. The highest gust speed at Cairngorm Summit occurred during storm Malik (see Section 5).



	1961–1990	1991–2020	2013–2022	2022
Tmax	31.3	33.5	35.7	40.3

FIGURE 56 UK highest maximum temperature station observations for each year 1910–2022. The table shows actual values (°C). The figure shows the UK national record through time – in 1911 (36.7°C), 1990 (37.1°C), 2003 (38.5°C), 2019 (38.7°C) then 2022 (40.3°C).



	1961–1990	1991–2020	2013–2022	2022
Tmin	−19.0	−15.5	−14.4	−17.3

FIGURE 57 UK lowest minimum temperature station observations for each year 1910–2022. The table shows actual values (°C). The figure shows the national record in 1982 and 1995 (−27.2°) – which also occurred in 1895.

As is typically the case, the sunniest day occurred in the north near the summer solstice.

Figures 56 and 57 show the UK's highest maximum and lowest minimum temperatures, by year, across all stations, from 1908 and 1900 respectively. The UK's average highest maximum temperature for the most recent decade 2013–2022 was 35.7°C, 2.2°C higher than 1991–2020 and 4.4°C higher than 1961–1990 – these changes being much greater than the equivalent increases for the UK annual mean temperature (0.3 and 1.1°C) (Figure 4). Prior to 1990, there were only 3 years in the period 1908–1989 where the average highest maximum temperature for 2013–2022, 35.7°C, was exceeded, in 1911, 1932 and 1976.

The UK's average lowest minimum temperature for the most recent decade 2013–2022 was −14.4°C, 1.1°C higher than 1991–2020 and 4.6°C higher than 1961–1990. The period 1961–1990 included some particularly extreme cold spells with temperatures falling below −20°C in 16 of these 30 years. For comparison, in the 21st century −20°C has been recorded in just 3 years: 2001, 2010 and 2021.

8 | YEAR 2022 CURRENT AND FUTURE CLIMATE CHANGE CONTEXT

8.1 | Temperature

An 'attribution' study was carried out to quantify how human-caused climate change has influenced the likelihood of the UK having a year such as 2022, that is, with an annual mean temperature of 10°C or higher. The study used a method previously developed for rapid attribution of extreme events (Christidis, 2021). This system uses large collections of climate model simulations drawn from the global Coupled Model Intercomparison Project phase 6 (CMIP6), with one set of simulations using only natural climate forcings, and another using all natural and human-caused forcings for the historical period and the SSP2-4.5 emissions scenario out to 2100 (Riahi et al., 2017). SSP2-4.5 is a scenario which gives a medium level of warming that is broadly in line with current global policy commitments.

These two sets of simulations provide estimates of the UK annual mean temperature exceeding 10°C in a natural climate without human-caused greenhouse gases, and in the current climate (taken as the period 2013–2032). The study found that the likelihood has increased from once in every 528 years (range 118–733) in a natural climate to once in every 3.4 years (range 3.2–3.6) in the current climate. So, overall, the likelihood of this event has increased by a factor of nearly 160 due to human-induced climate change in the central case. The attribution analysis also suggests that under the SSP2-4.5 scenario the 10°C threshold is set to be crossed almost every year by the end of the century.

Figure 58 plots annual T_{mean} for the UK from 1884 to 2022 alongside UKCP from 1961 to 2100, presenting the observations against the future climate context. These are probabilistic projections of the latest set of national climate projections for the UK under different scenarios

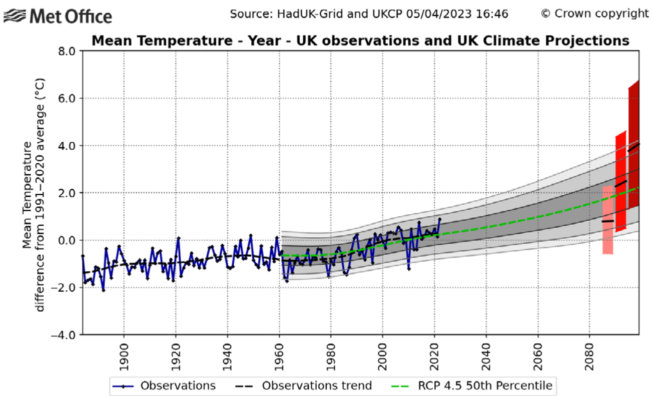


FIGURE 58 Annual mean temperature for the UK, 1884–2022 and UK Climate Projections plume plot 1961–2100 as anomalies relative to 1991–2020 showing Representative Concentration Pathway (RCP) 4.5. The grey shading shows the 5th–95th percentile, 10th–90th percentile, and 25th–75th percentile ranges. Other scenarios RCP 2.6 (light red), 6.0 (mid red) and 8.5 (dark red) are included in the 2080s showing the 50th percentile and 5–95 percentile ranges.

RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (Harris et al., 2022; Murphy et al., 2018). RCPs are broadly comparable with SSPs for temperature response (i.e. RCP 4.5 is broadly comparable with SSP2-4.5) although there are some differences in the detail including the greenhouse gas mix. The projections provide estimates of uncertainty in future change in monthly, seasonal and annual averages for key UK climate variables. The green line and grey shading show the RCP 4.5 intermediate pathway scenario and how T_{mean} would be projected to evolve through the 21st century based on this scenario. The spread represents the range of temperature accounting for both annual variability in UK climate and uncertainty in the magnitude of future change. Which emission pathway is followed will depend on how future emissions evolve globally and Earth's associated response. For example, RCP 8.5 would represent a backtracking on current global policy commitments. The figure therefore illustrates a range of possible outcomes through to 2100 and shows that thus far UK annual T_{mean} observations are broadly consistent with these projections.

By 2100 the RCP 4.5 scenario projects the UK annual mean temperature as +2.2°C relative to 1991–2020 by 2100 (50th percentile), ranging from +0.4 to +4.2°C (5th to 95th percentiles). Under the RCP 4.5 scenario, a year such as 2022 (anomaly +0.9°C, the UK's warmest year on record) would be around the 50th percentile – that is, considered an average year – by around 2060, and it would be close to the 10th percentile – that is, considered a cool year – by around 2100.

To provide a long-term perspective on the rate of change in temperature shown by these projections, the length of the UK's longest instrumental record CET series from 1659 is around 360 years, and for around three centuries to the late 20th century, fluctuations in the trend line in this series have generally been within ±0.5°C of the long-term mean over this period (Figure 12). For comparison, the future UKCP period (to 2100) is around 80 years. An intermediate scenario projects around 2°C of warming relative to 1991–2020 and a high emissions scenario 4.1°C of warming by 2100. This represents a change very much larger in magnitude than these previous fluctuations and in only a quarter of the timespan of the CET series, pushing our climate well outside the envelope of the current and historical range. Under the RCP 8.5 very high emission scenario an individual year on the 50th percentile would have an annual mean temperature of 13.2°C, which is 3.2°C warmer than 2022, currently the UK's warmest year on record.

In summary, the attribution study and climate projections together show that a year like 2022, which would have been exceptionally unlikely in the past, has a relatively high chance of occurrence in the current climate, due to climate change that has already happened, and will be increasingly likely to occur again in coming decades. By 2100, most years will be as warm as 2022 and some may be potentially very much warmer. This therefore clearly illustrates the dramatic changes projected in the UK's climate.

8.2 | Rainfall

Figure 59 similarly plots annual rainfall for the UK from 1836 to 2022 alongside UKCP from 1961 to 2100. As for Figure 58, this figure includes the same RCP 4.5 intermediate pathway scenario in grey and green, with other scenarios included, projected to 2100. Rainfall is a highly complex variable and, in the context of future climate change, the annual mean rainfall will mask many potential aspects of future changes – for example, changes in the distribution of rainfall through the year (e.g. winter rainfall increasing compared to summer rainfall decreasing) or changes in dry periods, or changes in rainfall intensity in wet weather. In terms of water resources, additional factors will add still further complexity, for example, a dependency not just on rainfall but also on evaporation rates.

All projections show a slight increase but, in contrast to temperature, there is almost no difference between the 50th percentile by 2100 between the four scenarios RCP 2.6, 4.5, 6.0 and 8.5, with the difference between these scenarios being an increased variance for the higher

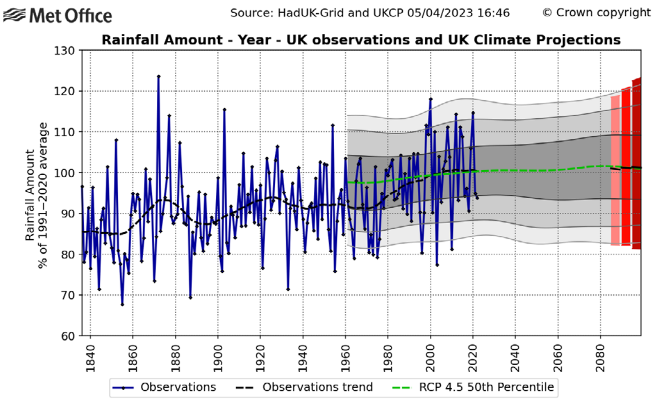


FIGURE 59 Annual rainfall for the UK, 1836–2022 and UK Climate Projections plume plot 1961–2100 as anomalies relative to 1991–2020 showing Representative Concentration Pathway (RCP) 4.5. The grey shading shows the 5–95 percentile, 10–90 percentile and 25–75 percentile ranges. Other scenarios RCP 2.6 (light red), 6.0 (mid red) and 8.5 (dark red) are included in the 2080s showing the 50th percentile and 5–95 percentile ranges.

emission scenarios. The other major difference when compared to temperature is that the range of 5th–95th percentiles by 2100 is still within that of the observations, even for the highest emissions scenario RCP 8.5 (i.e. the UK's wettest year and driest years, 1872 and 1855, lie outside this range). This reflects the very much smaller signal-to-noise ratio in rainfall compared to that for temperature (i.e. much greater annual variability relative to the long-term increase in the trend). For this same reason, identifying a trend in the UK annual mean rainfall observations is less straightforward than for temperature. By 2100, the RCP 4.5 50th percentile is virtually unchanged from the 1991–2020 mean with an increase of 1%.

9 | SIGNIFICANT WEATHER EVENTS OF 2022

This section describes notable weather events which occurred during 2022. The choice of event is determined by the National Climate Information Centre based on our many years' collective experience of monitoring the UK's climate, broadly taking into account a combination of spatial extent, severity and duration and any associated impacts. It does not represent a comprehensive list of all impactful weather affecting the UK during the year, which may be mentioned elsewhere in the report. A discussion of notable and named storms for 2022 is also included in the wind section of this report.

9.1 | Storm Eunice 18 February

Storm Eunice on 18 February 2022 was part of a sequence of three named storms (see Section 5). The analysis chart at 1200 UTC 18 February 2022 shows storm Eunice tracking rapidly east across England and Wales (Figure 60). The development of this storm was an example of explosive cyclogenesis, with the central pressure dropping by approximately 30 hPa within 18 h while the storm developed to the west of Ireland. The storm interacted with upper winds in the jet stream blowing at more than 200 mph.

The Met Office issued two red warnings for storm Eunice, with a wider amber warning area covering most of England and Wales, and further yellow warning areas for wind and snow across parts of Scotland, Northern Ireland and northern England (Figure 61). This was the second red warning issued for wind for a storm during the 2021/2022 season, following the red warning for storm Arwen on 26–27 November 2021 (see Kendon et al., 2021). It was the first time a red warning was issued for wind covering south-east England, including London.

Storm Eunice brought major weather impacts. Four people died in the UK and Ireland as a result of falling trees. Over a million homes were left without power as strong winds brought down trees. Schools and businesses were closed across Wales and the worst affected areas of England. There was major transport disruption, with trains cancelled, roads blocked by fallen trees and a number of overturned lorries. Several hundred flights were cancelled. The Port of Dover was temporarily closed to all shipping, and the Humber and Severn bridges were all closed for the first time in their history (the Humber bridge opened in 1981; the Severn Bridges in 1966 and 1996). The QEII Dartford Crossing was also closed. There were widespread reports of structural damage; the top of a church spire in Wells, Somerset was blown down and the Millennium Dome in London was damaged (see cover image). Thousands of trees – including large mature trees – were felled. Large waves, together with a storm surge on top of high spring tides battered western and southern coastlines and the Severn Estuary. For the first time, the whole of the Welsh Coastline was highlighted as being at severe risk of flooding.

The strongest winds from storm Eunice were around the coast of Wales and south-west coast of England with several stations recording gusts of over 70 Kt (81 mph) including 106 Kt (122 mph) at Needles Old Battery (Isle of Wight), 78 Kt (90 mph) at Isle of Portland (Dorset), 76 Kt (87 mph) at Mumbles Head (West Glamorgan), 73 Kt (84 mph) at Aberdaron

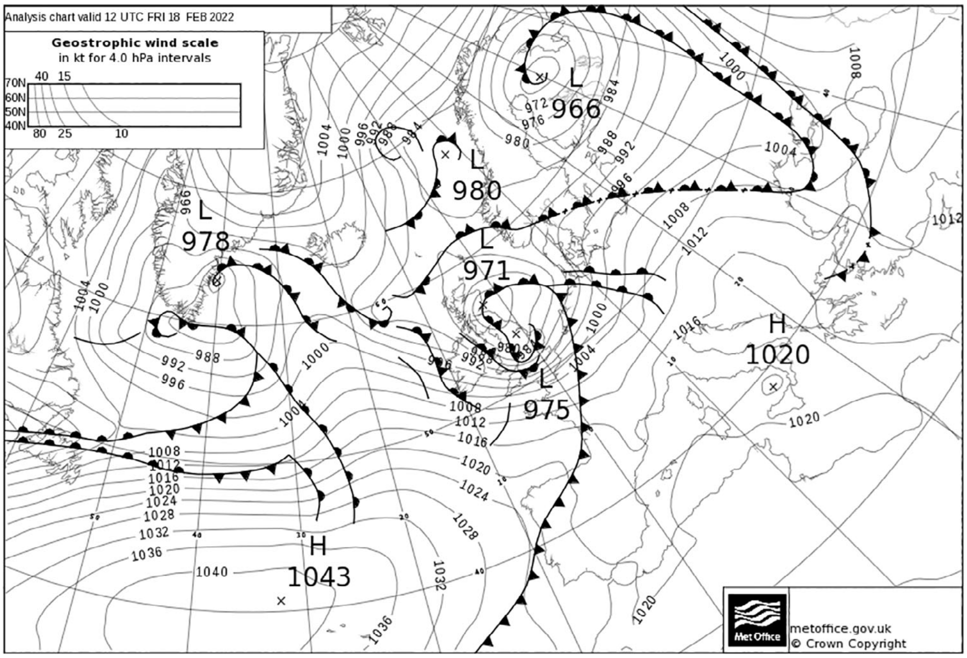


FIGURE 60 Analysis chart 1200 UTC 18 February 2022 showing storm Eunice.

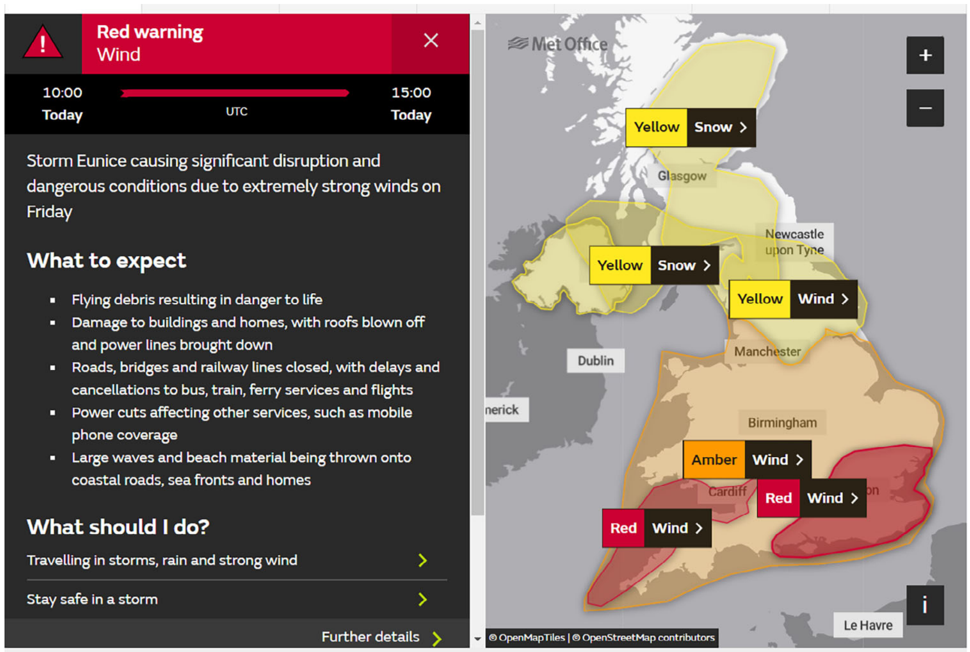


FIGURE 61 Red, amber and yellow wind warnings and yellow snow warnings for storm Eunice on 18 February 2022.

(Gwynedd) and 72 Kt (83 mph) at Pembrey Sands (Carmarthenshire) and Chivenor (Devon). Most stations in England south of London recorded gusts of over 60 Kt (69 mph) – such as 68 Kt (78 mph) at Charlwood (Surrey) and 67 Kt (77 mph) at Boscombe Down (Wiltshire) (Figure 62).

Wind speeds as high as this are extreme for southern England and south Wales and might be regarded as approximately 10 Kt higher than those experienced during a more typical winter storm. The 122 mph gust at Needles Old Battery set a new England gust speed record, exceeding the previous record of 103 Kt (118 mph) at Gwennap Head (Cornwall) on 15 December 1979. Many stations recorded their highest February gust since 26 February 1990, and some recorded their highest February gust on record, such as Chivenor (37 years) and Thorney Island, West Sussex (33 years).

Figure 63 shows hourly mean sea-level pressure at Chivenor (Devon), Brize Norton (Oxfordshire) and Heathrow (Greater London) during the passage of storms Dudley, Eunice and Franklin. The strongest winds tend to coincide with the rapid rise in pressure, with

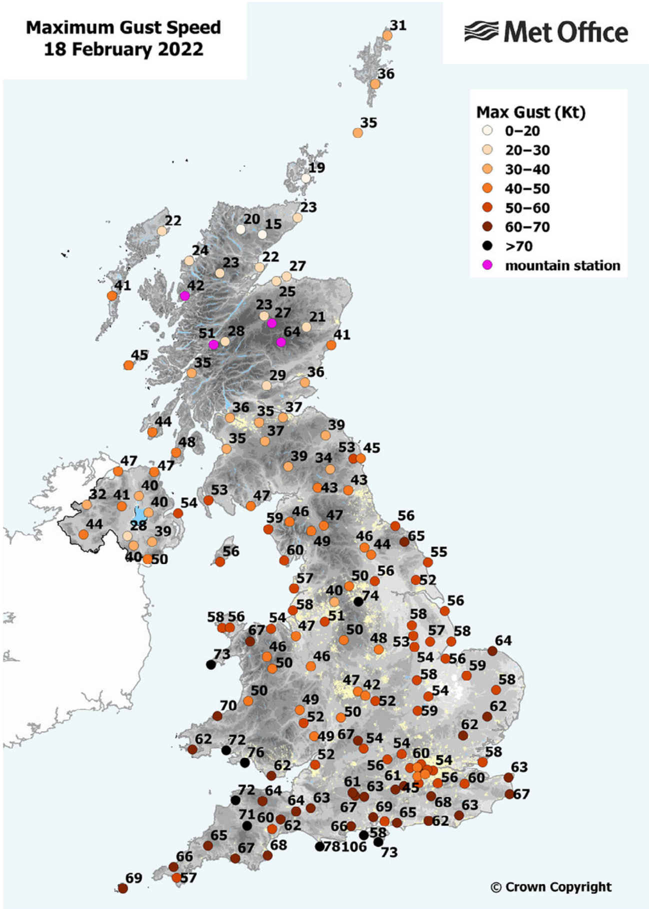


FIGURE 62 Maximum gust speeds from storm Eunice 18 February 2022.

corresponding gusts of 72 Kt (83 mph), 54 Kt (62 mph), and 61 Kt (70 mph) at these three stations during the passage of storm Eunice. Figure 64 shows hourly maximum gust speeds recorded at three stations on the south coast of the UK: Isle of Portland, Dorset, Needles Old Battery, Isle of Wight and Langdon Bay, Kent, with respective peak gusts 78 Kt (90 mph), 106 Kt (122 mph) and 67 Kt (77 mph). The spike in wind speeds on 19 February 2022 was due to the passage of the frontal system between storms Eunice and Franklin. Each of these storms tracked rapidly eastward across the UK so the duration of the strongest winds was fortunately fairly brief.

To compare storm Eunice with historical storms in the observational record, Figure 65 counts the number of stations across England and Wales recording gusts ≥60 Kt by date, based on observations from 1970 (i.e. over the last 50 years), taking into account a broad indication of severity and spatial extent. 42 stations across England and Wales recorded gusts in excess of 60 Kt, and based on this metric, storm Eunice was the most severe storm to affect England and Wales since 12 February 2014. This 2014 storm was one of a sequence of major storms during the 2013/2014 winter, and a similar red warning was issued for wind. Figure 66 shows maximum gust speeds for 12 February 2014 for comparison. Storm Eunice was broadly comparable with this storm, although 12 February 2014 was more severe across parts of Wales, with gusts of 94 Kt (108 mph) at Aberdaron, Gwynedd, 83 Kt (96 mph) at Lake Vyrnwy (Powys) and 81 Kt (93 mph) at Capel Curig (Conwy).

Figure 65 shows there are several more severe storms in the observational records; for example, wind gusts recorded during the Burns' Day storm of 25 January 1990 were approximately 10–15 Kt higher than storm Eunice, and this storm resulted in widespread severe damage and almost 50 lives lost. The storm of 26 February 1990 was also much more severe.

9.2 | 40°C recorded in the UK for the first time on 19 July

The UK experienced an unprecedented extreme heatwave in July 2022, with extreme temperatures recorded on both 18th and 19th. On 19th, 40.3°C was recorded at Coningsby (Lincolnshire), setting a new UK and England temperature record by a margin of 1.6°C, and several other stations across England also exceeded 40°C. This heatwave marked a major milestone in UK climate history, with 40°C being recorded for the first time.

The heatwave was associated with a southerly flow drawing a hot, dry airmass to the UK from the near continent, which was experiencing extreme heat. The analysis chart at 1200 UTC 19 July 2022 (Figure 67) shows the UK located between high pressure over continental Europe and a low pressure system to the north-west of Scotland. The exceptionally hot weather was caused by a ‘heat-dome’; an area of high pressure with falling air in the atmosphere trapping warm air at the surface.

The Met Office issued its first red warning for extreme heat since the Extreme Heat National Weather Warning Service was introduced in June 2021. The red extreme heat area extended from London to Manchester and Leeds with an amber area covering England and Wales and extending to parts of southern Scotland (Figure 68). The UK Health Security Agency and Met Office also issued a level 4 alert for the first time since the heatwave plan was introduced for England in 2004, resulting in the government declaring a national emergency.

The heat brought challenging conditions for the National Health Service with a spike in 999 calls, and care services supporting the elderly and vulnerable were put under increased stress. There were over 1000 estimated excess deaths in those aged 65 and over in

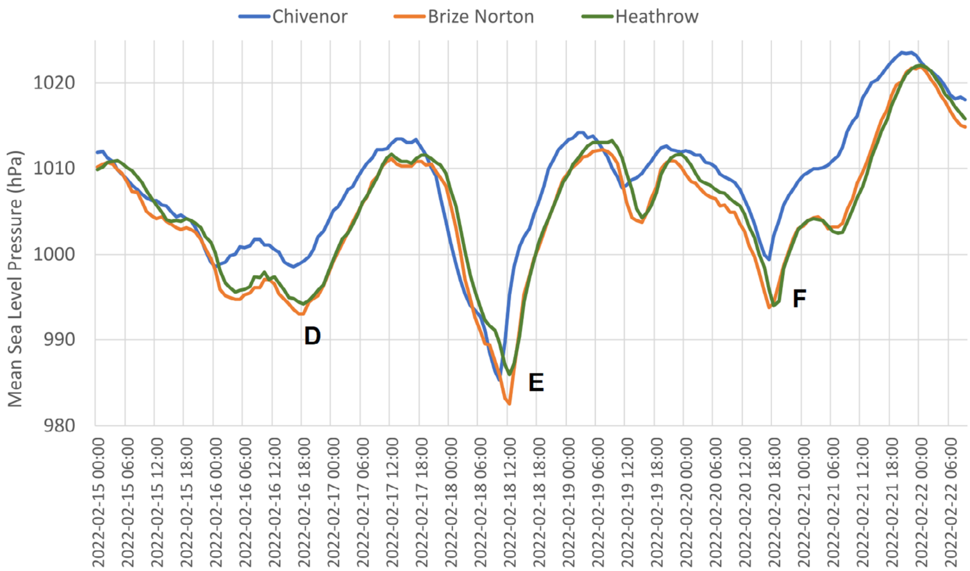


FIGURE 63 Hourly mean sea-level pressure at Chivenor (Devon), Brize Norton (Oxfordshire) and Heathrow (Greater London) from 15 to 22 February 2022 showing the passage of storms Dudley (D, 16th), Eunice (E, 18th) and Franklin (F, 20th).

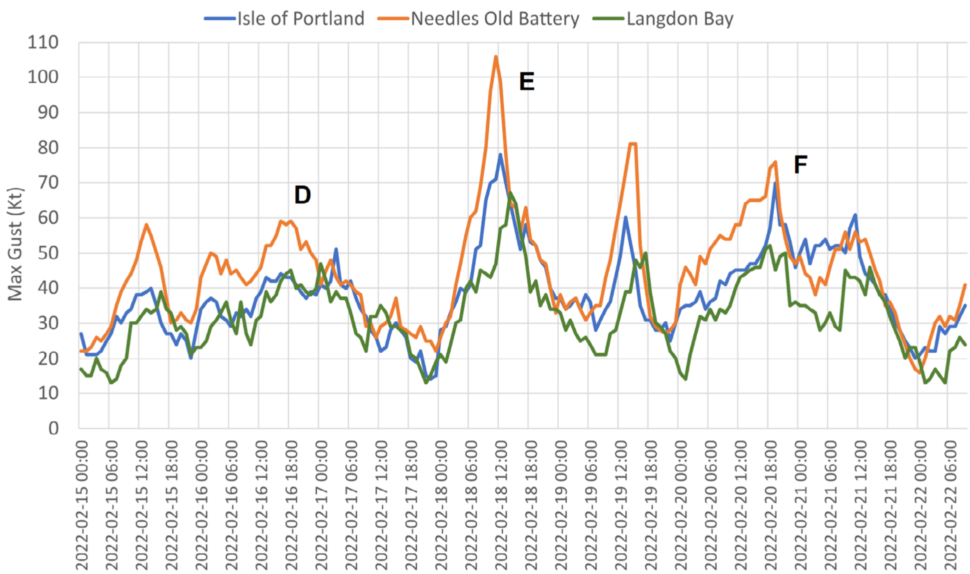


FIGURE 64 Hourly maximum gust speeds at Isle of Portland (Dorset), Needles Old Battery (Isle of Wight) and Langdon Bay (Kent) from 15 to 22 February 2022 showing the passage of storms Dudley (D, 16th), Eunice (E, 18th) and Franklin (F, 20th).

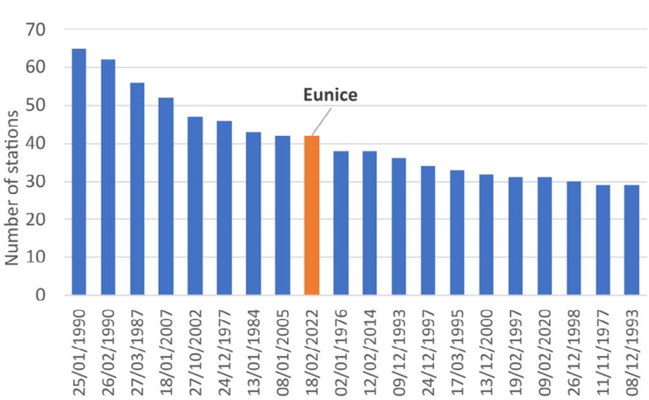


FIGURE 65 Number of stations by day across England and Wales recording a gust speed greater than or equal to 60 Kt (69 mph) based on observations from 1972.

England during this event (ONS and UKHSA, 2022). Multiple fires broke out and several fire services declared major incidents. A number of homes were gutted in Wennington, east London, a nursery was destroyed in Milton Keynes and several homes were damaged by fires in Maltby, Rotherham and in Norfolk. Network rail issued a 'do not travel' warning, and rail services were severely disrupted due to tracks buckling and overhead cables sagging; there were no trains on the East Coast Main Line on 19th. There were some problems with power cuts in parts of Yorkshire, Lincolnshire and the North East, and several fatalities associated with open water swimming. The heatwave in the UK was associated with a much wider heatwave across Western Europe; the Gironde region of south-west France was particularly badly affected by severe wildfires.

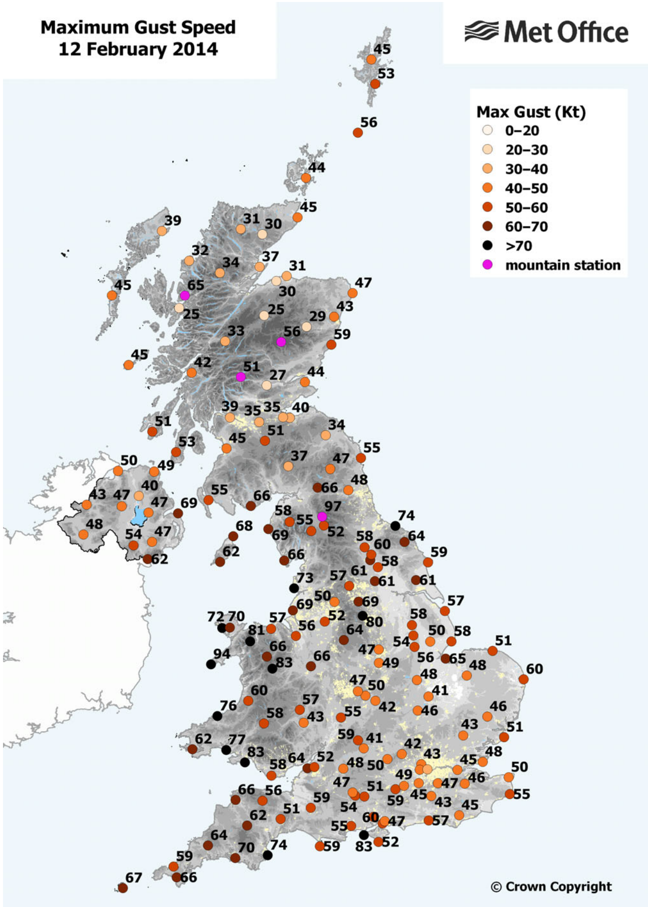


FIGURE 66 Maximum gust speeds 12 February 2014.

Figure 69 shows daily maximum temperatures on 18 and 19 July 2022, compared to 10 August 2003 and 25 July 2019; these being the four dates in the UK where daily maximum temperatures have exceeded 38°C. Temperatures on 18 July exceeded 35°C widely across central England and east Wales, reaching 36–37°C in some locations, with 37.1°C at Hawarden Airport, Flintshire setting a new Wales record by a margin of 1.9°C. Northern Ireland's highest temperature (31.2°C) also came within 0.1°C of the national record. The highest temperature on the 18th was 38.2°C at Pitsford (Northamptonshire). Temperatures on this date were broadly comparable with 25 July 2019 (the date of the previous UK record 38.7°C at Cambridge Botanic Garden) – although the heat extended further west into Wales, south-west England and Northern Ireland on 18 July 2022. On both of these dates, the hottest areas were much more extensive than the 10 August 2003 when it was largely confined to south-east England.

While temperatures on 18 July were exceptional, those of 19 July were typically 2–4°C hotter again in eastern areas making this date unprecedented and extraordinary in UK climate history. In total, seven stations reached 40°C or higher, and a further 30 stations reached at or above 39°C (see cover image of the interior of the Coningsby Stevenson Screen where 40.3°C was recorded). Overall, 46 climate stations across England equalled or exceeded the previous UK record of 38.7°C, across an extensive area from Suffolk to Warwickshire, and from Kent to North Yorkshire (Figure 70).

Figure 71 shows daily maximum temperature anomalies on 19 July 2022 against the 1991–2020 July long-term average. For comparison, 25 July 2019 is also shown. Table 11 lists daily maximum temperatures at selected stations on 19 July. Temperature anomalies exceeded 14°C extensively across England and parts of north Wales and southern Scotland, with anomalies of +16°C widely across central and northern England and in some locations +18°C. These represent temperatures of around 39–40°C compared to a July 1991–2020 average maximum temperature of around 21–22°C that might typically be expected in these areas at this time of year. Table 11 also includes the previous station records at these selected stations. At most of these listed stations, the previous station record was exceeded by a margin around 2 or 3°C, but for some stations – particularly those with the highest anomalies across central and northern England, the margin was considerably higher. For example, Bramham, West Yorkshire, exceeded its previous station record by an extraordinary 6.3°C.

The time series of daily area-average maximum temperatures for 2022 for the climate district of north-east England shows the extraordinary spike on 19 July 2022 (Figure 72), with the daily area-average maximum temperature for this area (extending from Lincolnshire to Northumberland as shown in Figure 71) of 37.0°C exceeding the previous record for this area with a margin of 4.8°C. The 18th and 19th were the two hottest days on record when averaged across the whole UK (in a series from 1960), and the UK-average maximum temperature exceeded 30°C for the first time (Figure 73, see also Figure 16a).

Figure 74 shows a histogram of daily mean CET 1772–2022. The daily mean CET for 19 July 2022 was 28.1°C making this the warmest day in this series with a margin of 2.8°C from the next warmest (25.9°C on 25 July 2019); an exceptional outlier in this 250-year series.

Tables 12–14 list UK, national and regional records broken in July 2022. These emphasize both the exceptional number of records broken during this event, and the margin by which they were broken, for regional records by 3 or 4°C in some instances. Similarly, new all-time records for any month were set at many long-running stations, again by wide margins, such as Durham (36.9°C, margin 4.0°C, 141 years)*, Sheffield (39.4°C, margin 3.8°C, 138 years), Bradford (37.9°C,

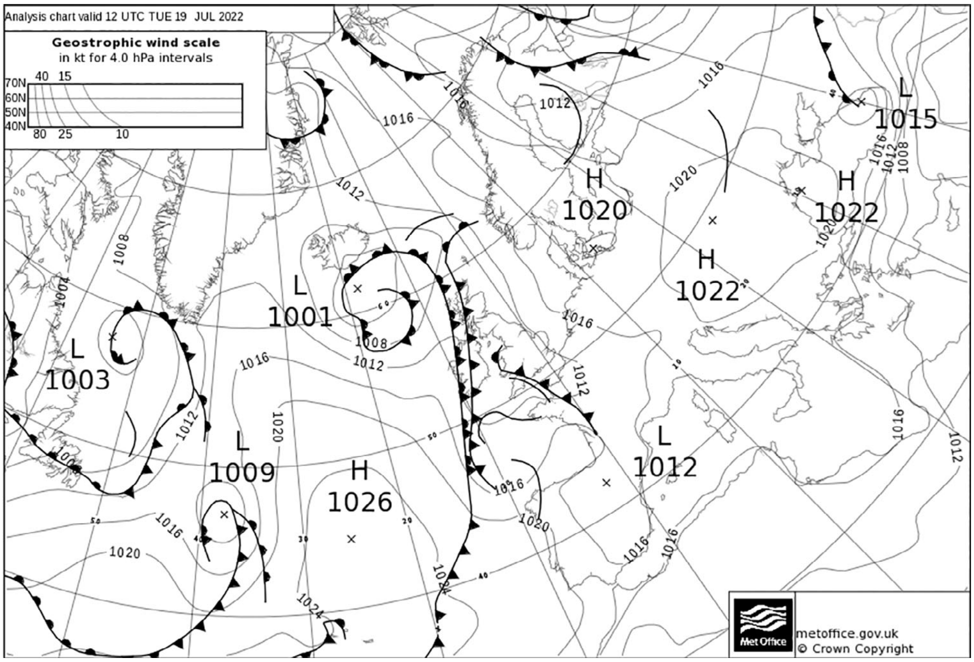


FIGURE 67 Analysis chart 1200 UTC 19 July 2022.

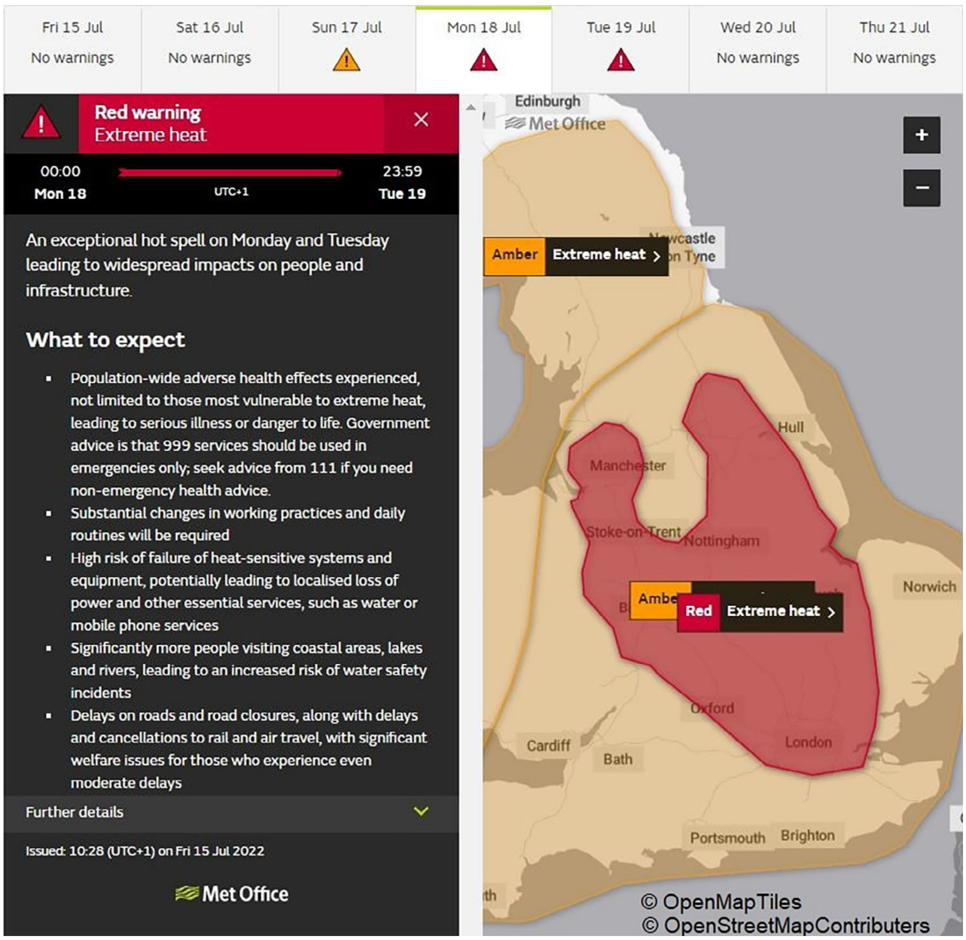


FIGURE 68 Red and amber extreme heat warnings for 18–19 July 2022 issued on the morning of Friday 15 July 2022.

margin 4.0°C, 114 years), and Cranwell, Lincolnshire (39.9°C, margin 3.6°C, 108 years). At all these stations the previous record was on 25 July 2019, the date when the all-time UK record was last set. *For more details of the long-running station at Durham, see Burt and Burt (2022) (published prior to this event).

Table 15 lists the UK's 10 hottest days on record (as the highest station daily maximum temperature). The

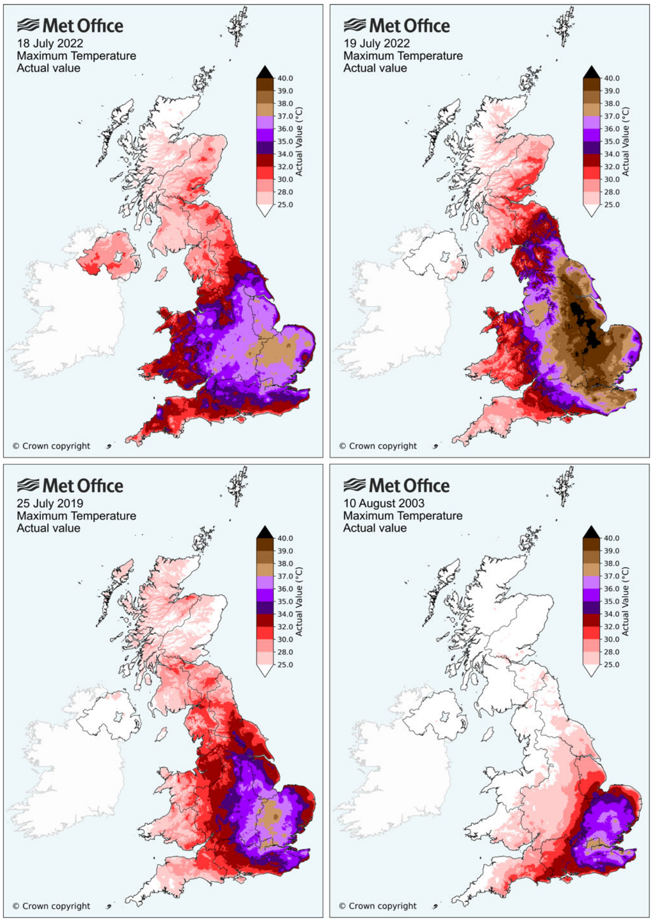


FIGURE 69 UK daily maximum temperature actual values on (a) and (b) 18 and 19 July 2022, (c) 25 July 2019 and (d) 10 August 2003.

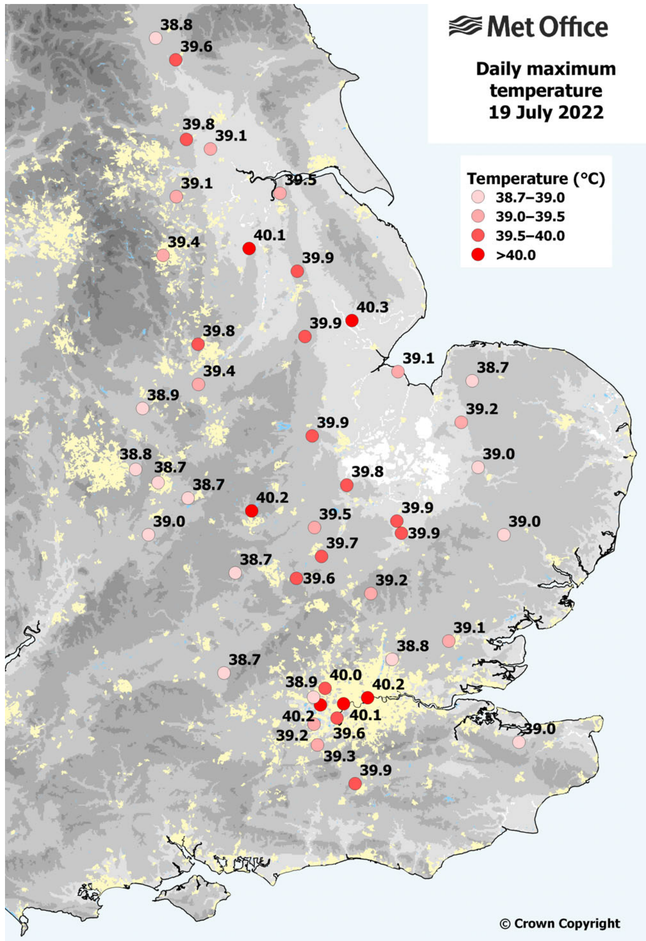


FIGURE 70 Daily maximum temperature on 19 July 2022 at the 46 climate stations across England which equalled or exceeded the previous UK record of 38.7°C.

UK national record of 36.7°C (98°F) at Raunds, Northamptonshire, set on 9 August 1911 stood for almost 80 years until it was broken by a reading of 37.1°C at Cheltenham, Gloucestershire on 3 August 1990. This was broken again with 38.5°C at Faversham, Kent on 10 August 2003, which in turn was broken by 38.7°C at Cambridge Botanic Garden on 25 July 2019, and then 40.3°C at Coningsby, Lincolnshire on 19 July 2022 (see also Figure 56). So, in contrast to the record being unbroken for almost 80 years during the 20th century, it has been broken three times in the 21st century so far. Seven of the UK's 10 hottest days (based on the highest daily maximum temperature) have occurred in the 21st century, with 5 in the most recent decade 2013–2022.

Christidis et al. (2020) carried out an attribution study to quantify how human-caused climate change influenced the likelihood of 40°C being recorded locally in the UK. (Unusually, this study was carried out prior to this event occurrence.) The study concluded that the chance of 40°C in the current climate was extremely low – less

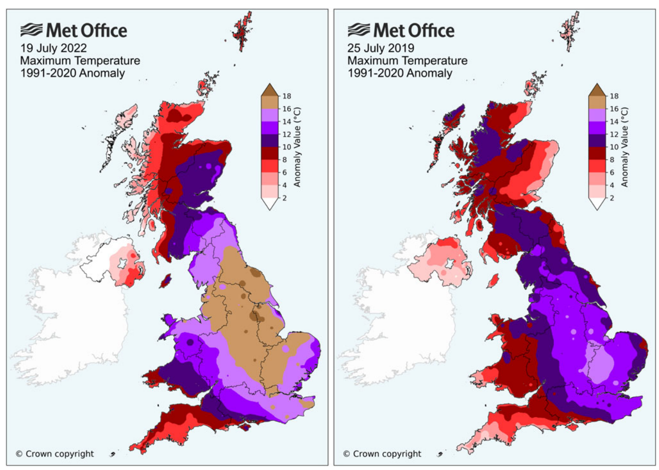


FIGURE 71 UK daily maximum temperature anomalies relative to the July 1991–2020 long-term average for (a) 19 July 2022 and (b) 25 July 2019.

TABLE 11 Daily maximum temperatures on 19 July 2022 at selected stations across England, showing the margin by which the previous UK record of 38.7°C exceeded, the margin by which the previous station record was exceeded, and the anomaly relative to the July 1991–2020 long-term average.

Station	Maxtemp (°C)	Previous UK record exceeded by (°C)	Difference from July 1991–2020 long-term average (°C)	Previous station record[a]	Previous station record exceeded by (°C)	Previous date[a]
Coningsby, Lincolnshire	40.3	1.6	18.1	34.8	5.5	31 July 2020
St James's Park, London	40.2	1.5	16.6	37.6	2.6	10 August 2003
Gringley-on-the-Hill, Nottinghamshire	40.1	1.4	18.5	35.4	4.7	25 July 2019
Charlwood, Surrey	39.9	1.2	16.8	36.5	3.4	10 August 2003
Wittering, Cambridgeshire	39.9	1.2	17.8	36.7	3.2	25 July 2019
Cambridge Botanic Garden	39.9	1.2	16.6	38.7[b]	1.2	25 July 2019
Bramham, West Yorkshire	39.8	1.1	18.5	33.5	6.3	3 August 1990
Topcliffe, North Yorkshire	39.6	0.9	18.5	34.2	5.4	25 July 2019
Sheffield, South Yorkshire	39.4	0.7	18.1	35.6	3.8	25 July 2019
Marham, Norfolk	39.2	0.5	16.7	36.5	2.7	25 July 2019
Santon Downham, Suffolk	39.0	0.3	16.1	36.4	2.6	25 July 2019
Faversham, Kent	39.0	0.3	15.9	38.5	0.5	10 August 2003
Wellesbourne, Warwickshire	39.0	0.3	16.2	36.2	2.8	31 July 2020, 25 July 2019
Coton-in-the-Elms, Derbyshire	38.9	0.2	17.0	34.9	4.0	25 July 2019
High Beach, Essex	38.8	0.1	15.9	36.7	2.1	10 August 2003
Houghton Hall, Norfolk	38.7	0.0	16.9	35.2	3.5	25 July 2019
Coventry, West Midlands	38.7	0.0	16.7	35.1	3.6	31 July 2020, 25 July 2019
Benson, Oxfordshire	38.7	0.0	15.9	37.0	1.7	25 July 2019

[a]Excluding the previous day, 18 July 2022 which for some of these stations also exceeded their previous station records before this event but by a smaller margin.
[b]Previous UK record.

than 1 in 100 each year – but nevertheless still as much as 10 times more likely when compared to a natural climate unaffected by human influence. It also found that by 2100, under a medium emission scenario (RCP4.5, see Section 8.1), the UK could see 40°C on average once every 15 years, and potentially as frequently as every 3–4 years under a high emissions scenario. So further events such as July 2022 will become increasingly likely by the latter part of the 21st century.

Despite the unprecedented heatwave, 2022 was not the UK's hottest summer for average maximum temperature; that remains as 1976 with 2022 ranked 4th (also exceeded by 1995 and 2018). Figure 75 compares UK area-average daily maximum temperatures for summer 2022 and summer 1976, with spells with an average maximum over 20°C shaded in red and grey respectively. Fortunately, the heatwave of July 2022 was brief, although there was a further spell of hot weather in early August. For comparison, in 1976, while the heatwave was much less extreme in terms of absolute temperatures (reaching a maximum of 35.9°C), it was very much more prolonged with spells through late June to mid-July and much of August. The summers of 1995 and 2018 also saw much more prolonged heat than 2022.

9.3 | Prolonged dry conditions January–August

The UK experienced a prolonged spell of dry weather from January to August 2022 with rainfall deficits most significant across southern and eastern England and Wales. February was the only notably wet month through this period although the wettest areas did not extend to the far south of England (Figure 31). Figure 76 shows rolling daily rainfall accumulations from January through the year 2022, for the region of southern England (defined as the area south of a line from North Wales to the Wash), compared to the 1991–2020 average. Note that the gradient of the long-term average line is slightly steeper in January and October to December because these months are climatologically wetter on average. For 2022 rainfall deficits increased markedly in January, April, June, July and August (reflected by the very shallow gradient on the chart) and by the start of September were at their maximum, with the January–August rainfall total for southern England as 304 mm, 62% of the 1991–2020 average and representing a deficit of 183 mm, equivalent to long-term average rainfall for March, April, May and half of June combined.

July 2022 was an especially dry month across southern England with less than 20% of average for most areas south-east of a line from the Bristol Channel to the Wash; much of south-east England received less than 10% and a few locations were effectively completely dry with 1 mm or less (Figure 77a). For southern England this was the equal-driest July on record in a series from 1836 (shared with 1911).

Rainfall totals for the UK for January–August were below average, apart from north-west Scotland, with 60% widely across southern England and some locations receiving 50% or less (Figure 77b). For southern England, this was the driest January to August since 1976, and equal-sixth driest in the series from 1836, shared with 1870 and only 1976, 1921, 1929, 1870 and 1887 drier (Figure 78). Both 1976 and 1921 were associated with major droughts across England and Wales (Marsh et al., 2007).

The major drought of 1976 was very much more severe, not just because the rainfall accumulations were much less (for southern England the January–August total was 228 mm in 1976 compared to 304 mm in 2022) – but also much more prolonged. Figure 79a,b compares monthly rainfall anomalies for southern England for the period 1971–1980 and 2013–2022. The 1976 drought was due to a 16-month run of dry months from May 1975 to August 1976, with only August 1975 wetter than average. Half of these months had less than 50% of normal rainfall for this region – and crucially the winter half-year months October 1975 to March 1976 were all dry, these being the critical period for recharge of water resources.

For southern England, summer 2022 was both the second warmest (for average maximum temperatures) and seventh driest, in series from 1884 and 1836 respectively. Figure 80 plots summer average maximum temperature against rainfall for southern England from 1884 to 2022. The summer was neither as warm nor as dry as 1976 but towards the edge of the distribution, with other warm, dry summers (2018, 1995 and 1911) and cold, wet summers (1912, 2012 and 2007) labelled.

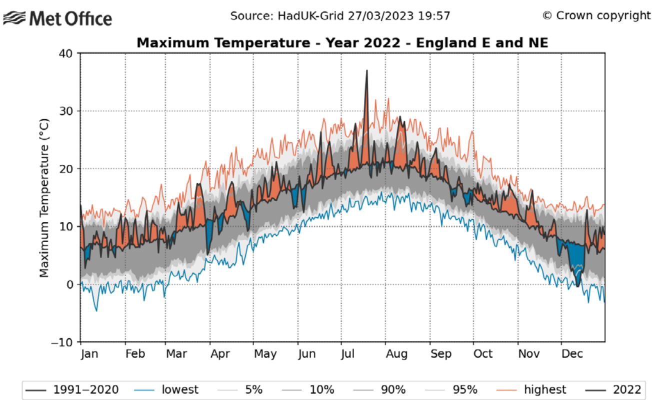


FIGURE 72 Daily mean maximum temperature for the climate district of north-east England for each calendar day of the year 2022. The black line shows the 1991–2020 average for each calendar day; the red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1960–2022 inclusive.

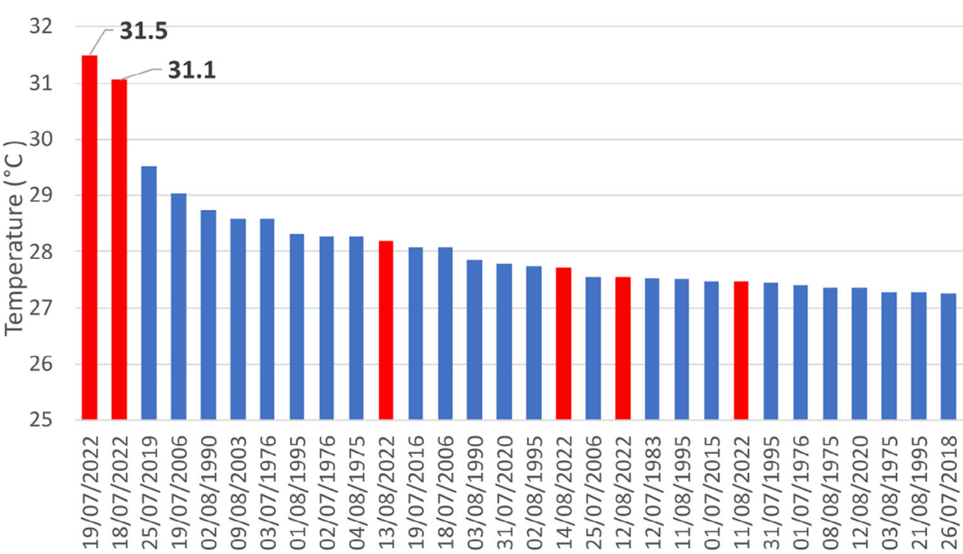


FIGURE 73 UK area-average daily maximum temperature for the 30 hottest days on record for the UK overall based on data from 1960. Days in 2022 are highlighted in red. In addition to the July heatwave, these include 4 days in August.

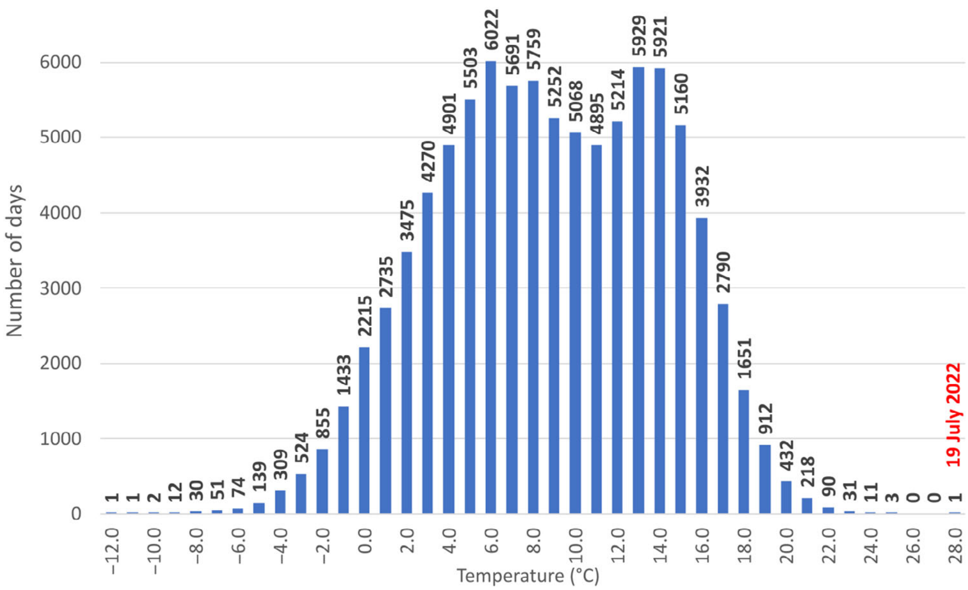


FIGURE 74 Histogram of daily mean Central England Temperature (CET) 1772–2022, including the count of each column. The mean CET value for 19 July 2022 was 28.1°C with the next highest value 25.3°C on 25 July 2019.

TABLE 12 UK and national highest daily maximum temperature records set in July 2022.

Record	Station	Temperature (°C)	Date	Previous record (°C)	Previous station	Previous date	Margin (°C)
UK	Coningsby, Lincolnshire	40.3	19 July 2022	38.7	Cambridge Botanic Garden	25 July 2019	1.6
England	Coningsby, Lincolnshire	40.3	19 July 2022	38.7	Cambridge Botanic Garden	25 July 2019	1.6
Wales	Hawarden Airport, Flintshire	37.1	18 July 2022	35.2	Hawarden Bridge, Flintshire	2 August 1990	1.9
Scotland	Charterhall, Borders	34.8	19 July 2022	32.9	Greycrook, Borders	9 August 2003	1.9

TABLE 13 Regional highest daily maximum temperature records set in July 2022.

Record	Station	Temperature (°C)	Date	Previous record (°C)	Previous station	Previous date	Margin (°C)
England E & NE	Coningsby, Lincolnshire	40.3	19 July 2022	36.3	Cranwell, Lincolnshire	25 July 2019	4.0
England NW	Nantwich, Cheshire	38.4	19 July 2022	34.6	Nantwich, Cheshire	3 August 1990	3.8
N Wales	Hawarden Airport, Flintshire	37.1	18 July 2022	35.2	Hawarden Bridge, Flintshire	2 August 1990	1.9
Midlands	Pitsford, Northamptonshire	40.2	19 July 2022	37.1	Cheltenham, Gloucestershire	3 August 1990	3.1
East Anglia	Cambridge, NIAB	39.9	19 July 2022	38.7	Cambridge Botanic Garden	25 July 2019	1.2
England SW	Bude, Corwall	36.0	18 July 2022	35.4	Saunton Sands, Devon	3 August 1990	0.6
S Wales	Gogerddan, Ceredigion	35.8	18 July 2022	34.6	Crossway, Gwent	3 August 1990	1.2
England SE & Central S	Heathrow and St James's Park, London	40.2	19 July 2022	38.5	Faversham, Kent	10 August 2003	1.7

TABLE 14 UK and national highest daily minimum temperature records set in July 2022.

Record	Station	Temperature (°C)	Date	Previous record (°C)	Previous station	Previous date	Margin (°C)
UK	Shirburn Model Farm, Oxfordshire	26.8	19 July 2022	23.9	Brighton, East Sussex	3 August 1990	1.9
England	Shirburn Model Farm, Oxfordshire	26.8	19 July 2022	23.9	Brighton, East Sussex	3 August 1990	1.9
Wales	Aberporth, Ceredigion	24.5	19 July 2022	22.2	Swansea, Victoria Park, West Glamorgan	29 July 1948	2.3

TABLE 15 The UK's 10 hottest days on record (highest station daily maximum temperature).

Station	Temperature (°C)	Date
Coningsby, Lincolnshire	40.3	19 July 2022
Cambridge Botanic Garden	38.7	25 July 2019
Faversham, Kent	38.5	10 August 2003
Pitsford, Northamptonshire	38.2	18 July 2022
Heathrow, London	37.8	31 July 2020
Cheltenham, Gloucestershire	37.1	3 August 1990
Heathrow, London	36.7	1 July 2015
Raunds, Northamptonshire	36.7^	9 August 1911
Worcester, Worcestershire	36.6	2 August 1990
Wisley, Surrey	36.5	19 July 2006

^Also Epsom, Surrey and Canterbury, Kent. Temperature at the time were published to the nearest whole degree Fahrenheit

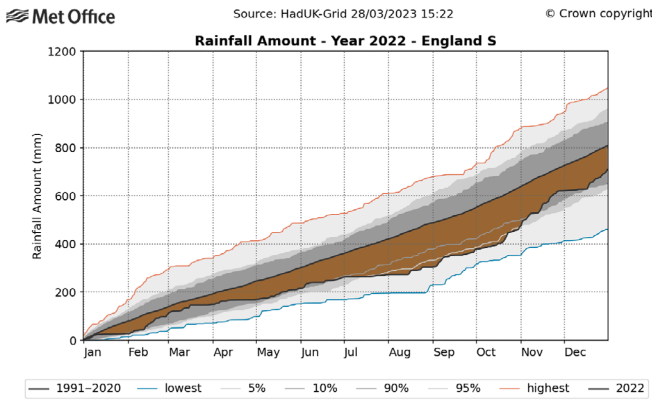


FIGURE 76 Rolling daily accumulation of rainfall totals for the year so far through 2022 for southern England, with the 1991–2020 long-term average (black), percentiles and highest and lowest values based on the daily series from 1891.

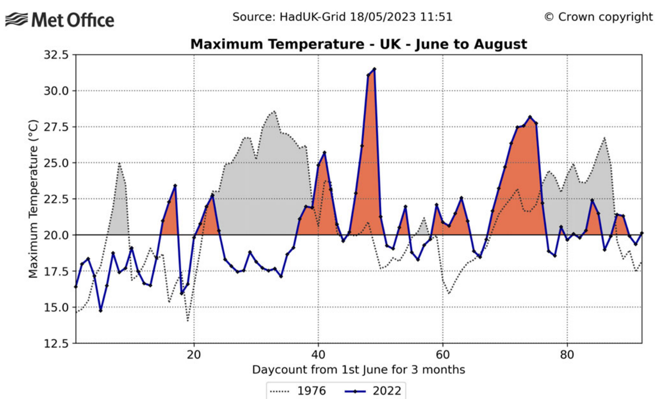


FIGURE 75 UK mean daily maximum temperature comparing summers 2022 and 1976, with spells of the UK mean daily maximum exceeding 20°C highlighted in red (2022) and grey (1976).

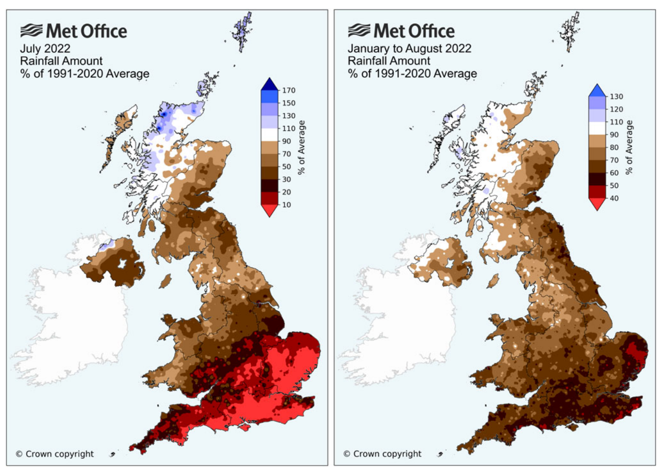


FIGURE 77 UK rainfall (a) July and (b) January–August 2022 as anomalies relative to 1991–2020.

A comparison of the median points for 1961–1990, 1991–2020 and the most recent decade 2013–2022 shows the warming trend, although only a very slight increase in rainfall.

The combination of both persistent lack of rain and summer warmth (increasing evaporation) led to concerns about water resources across England and Wales, with dry soil, reduced river flows and low reservoir and

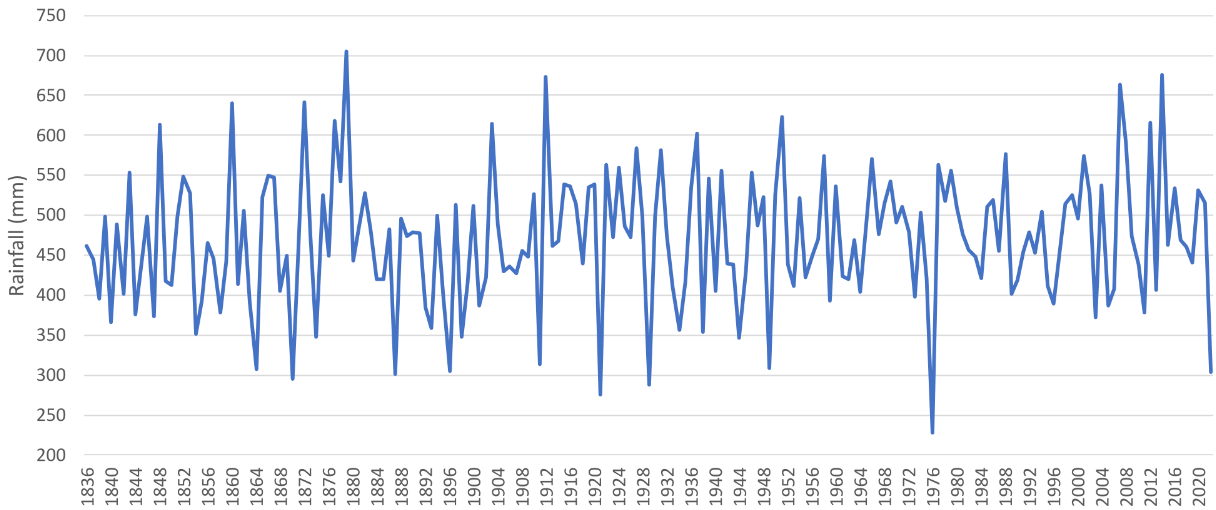


FIGURE 78 Southern England rainfall totals January–August 1836–2022.

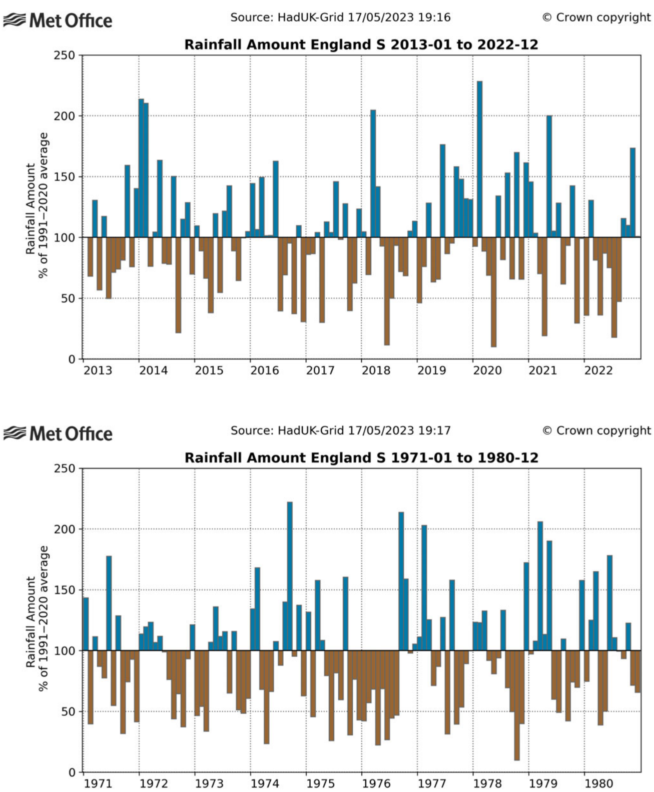


FIGURE 79 Monthly rainfall anomalies relative to 1991–2020 for southern England showing (a) 2013–2022 and (b) 1971–1980.

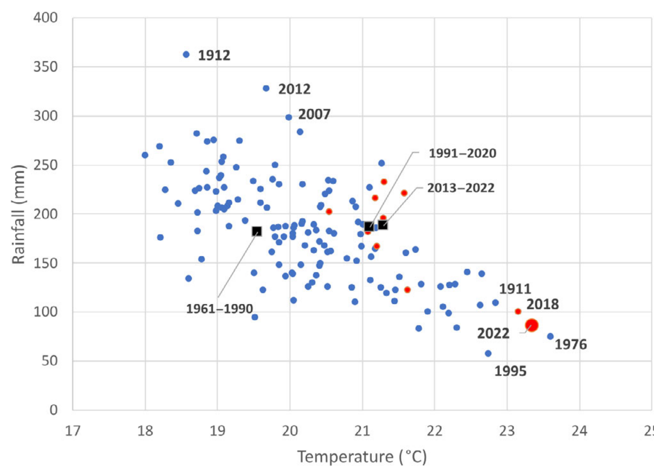


FIGURE 80 Scatter plot of mean maximum temperature against rainfall for southern England for summers 1884–2022. The 10 years for the most recent decade 2013–2022 are shown in red; the median points for the periods 1961–1990, 1991–2020 and 2013–2022 are shown as black squares; outlying years are labelled.

groundwater levels. By the end of August, drought status was declared across 11 of the 14 Environment Agency areas in England. In Wales, a drought was declared across southern and central parts on 18 August and extended to the whole country by 8 September. Temporary Use Bans (previously known as hosepipe bans) were implemented by eight water companies in England and Wales. The dry weather also caused difficult conditions for farmers and an increased risk of wildfires.

The recovery period was mainly in October and November. Rainfall in September and October was variable, but November was a wet month across southern England – especially parts of the far south-east with over twice the normal amount, and the rainfall deficits from January to August were significantly reduced (Figures 31 and 76). Even so, by the end of December they were not fully recovered and overall this was a fairly dry year across England and Wales – especially parts of East Anglia (Figure 29).

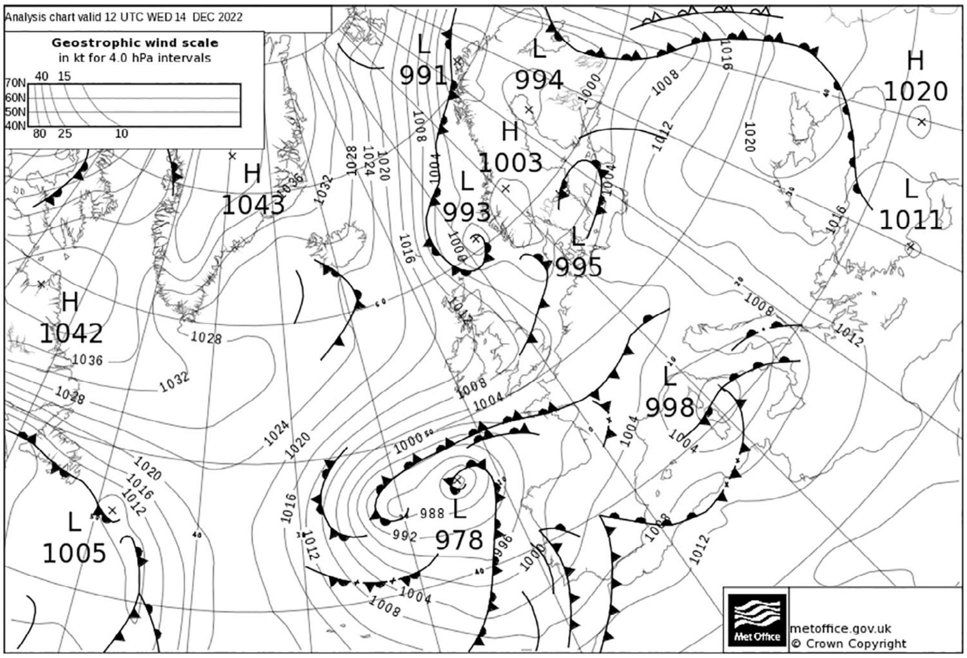


FIGURE 81 Analysis chart 1200 UTC 14 December 2022.

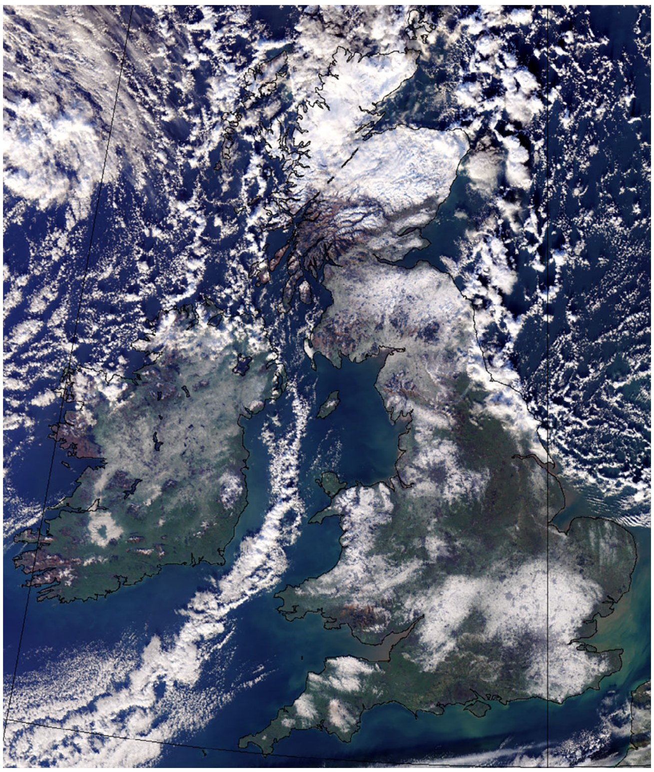


FIGURE 82 Visible satellite image of lying snow cover on 15 December 2022. Image copyright Met Office/NOAA/NASA.

9.4 | Spell of low temperatures 8–18 December

The UK experienced a prolonged spell of low temperatures accompanied by snowfalls from 8 to 18 December 2022. Figure 81 shows the UK in a cold northerly airstream of Arctic Maritime air bringing clear, cold conditions, with North Sea coasts and northern Scotland at risk of wintry showers, and milder Atlantic air and associated fronts constrained further south.

The prolonged spell of low temperatures resulted in ice forming on many inland lakes and waterways. Tragically four children died when they fell through the ice of a lake near Solihull, Birmingham on 11 December. On the afternoon of 11th and into the evening an area of heavy snowfall developed over parts of south-east England and London, with more than 10 cm of fresh snow unofficially recorded in parts of Kent and widespread transport disruption ensuing: the M25 in Essex was closed for several hours and multiple snow-related accidents were reported from the M20 and M2 across Kent, while gritting/ploughing vehicles became stuck in stationary traffic and unable to operate. Temporary runway closures were reported at Gatwick and Stansted airports to enable snow to be cleared. Unusually, there was lying snow across London (1 cm at Northolt on 12th but unofficially greater depths elsewhere). The wintry scenes in the capital saw members of the public sledging or even skiing in Greenwich Park; however the slippery conditions with snowy and icy pavements would inevitably have resulted in an increased number of slips, trips and falls, especially among the elderly.

Further north, heavy wet snowfall during the 12th, combined with strong winds, caused significant accretion and resulting damage to power transmission cables, especially across Shetland. Several thousand properties lost electricity supplies for several days and a major incident

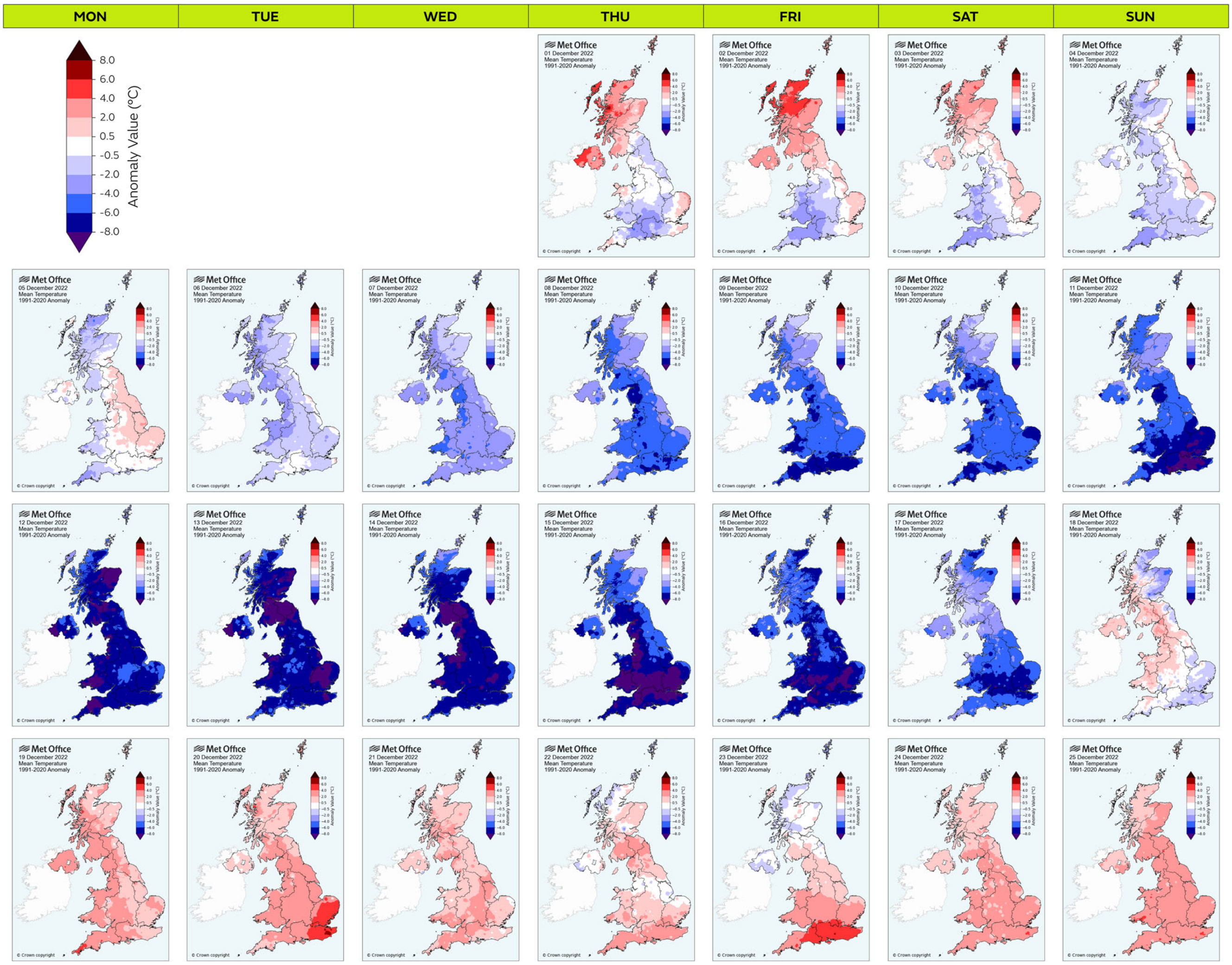


FIGURE 83 Calendar view of daily mean temperature across the UK from 1 to 25 December 2022 as anomalies relative to 1991–2020.

was declared. More widely, rail services were disrupted, there were difficult driving conditions and a number of schools were also closed, including in Cornwall. Heavy snow then fell again on the morning of the 16th across central Scotland (13 cm at Strathallan Airfield, Perthshire, 12 cm at Penicuik, Mid-Lothian). Several roads were closed including the A83, A85 and M90. Glasgow Airport suffered delays and cancellations, whilst later that day over 50 people were stranded on the A85 near Crianlarich.

On 18th, amid the transition to milder conditions, freezing rain affected much of the Pennines, North Yorkshire, Cumbria and Northumberland causing treacherous roads and pavements. After the thaw set in, some areas experienced water supply problems, notably areas supplied by Welsh Water, while Gloucestershire Royal Hospital had to use its own water reserves after the main supply was cut. A number of schools were also closed due to leaking or burst pipes.

Figure 82 shows areas of lying snow; while these were generally not deep they were fairly extensive, across the south-east and central southern England, the south-west moors, many upland areas of Wales and north-west England and parts of Scotland (especially the north-east). London and Manchester are clearly visible. A prominent line of convection runs down the Irish Sea in a northerly airstream, with some northern and eastern coastal areas affected by wintry showers.

Daytime temperatures struggled to rise above freezing, while daily minimum temperatures fell widely to between −5 and −10°C across the UK on several nights – with hard frosts even in cities and coastal areas, and some locations below −10°C. Figure 83 shows UK

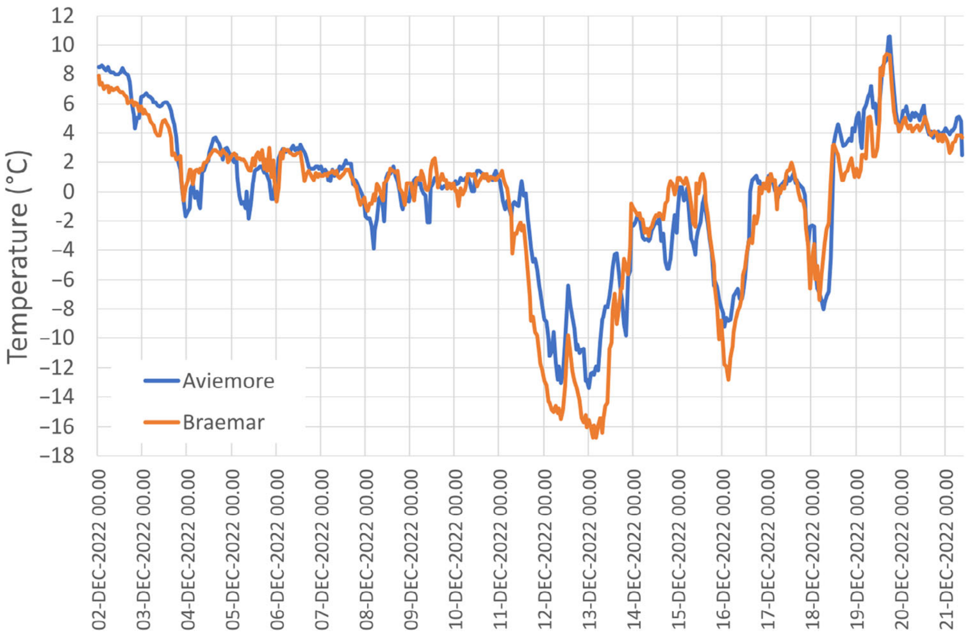


FIGURE 84 Hourly air temperature from 2 to 21 December 2022 at Aviemore (Inverness-shire) and Braemar (Aberdeenshire).

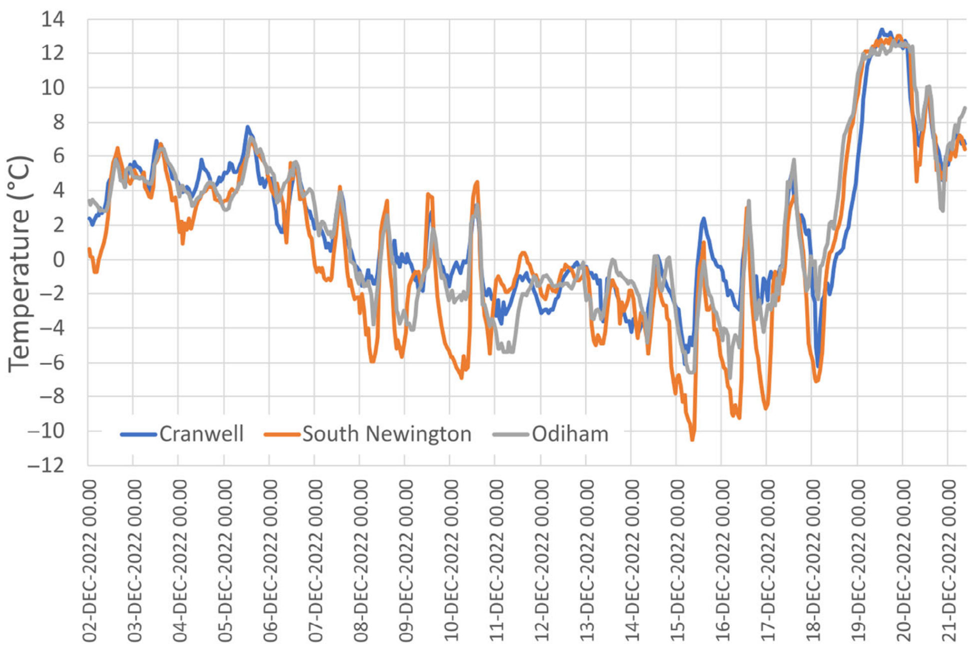


FIGURE 85 Hourly air temperature from 2 to 21 December 2022 at Cranwell (Lincolnshire), South Newington (Oxfordshire) and Odiham (Hampshire).

daily mean temperatures from the start of December through this spell as anomalies relative to the 1991–2020 December long-term average. In some areas daily mean temperatures were more than 8°C below normal for the time of year – for example, with a daily mean temperature of −5°C compared to 3°C as the December 1991–2020 average.

Figure 84 shows hourly air temperature from 2 to 21 December 2022 at Aviemore (Inverness-shire) and Braemar (Aberdeenshire). From 4 to 11, temperatures at both locations remained close to freezing before falling below −10°C on 11–12 December. Braemar recorded a daily maximum temperature of −9.3°C on 12th – the UK's lowest value of this spell and the lowest maximum since December 2010 – and also the UK's lowest daily minimum of −17.3°C on 13th. This is notably low, although not exceptional; in February 2021 this station recorded −23.0°C.

Figure 85 shows hourly air temperature for the same time period at Cranwell (Lincolnshire), South Newington (Oxfordshire) and Odiham (Hampshire), and illustrates the run of hard frosts. On 15 December, South Newington recorded a minimum of −11.1°C and temperatures across many areas fell widely to −5 to −10°C, including in London, with −7.6°C at Kew Gardens. Coastal areas also recorded some very hard frosts, for example, −8.4°C at Pembrey Sands (Carmarthenshire) on 16th. Many stations recorded their lowest December daily maximum and daily minimum temperatures since December 2010. Temperatures then rose dramatically on 18 December – for example, at South Newington an increase of over 17°C within 24 h marking the change of air mass across the UK.

This was one of the most significant spells of low winter temperatures to affect the UK since the exceptional December of 2010. Figure 86 compares UK-average daily mean temperature for three spells: December 2022 (in blue), February to March 2018 (the 'Beast from the East') (in red) and December 2010 (in green). While this event was slightly more prolonged, it was broadly comparable to February/March 2018. December 2010 was very much more severe, with two separate spells each colder and of longer duration than December 2022.

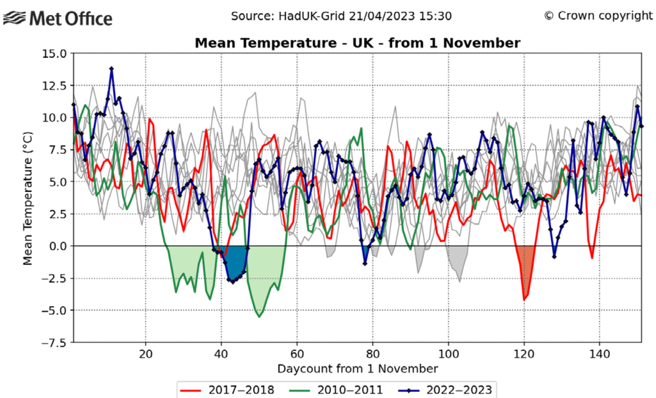


FIGURE 86 Comparison of UK daily mean temperature from 1 November for 151 days (to the end of March) for years 2022–2023, 2017–2018 and 2010–2011. Other years of the most recent decade from 2013 to 2014 onwards are shown in pale grey, with spells where the UK daily mean temperature has fallen below 0°C shaded.

While the December 2022 event demonstrates that spells of severe winter weather in the UK are still possible in the current climate, there is a clear downward trend in the number of such events. Figure 87 shows the number of days in each calendar year 1960–2022 with a UK daily average mean temperature below 2 and 0°C (indicative of a cold snap). Comparing the periods 1961–1990 and 1991–2020, the number of days <2°C has reduced by a third, and the number of days <0°C has halved over this 30-year period (Table 16).

10 | PHENOLOGY

Phenology is the study of recurring biological events in relation to climate; typically of the dates of first and last events as they occur each year. It provides clear indicators of nature's response to weather and climate and, in the UK, is a citizen project called Nature's Calendar relying exclusively on volunteer observers. A summary of phenological recording in the UK was given in Sparks and Collinson (2008).

In this section, we summarize average UK changes in four species of woody plants, four flower species, four invertebrate species, and four vertebrate species. These are based on simple annual averages of submitted observations (minimum 100), without geographical correction. Unfortunately, due to computer problems, 2021 values are only available for the woody

TABLE 16 Total number of days with UK area-average daily mean temperature below 2 and 0°C for periods 1961–1990 and 1991–2020.

Period	T_{mean} <2°C	T_{mean} <0°C
1961–1990	1085	420
1991–2020	706	207

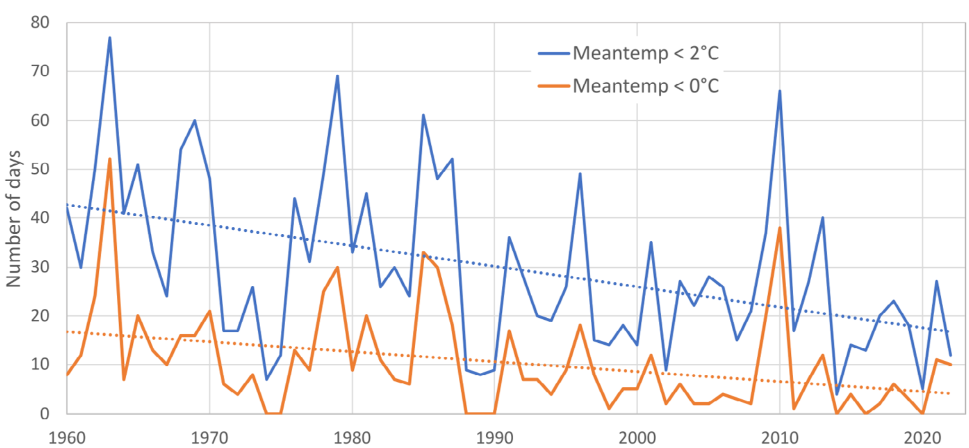


FIGURE 87 Number of days per year with UK area-average daily mean temperature below 2 and 0°C, including linear trend lines.

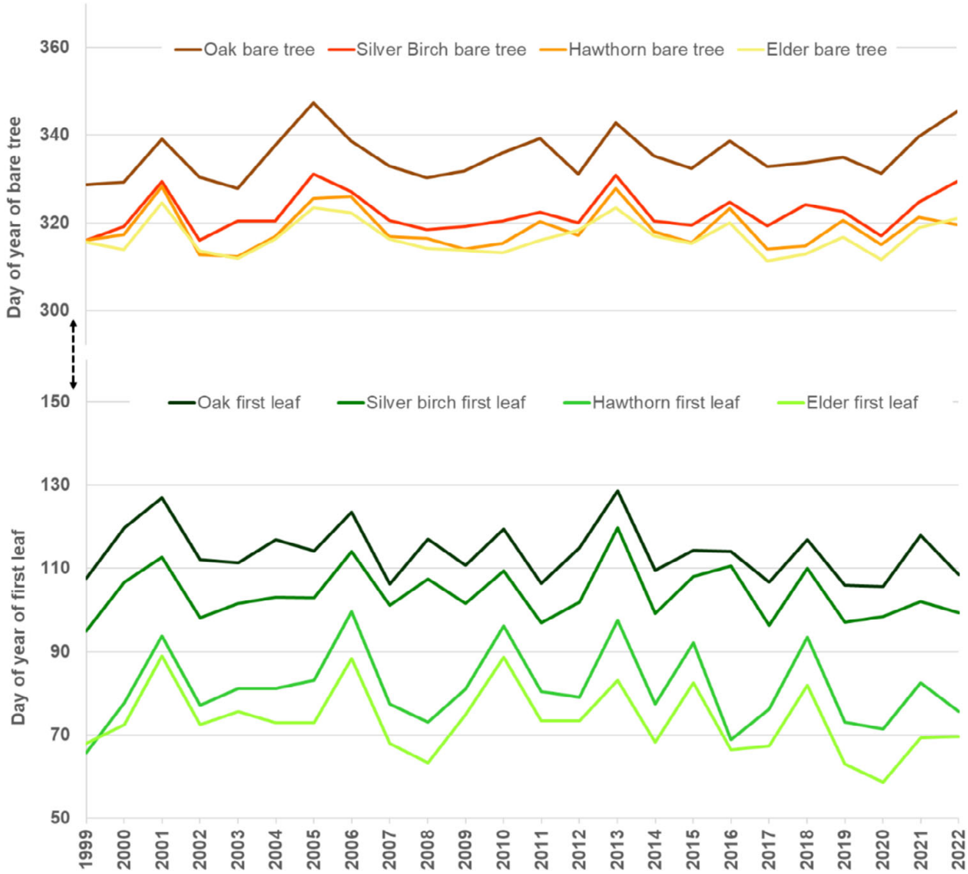


FIGURE 88 Mean day of year of first leaf and bare tree phenology indicators for four common shrub or tree species: Elder, Hawthorn, Silver Birch and Oak, derived from UK observations contributed to Nature's Calendar from 1999 to 2022.

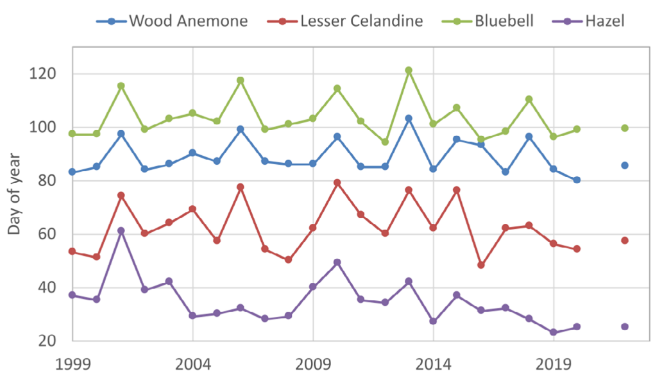


FIGURE 89 Mean day of year of first flowering for four flower species: Hazel, Lesser Celandine, Wood Anemone and Bluebell, derived from UK observations contributed to Nature's Calendar from 1999 to 2022.

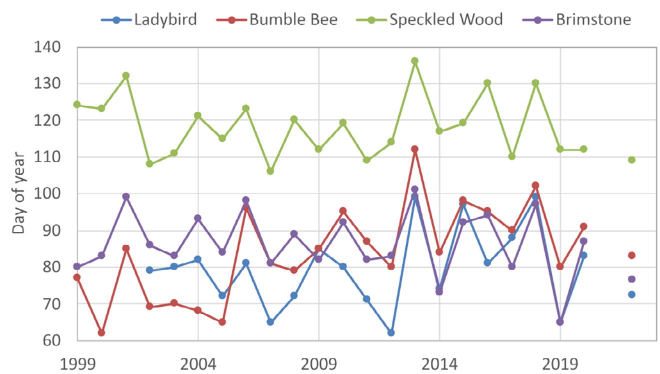


FIGURE 90 Mean day of year of first appearance of four invertebrate species: 7-spot Ladybird, Brimstone butterfly, Red-tailed Bumblebee and Speckled Wood butterfly, derived from UK observations contributed to Nature's Calendar from 1999 to 2022.

species. For these woody species we summarize both first leaf and bare tree dates. Of the four woody species, Elder and Hawthorn are the earliest to come into leaf (in mid- to late-March), with Silver Birch and Pedunculate Oak about a month later. In autumn, bare tree dates for these species are more condensed, typically occurring in mid- to late-November. The flower species range from Hazel in January to Bluebell in April. With the exception of Speckled Wood butterfly, the other listed invertebrates overwinter as adults which tend to emerge earlier in spring. The vertebrates are a diverse group: the first song of the resident Song Thrush, evidence of breeding (frogspawn) of the cold-blooded Common Frog, first appearance of the short distance migrant/resident bird Chiffchaff, and first appearance of the long distance migrant bird Swallow.

Indicators for spring 2022 were early by 1–10 days for all species except Swallow (Figures 88–91, Table 17). Chiffchaff had its earliest date in this series

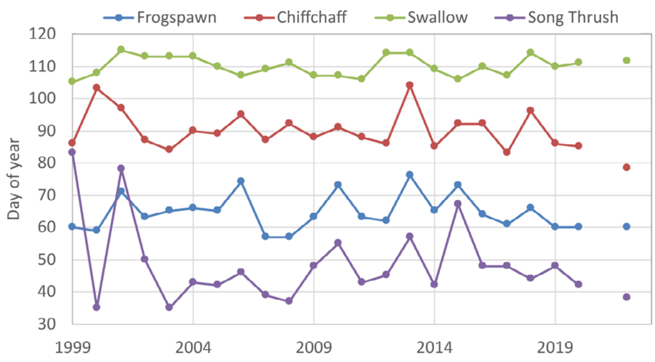


FIGURE 91 Mean day of year of first song of Song Thrush, observation of Chiffchaff and Swallow and appearance of Common Frog spawn, derived from UK observations contributed to Nature's Calendar from 1999 to 2022.

from 1999, and Hazel had its second earliest flowering date. February CET was notably warm in 2022 and helped to advance the early stages of spring. Another warm October resulted in bare tree dates 1–10 days later than the baseline, with the UK mean date for Oak being the second latest in the 24-year period under investigation.

Overall, the leaf-on season was 7–16 days longer than the baseline because of season extensions in both spring and autumn. Spring responses to temperature varied from 1 to 7 days earlier for every 1°C increase in mean temperature of the 1–3 months prior to the month of mean date. In contrast, tree bare dates in autumn typically showed a response of about 2–3 days later for every 1°C increase in October temperature.

AUTHOR CONTRIBUTIONS

Mike Kendon: Writing – review and editing. **Mark McCarthy:** Writing – review and editing. **Svetlana**

TABLE 17 Mean dates of example events for woody plant species, flowers, invertebrates and vertebrates derived from UK observations contributed to Nature's Calendar from 1999 to 2022.

Group	Event	Species	Mean first date 1999–2020/2021	2022 mean first relative to 1999–2020/2021	Mean response to a 1°C increase in month(s) right	Month(s)
Woody plants	First leaf	Elder	14 Mar	−4	−6.3	JF
		Hawthorn	22 Mar	−6.2	−6.9	JFM
		Silver Birch	14 Apr	−4.7	−5.6	MA
		Oak	24 Apr	−5.7	−5.8	MA
Woody plants	Bare	Elder	12 Nov	4.5	2.1	O
		Hawthorn	14 Nov	1	2.5	O
		Silver Birch	17 Nov	7.5	2.5	O
		Oak	30 Nov	10.5	3.1	O
Flowers	First flower	Hazel	24 Jan	−9.8	−4.3	J
		Lesser Celandine	26 Feb	−5.4	−5.0	J
		Wood Anemone	26 Mar	−3.5	−4.7	FM
		Bluebell	9 Apr	−4.3	−6.4	JFM
Invertebrates	First seen	7-spot Ladybird	13 Mar	−7.3	−4.6	M
		Brimstone butterfly	17 Mar	−9.9	−5.5	M
		Red-tailed Bumblebee	23 Mar	−1.3	−5.9	M
		Speckled Wood butterfly	19 Apr	−9.3	−7.3	MA
Vertebrates	First singing	Song Thrush	7 Feb	−10.7	(−3.3)	(J)
	First seen	Frogspawn	1 Mar	−4.7	−4.6	JFM
		Chiffchaff	19 Mar	−12.0	−4.8	MA
		Swallow	21 Apr	+1.6	(−0.9)	(A)

Note: Columns show the mean dates for the baseline period (1999–2021 for woody species, otherwise 1999–2020), the anomaly in days for 2022 relative to this period, the temperature response (days change per °C: −ve earlier, +ve later) and months of maximum temperature sensitivity. Values in brackets do not reach statistical significance at $p < 0.05$.

Jevrejeva: Writing – review and editing. **Andrew Matthews:** Writing – review and editing. **Joanne Williams:** Writing – review and editing. **Tim Sparks:** Writing – review and editing. **Fritha West:** Writing – review and editing.

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APPENDIX A: DATASETS

A.1 | NAO index

The WNAO index is traditionally defined as the normalized pressure difference between the Azores and Iceland. This represents the principal mode of spatial variability of atmospheric pressure patterns in the North Atlantic. The WNAO index presented in this report is an extended version of this index based on a series maintained by the University of East Anglia Climatic Research Unit, using data from stations in Gibraltar and south-west Iceland (Jones et al., 1997). These two sites are located close to the centres of action that comprise the WNAO. Data from these stations have been used to create homogeneous pressure series at the two locations which extend back to 1821. The WNAO index in this report is based on these data and presented back to 1850, with winter defined as December to February, to provide consistency with winter statistics presented elsewhere in this report.

For the UK, a positive WNAO index tends to be associated with higher temperatures and higher rainfall (R^2 values of 0.56 for winter mean temperature and 0.26 for winter rainfall based on years 1885–2022 and 1850–2022 respectively, see Appendix B5). This means that over half of the annual variability for UK winter mean temperature and over a quarter for rainfall may be associated with the WNAO. Importantly, however, it also implies that the WNAO is unable to fully explain the variability of UK winters because the complexity of weather types and associated temperature and rainfall patterns through the season cannot be fully accounted for by this single index – the correlation with rainfall in particular being fairly weak. This is because other modes of spatial variability in atmospheric pressure patterns also affect the UK's weather. For example, the East Atlantic (EA) and Scandinavian (SCA) patterns – the second and third modes of spatial variability represented in their positive phases by low pressure to the west of Ireland and high pressure over Scandinavia respectively – also exert an influence (Hall & Hanna, 2018). The influence of WNAO may also differ regionally across the UK, for example, for rainfall across the north-west compared to the south-east, which overall UK rainfall statistics will tend to smooth out (West et al., 2018).

The centres of action that define the summer NAO (SNAO) correspond to grid-point pairs 60° N, 5° E and 80° N, 50° W – corresponding to locations to the east of the Shetland Islands and in north-west Greenland respectively These locations reflect the smaller spatial scale and a more northerly location of the summer Atlantic storm track (Folland et al., 2009). Due to the location of these points a station-based SNAO series cannot be used. Instead, the SNAO index has been calculated from the 20th-century reanalysis (Slivinski et al., 2019) and extended to the present day using the ERA5 reanalysis (Hersbach et al., 2020).

The index is calculated as the difference in seasonal mean sea-level pressure between these grid-point pairs for each year from 1850 to 2022 inclusive. Summer is defined as June, July and August to provide consistency with summer statistics presented elsewhere in the report. Note this SNAO definition differs from Folland et al. (2009) which uses July and August only. For the UK, a positive SNAO tends to be associated with higher temperatures and lower rainfall (R^2 values of 0.21 for summer mean temperature and 0.49 for summer rainfall based on years 1884–2022 and 1850–2022 respectively). So, as with the WNAO, this index is unable to fully explain the variability of UK summers which will also be influenced by other modes of spatial variability. However, in contrast to the WNAO, for the SNAO it is the correlation with temperature, rather than rainfall, that is weak. The efficacy of the 20th-century reanalysis to calculate the SNAO index prior to 1880 is likely to be limited by data availability, so uncertainties are likely to be larger early in the series.

A.2 | HadUK-Grid dataset

The principal source of data in this report is the HadUK-Grid dataset, comprising monthly and daily gridded data covering the UK (Hollis et al., 2019). The primary purpose of these data is to facilitate monitoring of UK climate and research into climate change, impacts and adaptation. All gridded data are at 1 km resolution. The grids are based on the GB national grid, extended to cover Northern Ireland and the Isle of Man, but excluding the Channel Islands. This dataset is updated annually. This report uses version 1.2.0.0 of the dataset. The previous version 1.1.0.0 was used in the State of the UK Climate 2021 report (Kendon et al., 2022). Improvements and critical investigation of the HadUK-Grid dataset, and the associated underlying station data, remain an active and ongoing task.

The underlying UK station data used to produce the gridded dataset is the Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Database, but this has been supplemented by further recently digitized historic data from multiple sources including British Rainfall and Met Office Monthly and Daily Weather Reports. The most significant developments for this release of the HadUK-Grid dataset are:

> Firstly, the inclusion of an updated version of digitized monthly rainfall data from a project called Rainfall Rescue, based on data contained within the 'Ten year rainfall' collection (Met Office Digital Library and Archive, 2020). This collection of

transcribed data went through an extensive process of consolidation, quality control and verification of metadata, described in detail by Hawkins et al. (2022). This version of HadUK-Grid has been built using the second version of this Rainfall Rescue collection (v2.0.0, Hawkins, 2023).

Secondly, the inclusion of digitized monthly sunshine data for the period 1910–1918 held within Met Office MWRs and digitized by the Met Office National Climate Information Centre.

Thirdly, the inclusion of the additional year, 2022.

Table A1 shows the monthly and daily grids from HadUK-Grid used for this report, including the year from which variables are available. Derived annual grids are also included. Daily temperature has been gridded back to 1960, with daily rainfall back to 1891. With daily data, there is often a weaker link between the data and the geographical factors which shape the average over a longer time-scale. Metrics in this report based on the daily rainfall grids are only presented from 1961, even though these grids extend back to 1891. This is because of the step-change in station network density for daily rainfall in 1961 (Figure A3). The smaller number of stations before this date used for the daily rainfall grids means that further work is needed to determine the extent to which any trends in metrics in earlier years are influenced by the relatively low station network density.

Several of the monthly climate variables (days of air frost, days of rain ≥1 mm and days of rain ≥10 mm) have been derived from the daily grids (daily T_{min} and daily rainfall respectively) rather than gridded from monthly

TABLE A1 Monthly and daily variables presented in this report, gridded over the UK at 1 km resolution.

Climate variable	Definition	First year available	Gridding time-scale
Max air temperature	Monthly average of daily max air temperatures (°C)	1884	Monthly
Min air temperature	Monthly average of daily min air temperatures (°C)	1884	Monthly
Mean air temperature	Monthly average of mean daily max and mean daily min air temperatures (°C)	1884	Monthly
Days of air frost	Count of days when the min air temperature is below 0°C	1960	Monthly[a]
Days of ground frost	Count of days when the grass min air temperature is below 0°C	1961	Monthly
Heating degree days	Day-by-day sum of number of degrees by which the mean temperature is less than 15.5°C	1960	Annual[b]
Cooling degree days	Day-by-day sum of number of degrees by which the mean temperature is more than 22°C	1960	Annual[b]
Growing degree days	Day-by-day sum of number of degrees by which the mean temperature is more than 5.5°C	1960	Annual[b]
Precipitation	Total monthly precipitation amount (mm)	1836	Monthly
Days of rain ≥1 mm	Number of days with ≥1 mm precipitation	1891	Monthly[a]
Days of rain ≥10 mm	Number of days with ≥10 mm precipitation	1891	Monthly[a]
Rainfall intensity	Total precipitation on days with ≥1 mm divided by the count of days with ≥1 mm during the year	1891	Annual[b]
Sunshine	Total hours of bright sunshine during the month based on the Campbell-Stokes recorder	1910	Monthly
Windspeed	Monthly mean wind speed (Kt)	1969	Monthly
Max air temperature	Daily max air temperatures (°C)	1960	Daily
Min air temperature	Daily min air temperatures (°C)	1960	Daily
Precipitation	Daily precipitation amount (mm)	1891	Daily

Note: The table also includes monthly and annual grids derived from daily grids.
[a]Denotes monthly grids derived from daily grids.
[b]Denotes annual grids derived from daily grids.

TABLE A2 Approximate total number of observations used for each variable.

Climate variable	Number of years	Number of grids	Average number of stations values per grid	Total number of station values
Monthly T_{max}	139	1668	358	598,000
Monthly rainfall	187	2244	3485	7,820,000
Monthly groundfrost	62	744	389	289,000
Monthly sunshine	113	1356	240	325,000
Monthly windspeed	54	648	140	91,000
Daily T_{max}	63	23,011	514	11,800,000
Daily rainfall	132	48,212	1907	91,900,000

TABLE A3 Formulae used for calculating cooling or growing degree days above thresholds of 22 and 5.5°C.

Condition: Daily T_{max} T_{min} and T_{mean} above or below $T_{threshold}$	Degree-day value
$T_{max} \le T_{threshold}$	0
$T_{min} \ge T_{threshold}$	$T_{mean} - T_{threshold}$
$T_{mean} \ge T_{threshold}$ and $T_{min} < T_{threshold}$	$0.5\ (T_{max} - T_{threshold}) - 0.25\ (T_{threshold} - T_{min})$
$T_{mean} < T_{threshold}$ and $T_{max} > T_{threshold}$	$0.25\ (T_{max} - T_{threshold})$

TABLE A4 Formulae used for calculating heating degree days below a threshold of 15.5°C.

Condition: Daily T_{max}, T_{min} and T_{mean} above or below $T_{threshold}$	Degree-day value
$T_{min} \ge T_{threshold}$	0
$T_{max} \le T_{threshold}$	$T_{threshold} - T_{mean}$
$T_{mean} \le T_{threshold}$ and $T_{max} > T_{threshold}$	$0.5\ (T_{threshold} - T_{min}) - 0.25\ (T_{max} - T_{threshold})$
$T_{mean} > T_{threshold}$ and $T_{min} < T_{threshold}$	$0.25\ (T_{threshold} - T_{min})$

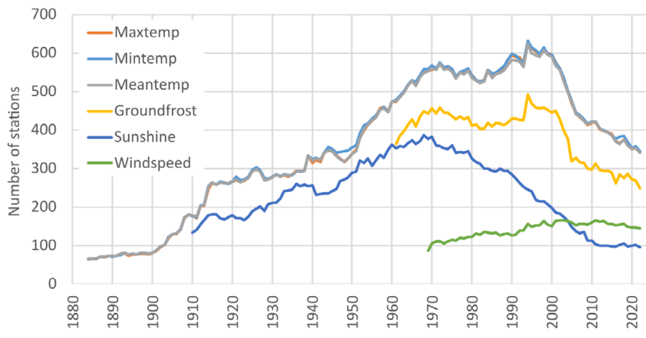


FIGURE A1 Numbers of stations used for gridding – monthly T_{max}, T_{min}, T_{mean} (1884–2022), monthly days of ground frost (1961–2022), monthly sunshine (1910–2022) and monthly windspeed (1969–2022).

station values directly. This approach has the advantage of ensuring that these monthly variables are consistent with the daily grids on which they are based (which would not be the case if they were gridded from station data). Because the gridding is at a daily timescale, we also anticipate that there will be a better overall representation of spatial variation in these monthly derived variables. Annual degree-day and rainfall intensity grids have also been derived from daily temperature and daily rainfall grids respectively. In contrast, monthly temperature and rainfall grids are gridded from monthly station data, rather than being derived from daily temperature and rainfall grids. This means that they are not exactly consistent (indeed observations from monthly raingauges, or digitized monthly rainfall data from Rainfall Rescue, can only go into the monthly rainfall grids) – but in general differences are small.

The approximate total number of station values used to generate the grids for each variable is given in Table A2. In total well over 100 million station values have been used to generate the HadUK-Grid dataset, with more than 90% of these accounted for by daily temperature and daily rainfall. Note however that for monthly variables (e.g. monthly mean maximum temperature), the majority of the monthly station values will have themselves been derived from daily station values (e.g. daily maximum temperature). So in practice the number of *station values* used to generate the grids will differ from the number of *station observations* extracted from the MIDAS database or the other recently digitized data sources.

Figures A1–A3 show the number of stations used for creating monthly and daily grids for each of the variables. For monthly temperature, the number of stations varies from fewer than 100 for the period 1884–1900, increasing

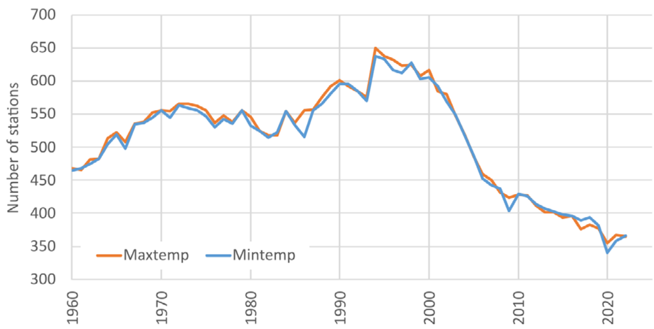


FIGURE A2 Numbers of stations used for daily temperature 1960–2022. The numbers are very similar to those for monthly T_{max} and monthly T_{min} as shown in Figure A1.

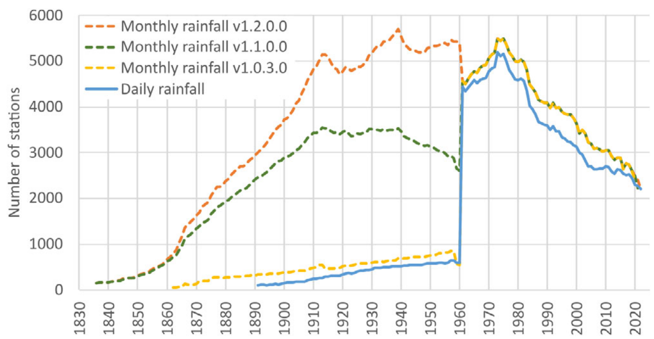


FIGURE A3 Numbers of stations used for monthly rainfall (1836–2022), daily rainfall (1891–2022) and the previous versions of monthly rainfall v1.1.0.0. and v1.0.3.0. The dramatic uplift in monthly station numbers pre-1960 is due to the inclusion of the two versions of Rainfall Rescue data v1.0.0 (used in State of the UK Climate 2021) and v2.0.0 (used in State of the UK Climate 2022). From 1961 onwards v1.0.3.0, v1.1.0.0 and v1.2.0.0 follow the same line.

to between 200 and 400 from the 1910s to 1950s and reaching a peak of over 500 stations from the 1960s to 1990s, followed by a subsequent decline to below 400 stations in the most recent decade. The number of stations recording monthly days of ground frost (i.e. with a grass minimum thermometer) is typically around 100 fewer than air temperature from the 1960s onwards. The number of monthly sunshine stations rises from around 150 to almost 400 from the 1910s to 1970, followed by a steady decline to around 100 stations in the most recent decade. The number of monthly windspeed stations rises from 100 to 120 in the 1970s and 1980s to around 150 stations in the most recent decade (Figure A1). As would be expected the number of stations for daily temperature over the period 1960–2022 matches that for monthly temperature (Figure A2).

Figure A3 shows the number of stations for rainfall, and the impact of inclusion of the Rainfall Rescue data v2.0.0 in comparison to the previous two versions of the dataset v1.1.0.0 (which used Rainfall Rescue data v1.0.0) and v1.0.3.0 of the dataset which did not use Rainfall Rescue data. The effect of adding Rainfall Rescue data v2.0.0 has been to remove altogether the previous step-increase in the station network numbers for monthly rainfall from 1960 to 1961 in v1.1.0.0 and 1.0.3.0. However, the overall impact of the v2.0.0 of Rainfall Rescue is generally much less than that of v1.0.0 and the increase in number of observations prior to 1961 smaller.

The v1.0.0 stations were originally prioritized based on station record length and maximizing the number of stations in the 19th century. The v1.1.0.0 grids for the 20th century already had reasonable geographical coverage across the UK, so while the updated Rainfall Rescue data have added greater spatial detail, particularly in the 20th century, they have not significantly altered large-scale metrics (such as the UK rainfall series). The benefit of the v2.0.0 data is also not as great as the station count uplift suggest because the spatial coverage of Rainfall Rescue data includes significant clustering across some parts of the UK, while others remain relatively data sparse. Figure A4 compares monthly rainfall for September 1916 and 2022, showing the number of stations used for each grid. The 1916 station network, although comprising approximately twice as many stations as in 2022, has clustering across south-east and north-west England and Scotland's Central Belt, while other areas such as west Wales and northern Scotland remain relatively data sparse. In comparison, the 2022 network, while comprising a smaller number of stations overall has a much more even geographical coverage.

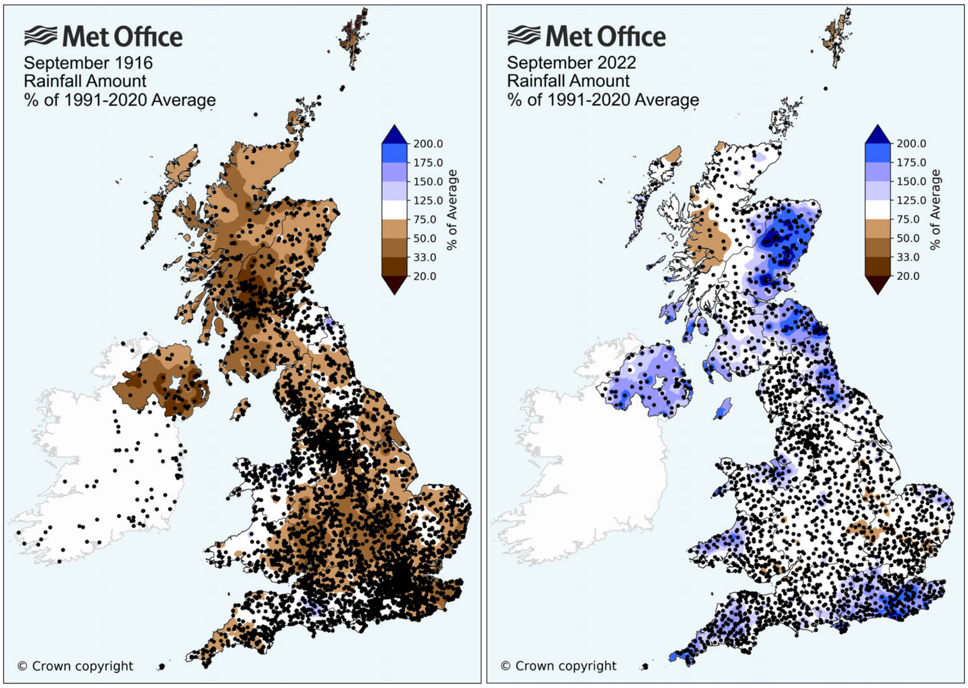
It is interesting to note that these rainfall observations continued through World War 1 and this dataset remains a remarkable tribute to the observers of the time 'Much of the observing work is being done by willing substitutes for men who have gone to the front' (British Rainfall 1916, British Rainfall Organization, 1917). The digitized data also include stations across Ireland (at that time part of the UK).

A.3 | The observing network in 2022

Figure A5 shows the state of the UK's observing network in 2022 based on data availability from stations that have actively returned data during the year. The networks are designed and maintained to achieve a good spatial coverage with stations representative of all areas of the UK. Due to the high spatial variation in rainfall, the network is much denser than for other variables, but even so highly localized events may still be missed.

While the majority of the UK is reasonably well covered, some areas, notably western Scotland, are more

FIGURE A4 The station network used in HadUK-Grid v1.2.0.0 comparing monthly rainfall for September 1916 (4945 stations) and September 2022 (2137 stations).



data-sparse than others, but these also tend to correspond to areas with a smaller population. Coverage for some variables (notably sunshine) may considerably reduce if data for an individual station is missing, and where surrounding stations struggle to cover the gap – i.e. if there is limited redundancy in the network. Overall however, even though the current number of stations may be fewer than in earlier decades (e.g. the 1970s), the spatial distribution of stations is more even, and so there is an improvement in the overall network's ability to capture the spatial characteristics of climate variables over that day, month, season or year.

A.4 | Long-term average grids

The long-term averages for the WMO standard 30-year climatological reference periods 1961–1990 and 1991–2020 presented in this report have been calculated from long-term average monthly gridded datasets at 1 km. These gridded long-term averages have been derived as simple averages of the individual monthly grids spanning the each 30-year period. The long-term averages for nations and regions quoted in this report are therefore self-consistent with the long-term average calculated from monthly, seasonal and annual series in the report, although we note this is not exactly true for winter since 30 individual winters in the period will include the previous December (e.g. December 1960 for the period 1961–1990) and omit the last December (December 1990) – although in practice any difference will usually be very small.

The Introduction section explains the choice of average periods used in this report. More background and discussion regarding averaging periods are provided in Hulme (2020).

A.5 | Annual degree days

Degree-day datasets were generated from the daily temperature grids, as indicated in Table A1, using formulae given in Table A3 and A4. The daily mean temperature T_{mean} is calculated from the daily maximum temperature T_{max} and the daily minimum temperature T_{min} as $(T_{max} + T_{min})/2$. The degree-day value is estimated differently depending on which of T_{max}, T_{mean} or T_{min} are above (for cooling degree days and growing degree days) or below (for heating degree days) the defined threshold.

A.6 | Consistency and quality control

Quality control of station observations held in the Met Office Integrated Data Archive System (MIDAS) database is the responsibility of the Met Office Observations Quality Management (OBQM) team. This team runs a suite of both automated and manual quality control checks on MIDAS, which is the source of the majority of the station data used in HadUK-Grid. The other digitized data sources have also had quality checks at time of digitization where possible. For example, tables of monthly rainfall published in British Rainfall also include annual totals, so the latter can be used as a closure check on the monthly totals. Development of the HadUK-Grid dataset

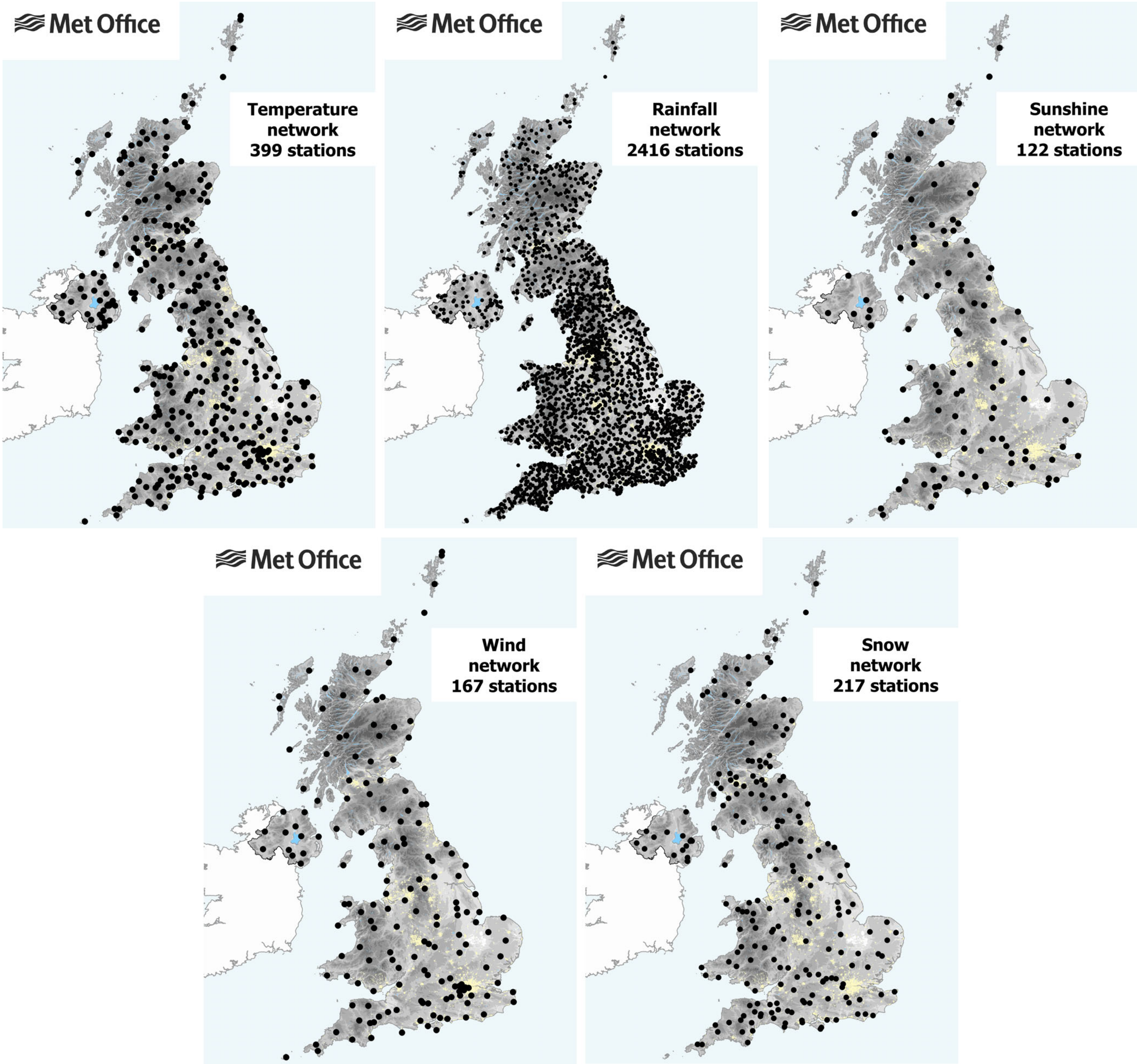


FIGURE A5 State of the UK observing network in 2022. The number of observations is indicative as these may vary on a daily basis due to data availability.

and improvement in quality control processes to remove as much suspect data as possible, whilst avoiding the removal of good data, remains an active area of research and development and will feed into future versions. Further details are beyond the scope of this report.

The HadUK-Grid dataset uses open-source ancillary files for terrain elevation, proximity to coast and urban land use that are used within the interpolation scheme, which provides traceability. The dataset is also version controlled – including a version-controlled numbering system, so State of the UK Climate publications can all be linked to a specific version of the dataset. This report uses version 1.2.0.0 of the HadUK-Grid dataset. Details of the HadUK-Grid dataset are provided in Hollis et al. (2019).

A.7 | Quality control of record values

Quality control of station observations is particularly important for potential new record values, especially those of high profile such as the new UK highest maximum temperature record of 40.3°C at Coningby Lincolnshire on 19 July 2022. The Met Office has an established process for verifying potential new records, managed by the Site Weather Assessment Team (SWAT). Whenever a potential new record occurs, this team undertakes a detailed manual assessment prior to the new record's acceptance. This assessment includes: a site assessment to take into account any potential issues affecting exposure; checking instrument calibration dates; and a detailed check of the observations (at an automated site this would typically comprise minute-resolution data), including checks with neighbouring stations. At a manual station, verification may also involve a discussion with the observer. Supplementary evidence or observations would be used where possible (e.g. rain-radar).

The SWAT team makes a final decision based on collective expert judgement using all available evidence, based on the general premise that an observation should be assumed valid unless there is clear supporting evidence to the contrary. The record's acceptance or rejection is confirmed in as timely a manner as possible, typically within a week.

A.8 | Areal series

The monthly series for the UK and countries are calculated as area-averages derived from the 1 km monthly gridded datasets. Each monthly value is an average of all the individual 1 km grid point values which fall within the UK or country. The seasonal and annual series in turn are calculated from the monthly areal series. This approach enables a single statistic to be produced for each area (UK or country) from each grid, despite the fact that the UK's climate has a very high degree of spatial variation (e.g. with elevation). These statistics are self-consistent through time.

In the same way, long-term averages are calculated as an average of all the individual 1 km long-term average grid points which fall within the UK or country. As noted above, the long-term average statistics are consistent with the monthly statistics with the exception of winter. Daily area-averages have similarly been calculated from the 1 km daily gridded datasets.

Statistics for the UK and countries are useful for monitoring annual variability, trends and extremes but inevitably may mask considerable spatial variation across the area as illustrated by the anomaly maps.

A.9 | Global surface temperature

HadCRUT.5.0.1.0 is a gridded dataset of global historical surface temperature anomalies relative to a 1961–1990 reference period. Data are available for each month from January 1850 (Morice et al., 2021). The HadCRUT5 dataset of global surface temperature comprises a blend of the CRUTEM5 land-surface air temperature dataset (Osborn et al., 2021) and the HadSST4 SST dataset (Kennedy et al., 2019). CRUTEM5 anomaly fields are based on a compilation of monthly mean temperature records from a global network of several thousand weather stations. HadSST is produced by taking in situ measurements of SST from ships, moored and drifting buoys, stored in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). The HadCRUT5 global average values are calculated as the 'best estimate' mean of 200 ensemble member dataset realizations that sample the distribution of uncertainty. HadCRUT5 is one of several global surface temperature datasets, with others produced by NOAA, NASA and Berkeley Earth.

A.10 | Central England temperature

The Central England temperature (CET) monthly series, beginning in 1659, is the longest continuous temperature record in the world (Manley, 1974). It comprises the mean of three observing stations covering a roughly triangular area of England from Bristol to London to Lancashire; the current stations used for this series are Pershore College (Worcestershire), Rothamsted (Hertfordshire) and Stonyhurst (Lancashire) although the stations used in this series have changed in the past. A CET daily series is also available from 1772 (Parker et al., 1992).

Following each station change, the data are adjusted to ensure consistency with the historical series by analysing periods of overlap between stations, and since 1974 the data have been adjusted to allow for any artificial warming effects due to the expansion of local built-up areas. Parker and Horton (2005) and Parker (2010) have investigated uncertainties in the CET series. This version of the report has adopted an updated version of the CET series v2.0.0 (Legg et al., 2023).

The CET series is a station-based series using data from a *combination* of observing stations. Climate records in the UK may also come from *individual* climate stations, examples of which include the long-running stations at Oxford and Durham. Comprehensive descriptions of these two stations and their associated climate series are provided in Burt and Burt (2019, 2022).

A.11 | Sea-surface temperature data

The Met Office Hadley Centre's sea-surface temperature (SST) data set, HadSST.4.0.1.0 is a monthly global field of SST anomalies relative to a 1961–1990 reference period. The data are on a 5° latitude by 5° longitude grid from 1850 to date. This is derived from a combination of fixed and drifting buoys, ship bucket and engine room intake thermometers and hull sensors. The data have

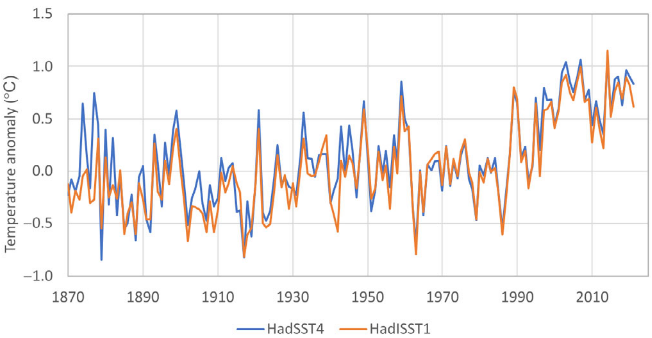


FIGURE A6 Comparison of UK near-coast SST from HadISST1 and HadSST4 as anomalies relative to 1961–1990.

been adjusted to minimize the effects of changes in instrumentation throughout the record. The data set is presented as a set of interchangeable realizations that capture the temporal and spatial characteristics of the estimated uncertainties in the biases (Kennedy et al., 2019).

The UK near-coast SST series in this report comprises the average of the 5° latitude-longitude grid-cells adjacent to the coast of the Great Britain. This approach differs to State of UK Climate 2021 which used the HadISST1 dataset on a 1° latitude by 1° longitude grid (Rayner et al., 2003). Although HadSST4 has a lower spatial resolution than HadISST1, it has a more up-to-date homogenisation so should be better for identifying long-term trends, and it also has uncertainty information as shown in Figure 28. Figure A6 compares the UK near-coast SST for these two series. They are highly correlated (R^2 0.87 for the period 1870–2021) and differences are generally small.

A.12 | England and Wales precipitation series

The England and Wales precipitation (EWP) series has monthly data back to 1766, and is the longest instrumental series of this kind in the world. The daily EWP series begins in 1931. The series incorporates a selection of long-running rainfall stations to provide a homogeneity-adjusted series of areal-averaged precipitation. EWP totals are based on daily weighted totals from a network of stations within each of five England and Wales regions.

The extent to which seasonal trends apparent in the EWP series are influenced by homogeneity issues (e.g. the number of stations used historically to compile the EWP series, how well the network has historically captured orographically enhanced rainfall across high ground, how well the network has historically captured precipitation which has fallen as snow) remains an area of investigation, and trends in the series should be treated with caution (Murphy et al., 2020). Various papers detail the development of the EWP series (Alexander & Jones, 2001; Simpson & Jones, 2012; Wigley et al., 1984). Figure 34 shows that the EWP series is highly correlated with the England and Wales series (i.e. the areal-average for England and Wales combined) from the HadUK-Grid dataset from 1836.

A.13 | Rain gauge and snow depth data

Daily rainfall data presented in this report are 0900–0900 UTC totals from either daily or tipping-bucket rain-gauges registered with the Met Office. The rain-gauge network has diminished from over 4000 rain-gauges across the UK in the 1960s to between 2500 and 3000 in the 2010s. The majority of these gauges are owned and maintained by the Met Office, the Environment Agency, Natural Resources Wales, SEPA and Northern Ireland Water. The spatial distribution of the network has changed with time but nevertheless the high network density ensures that most rainfall events will be well captured, although inevitably highly localized convective rainfall events may be missed.

Snow depth data are recorded at 0900 UTC. These are either spot observations from automatic snow depth sensors or manual observations of representative level depth in a location free from drifting or scour by wind; ideally the average of three measurements would be recorded. The network comprised over 400 stations from 1960 to 2000 but has subsequently reduced to around 200 stations in 2022.

A.14 | Sunshine data

The UK's sunshine network in 2022 comprises two instrument types: approximately 40% Campbell-Stokes (CS) sunshine recorders which are read manually; the remainder Kipp & Zonen CSD-1 (KZ) automatic sunshine recorders. An upward adjustment of KZ totals is made to give a monthly 'CS equivalent sunshine'. This ensures that the full sunshine network (automatic and manual) is used while maintaining consistency between the two instrument types. Legg (2014a) and references therein provide further details.

The inclusion of the additional 9 years of data from 1910 to 1918 from Monthly Weather Reports has extended the UK sunshine series to 113 years; in total an additional 17,700 observations. These data went through a process of consolidation, quality control and verification of metadata within the Met Office National Climate Information Centre prior to their use. On average, there are around 160 stations for each grid (around 50% more

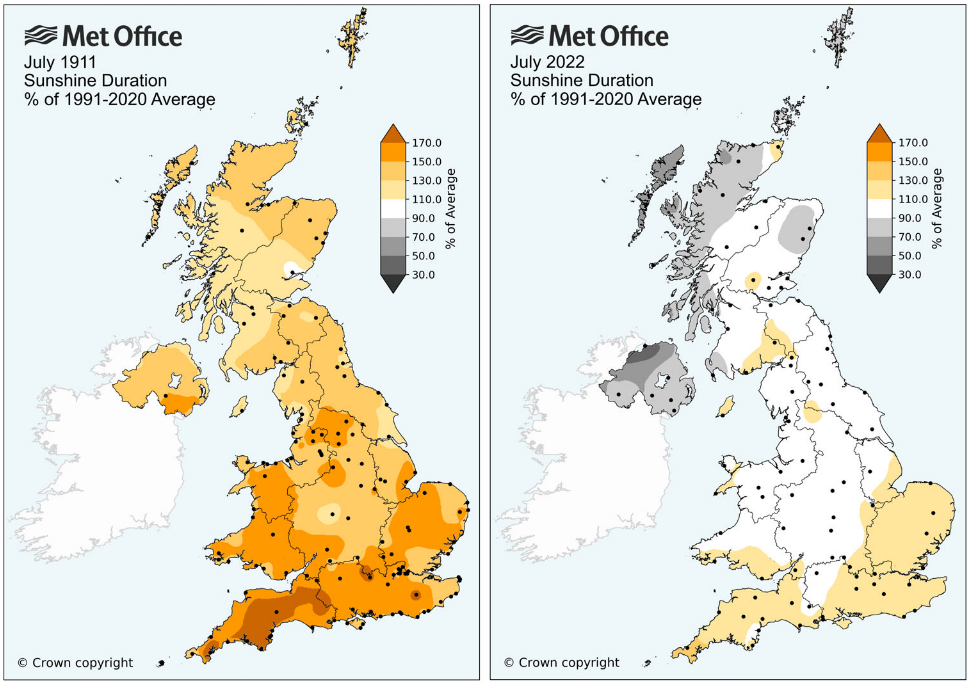


FIGURE A7 The station network used in HadUK-Grid v1.2.0.0 comparing monthly sunshine for July 1911 (141 stations) and July 2022 (94 stations).

than the current network). However, as with the Rainfall Rescue data, the historic sunshine data show significant spatial clustering. Figure A7 compares monthly sunshine for July 1911 and 2022, showing the number of stations used for each grid. July 1911 was the sunniest July for England in the series from 1910. The figure shows the tendency for sunshine stations at this time to be located around the coast; particularly the coastline of England and Wales (there are almost 30 stations along the south coast of England alone). At that time many of these locations would have been popular destinations for summer holidays, with resorts keen to attract visitors by emphasizing their sunny climate credentials.

A.15 | Wind data

Wind speeds are measured by cup anemometers located on a standard 10-m height mast. The rate of rotation is proportional to the speed of the wind. These were introduced by the Met Office for wind measurement at surface stations during the 1950s (Sloan & Clark, 2012). At mountain stations, wind speeds are measured by heated sonic anemometers which have no moving parts and avoid potential problems with icing. Due to data availability, the wind analyses within this report are based on data from 1969 and 1972.

A.16 | Sea-level data

Sea-level changes around the British Isles are monitored by the UK national network of tide gauges; for 2022 this network comprised 42 stations. For more than 100 years, tide gauges have provided measurements of sea-level change relative to the Earth's crust. However, tide gauges are attached to the land, which can move vertically thus creating an apparent sea-level change.

A UK sea-level index for the period since 1901 computed from sea-level data from five of these stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool) provides the current best estimate for UK sea-level rise, excluding the effect of this vertical land movement. The records from each station are combined after removing the long-term trend from each to account for varying vertical land movement rates across the country. After aggregating the records, the calculated country-wide average vertical land movement rate of 1.4 mm·year^{-1} is reintroduced (Bradley et al., 2011; Woodworth et al., 2009).

As mentioned in Woodworth et al. (2009), the network of 42 stations falls under the responsibility of the Environment Agency. Only five sites date back to the beginning of the 20th century: the others did not begin until the 1950s. In creating the long-term index, we follow Woodworth's approach, which only uses data from the long-term series. Woodworth et al. (2009), which is based on data from up to 2006, notes that throughout the course of the record, at least three of the five stations are present for all years apart from three, the last of which was 1915. Unfortunately, from 2007 onward, there have been more gaps in observations for the five stations. A UK national report in 2019 for the Global Sea Level Observing System (GLOSS) provides more information about issues with the network, available at https://www.

goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=24144.

The tide gauge data used in this study is provided by the British Oceanographic Data Centre (https://www.bodc.ac.uk) and is funded by the Environment Agency. Trends in the index have been calculated by fitting linear trends using the CATS (Create and Analyse Time Series) package described in Williams (2008) which produces realistic estimates of uncertainty by accounting for autocorrelation in the series.

The data for the storm surge analysis is also supplied by BODC and processed for the National Tidal and Sea Level Facility (https://ntslf.org) specifically for short-term surge analysis. For Surge Quality Control, sites with possible datum shifts and levelling uncertainties not suitable for long-term trend analyses are included. This provides a larger dataset to analyse the storm surge, but as a result levels may not be comparable between sites or year-to-year.

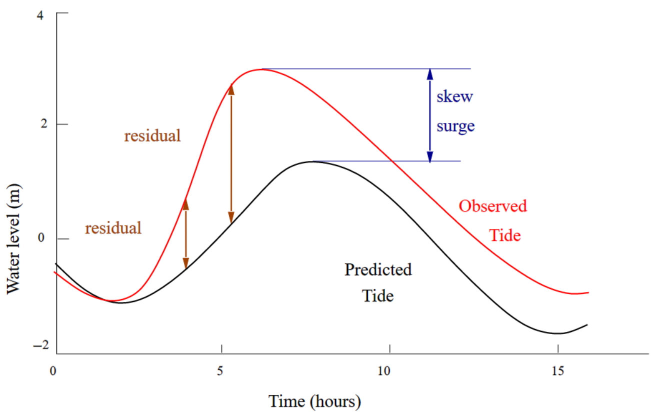


FIGURE A8 Diagram of skew surge showing the difference between predicted tide and observed tide.

Skew surge is the difference between the peak observed tide and peak astronomical tide, which is the part that can be predicted months in advance (Figure A8). It is usually slightly smaller than the 'non-tidal residual' that is sometimes reported, but is a more robust measure of peak impact, being independent of timing (Williams et al., 2016).

A.17 | Phenology data

Nature's Calendar, run by the Woodland Trust, has been collating information on the timing of the seasons for over 20 years. Furthermore, it has built up a considerable database of older data, derived from a number of sources. Current data, recorded by citizen scientists across the UK, identify dates on which particular phenological events are observed. Here, we show UK mean dates for the first unfolded leaf ('first leaf') in spring and first bare tree ('bare tree') in autumn for four common shrub or tree (woody) species: Elder (*Sambucus nigra*); Hawthorn (*Crataegus monogyna*); Pedunculate Oak (*Quercus robur*); Silver Birch (*Betula pendula*). We also show spring events as follows: first flowering dates for Hazel (*Corylus avellana*), Lesser Celandine (*Ficaria verna*), Wood Anemone (*Anemone nemorosa*), and Bluebell (*Hyacinthoides non-scripta*); first appearance dates for 7-spot Ladybird (*Coccinella septempunctata*), Brimstone butterfly (*Gonepteryx rhamni*), Red-tailed Bumblebee (*Bombus lapidarius*) and

TABLE B1 1σ Uncertainty (standard error) ranges for annual T_{mean}, rainfall and sunshine.

Temperature (°C)					
Year range	**UK**	**England**	**Wales**	**Scotland**	**Northern Ireland**
1910–1919	0.04	0.04	0.06	0.06	0.08
1961–1965	0.03	0.03	0.04	0.03	0.04
2006–2012	0.03	0.03	0.04	0.04	0.04
Rainfall (%)					
Year range	**UK**	**England**	**Wales**	**Scotland**	**Northern Ireland**
1910–1919	1.2	1.2	3.0	2.8	3.7
1961–1965	0.3	0.3	0.6	0.5	0.8
2006–2012	0.4	0.4	0.9	0.7	1.6
Sunshine (%)					
Year range	**UK**	**England**	**Wales**	**Scotland**	**Northern Ireland**
1929–1935	0.7	0.8	1.0	1.0	1.6
1959–1964	0.6	0.8	0.9	0.8	1.4
2005–2012	0.7	0.9	1.1	1.1	1.8

Speckled Wood butterfly (*Pararge aegeria*); first recorded dates of the song of Song Thrush (*Turdus philomelos*), the appearance of Common Frog (*Rana temporaria*) spawn, first observation of Chiffchaff (*Phylloscopus* collybita) and of Swallow (Hirundo rustica). The UK mean dates are based on simple annual averages of submitted observations (minimum 100), without geographical correction.

Dates for 2022 for these phenology indicators are compared against annual means for the baseline period (1999–2021 for first leaf and bare tree, 1999–2020 for the other indicators). 2021 data to calculate these annual means were only available for the woody species due to computer problems. To assess the relationships with temperature for each spring event, we have regressed the 1999–2022 annual mean dates on monthly CET for the month incorporating the mean date and the preceding 2 months. We report the response to a 1°C increase in the months that were significantly associated with mean dates. We also compare 1999–2022 annual means of bare dates to October mean CET, since experience has shown that the influential window for autumn events is much shorter. CET provides a reasonable representation of the inter-annual temperature variations across the UK, for comparison with the UK-wide phenology indicators.

APPENDIX B: TIME SERIES, TRENDS AND UNCERTAINTY

B.1 | Time series and trends shown in this report

The time series in this report are plotted on either actual or anomaly scales and include a smooth trend. This means that both annual variability and the longer-term trend (removing short-term variability) can be viewed simultaneously. For some series, there may be few individual years that fall close to this long-term trend; and many or even most years may fall well above or well below.

The smooth trend-lines are constructed using a weighted kernel filter of triangular shape, with 14 terms either side of each target point. The kernel defines how much weighting the terms either side of a point in the series have in estimating the smoothed average at that point; in this case the triangular shape using 14 data points either side means that data points further away have less influence. The effect is to smooth out the year-to-year variations and estimate any longer-term variations in the data. The kernel is reflected at the ends of the time series so the trend lines cover the full length of the series. However, this process of reflection will tend to damp any trends at the ends of the time series, so the trend line for the first and last decade of each series should be interpreted cautiously. The method of creating smoothed trend-lines using a 'non-parametric regression' is described in Mudelsee (2019), who describes the advantages and disadvantages of various possible statistical approaches in trend analysis of climate time series.

Climate records at individual stations may be influenced by a variety of non-climatic factors such as changes in station exposure, instrumentation and observing practices. Issues of changing instrumentation and observing practices will tend to be of greater importance early in the series, particularly before the 20th century. In contrast, station exposure issues related to urbanization, which may for example affect temperature-related variables, may be of greater importance in the late part of the series from the mid-20th century, although this is likely to vary on a station-by-station basis – for example, whether a station is located in the centre of a large city or nearer the periphery, the latter being more likely to have changed over time. Identifying and correcting such factors in climate monitoring is referred to as homogenisation. Some homogenisation has been undertaken for some series presented in this report, such as the CET record, and the adjustment of sunshine records described in Appendix A14. For most variables however the individual station data in this report have not been explicitly homogenized to account for these non-climatic factors.

B.2 | Uncertainty estimates

Earlier studies have considered uncertainties in the gridded data and areal-averages based on a 5-km 'legacy' gridded dataset previously used for UK climate monitoring (Legg, 2011, 2014b). The HadUK-Grid 1 km gridded dataset, while at a different resolution, uses the same method of interpolation. The uncertainty estimates presented here will therefore be broadly representative although these numbers will not reflect recent additions to the dataset (particularly Rainfall Rescue). A reappraisal for the latest version of HadUK-Grid is still needed; this is work in progress.

A key source of uncertainty is associated with spatial sampling – that is, the density of the observation network. In general, uncertainty ranges for areal-averages of monthly mean temperature, rainfall and sunshine increase in the past as the network density reduces. However, for rainfall, this spatial sampling has been greatly improved pre-1960 due to the inclusion of Rainfall Rescue data, as discussed in the next section. The uncertainty estimates in these earlier studies have been adjusted upward to acknowledge other sources of error, for example, observational errors such as random errors in instrument readings, calibration errors or structural

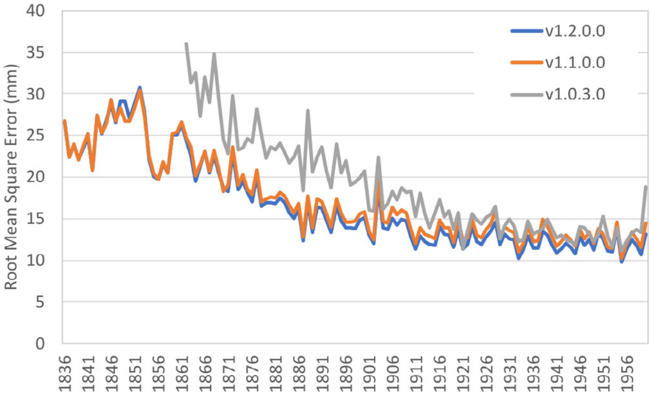


FIGURE B1 Root mean square errors estimated for monthly rainfall for different versions of the HadUK-Grid dataset v1.2.0.0, v1.1.0.0 and v1.0.3.0 from 1836 to 1960 using a leave-one-out cross-validation.

uncertainty (the latter implying that alternative methods of analysis may produce slightly different results).

Table B1 lists 1σ uncertainty (standard error) ranges for annual mean temperature, rainfall and sunshine for different periods in the legacy 5 km gridded dataset. Indicative date periods are presented here. These correspond to: the earliest years in the 5 km dataset where the availability of station data was generally lowest and uncertainty highest; a period in the dataset around the 1960s which for rainfall corresponds to a step increase in availability of station data and corresponding decrease in uncertainty (note that this step is no longer present for monthly rainfall in v1.2.0.0); and a relatively recent period in the dataset indicating current uncertainty. More comprehensive tables covering the full date range can be found in Legg (2014b). We have applied a conservative reduction factor of $\sqrt{2}$ to convert monthly uncertainty ranges to annual. Uncertainty associated with individual months of the year cannot be considered independent but it is reasonable to assume that winter half-year biases are likely to be different in nature from summer half-year biases (Parker, 2010). Seasonal uncertainty ranges are likely to be similar to monthly uncertainty ranges presented in Legg (2014b). Uncertainties in the CET and EWP series have also been investigated elsewhere (Parker, 2010; Parker & Horton, 2005; Simpson & Jones, 2012).

Uncertainties in areal rainfall statistics may potentially be large for small (county-sized) areas early in the series as the number of stations reduces, although this is particularly dependent on the spatial distribution. In general, rainfall will be affected to a much greater extent than temperature due to the much greater spatial variability, whereas temperature tends to be a much smoother varying field. This means that ranking of years (e.g. the wettest autumn in the series for county X) may change as more observations from digitized data sources continue to be added to the dataset in the future.

B.3 | Rainfall rescue improvements

The inclusion of the Rainfall Rescue provides significantly improved representation of the spatial detail in rainfall and consequently better representation of historical extremes. One statistic used to demonstrate this can be from 'leave-one-out' cross-validation. Here each station is in turn excluded from the gridding process, and an estimate is made for that location from the other stations. The root mean square error (RMSE) across all stations can then be used as an indicator of the uncertainty in monthly rainfall estimates at point locations. This is shown in Figure B1. This figure shows the marked improvement (reduction) in uncertainty in the two versions 1.2.0.0 and 1.1.0.0 which include Rainfall Rescue data compared to the version without Rainfall Rescue data (v1.0.3.0), particularly through the 19th century. However, there is little further improvement shown between these two versions, demonstrating that the first version of Rainfall Rescue (v1.0.0), was generally able to well capture the characteristics of rainfall across the UK over this period, with v2.0.0 adding more spatial detail.

It is beyond the scope of this publication to explore the details of the new dataset in extensive detail, which will be the subject of separate studies. See also Appendix A2.

B.4 | Other sources of uncertainty

The summary rainfall statistics for the UK and countries presented in this report are based on an areal average of the rainfall total in mm, rather than an areal average of the rainfall anomaly field as a percentage. This is judged to be the simpler and more readily comprehensible statistic for the majority of users and is directly proportional to the total volume of rainfall across the country. However, it means that climatologically wetter areas of the UK have a greater influence on the overall UK summary statistic than the drier areas, rather than all equal-sized areas having equal influence (as would be the case using an areal average of the rainfall anomaly field). This introduces uncertainty because the rank of each year relative to the others may vary depending on which of these two metrics is chosen (Kendon & Hollis, 2014). It may also influence any trend in overall UK rainfall if this varies spatially between climatologically wetter and drier parts of the UK.

A further source of uncertainty in the rainfall data is introduced by measurement of precipitation which has fallen as snow. At manually read rain gauges the observer will measure precipitation equivalent of fresh snow fallen at 0900 UTC, whereas at automatic rain gauges any snow collected will be recorded when it subsequently melts; quality control of these data may then re-apportion this precipitation to previous days. However, inevitably snow measurement can be problematic, for example, if wind eddies may carry snow over or blow it into or out of the gauge, in many situations estimation of precipitation from snow may be either underestimated or overestimated. This important limitation as noted for Figure 34 is acknowledged and investigated by Murphy et al. (2020). However, this now tends to be usually less of a problem than during colder, snowier years of earlier decades.

B.5 | Coefficient of determination

The coefficient of determination, R^2, as presented in this report is a measure of the strength of the linear relationship between a predictor variable and a dependent variable, where R is the correlation coefficient, based on a linear least-squares regression. This means the R^2 value is a statistical measure of how closely the dependent variable can be predicted from the predictor variable. An R^2 value of 1 would indicate a perfect correlation, in which the dependent variable can be predicted without error from the predictor variable. An R^2 value of 0 would mean the predictor variable has no predictive value for the dependent variable. An R^2 value of 0.5 would mean that 50% of the variance in the dependent variable can be explained by variations in the predictor variable. R^2 values exceeding 0.9 for time series in this report would indicate that they are very highly correlated.

B.6 | Rounding

Values quoted throughout this report are rounded, but where the difference between two such values is quoted (e.g. comparing the most recent decade with 1991–2020), this difference is calculated from the original unrounded values.

APPENDIX C: USEFUL RESOURCES

C.1 | Met Office

Annual State of the UK climate publications from 2014 https://www.metoffice.gov.uk/research/climate/maps-and-data/about/state-of-climate

UK climate information https://www.metoffice.gov.uk/research/climate/maps-and-data

HadUK-Grid information https://www.metoffice.gov.uk/climate/uk/data/haduk-grid/haduk-grid

The CET dataset is maintained by the Met Office Hadley Centre and can be downloaded at https://www.metoffice.gov.uk/hadobs/hadcet/

The EWP dataset is maintained by the Met Office Hadley Centre and can be downloaded at https://www.metoffice.gov.uk/hadobs/hadukp/

The HadSST4 dataset is maintained by the Met Office Hadley Centre and can be downloaded at https://www.metoffice.gov.uk/hadobs/hadsst4/

The HadCRUT5 dataset is maintained by the Met Office Hadley Centre and can be downloaded at https://www.metoffice.gov.uk/hadobs/hadcrut5/

Met Office UK Storm Centre Name our Storms project https://www.metoffice.gov.uk/weather/warnings-and-advice/uk-storm-centre/index

Scanned copies of British Rainfall can be downloaded from the Met Office digital library and archive at https://digital.nmla.metoffice.gov.uk/SO_5470d19c-4866-40fc-9ae9-7dcb2fc0f823/

Further information on data products available from the Met Office may be obtained by contacting the Customer Centre https://www.metoffice.gov.uk/about-us/contact

C.2 | External links

The Met Office is not responsible for the content of external internet sites.

Access to HadUK-Grid dataset (open access) https://catalogue.ceda.ac.uk/uuid/3d30627eee5a48be844c32723b7b6be8

Access to a copy of the Met Office Midas database is available to researchers on registration at https://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0

An open access version of the Met Office Midas database is available at https://catalogue.ceda.ac.uk/uuid/dbd451271eb04662beade68da43546e1

Bulletin of the American Meteorological Society (BAMS) State of the Climate Report https://www.ametsoc.org/index.cfm/ams/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/

Centre for Ecology and Hydrology, National Hydrological Monitoring Programme, Monthly Hydrological Summaries for the UK https://nrfa.ceh.ac.uk/monthly-hydrological-summary-uk

Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), *date of access*. https://cds.climate.copernicus.eu/cdsapp#!/home

Environment Agency Water Situation Reports for England https://www.gov.uk/government/collections/water-situation-reports-for-england

Lamb weather types and UK Jenkinson Gale Index maintained by the University of East Anglia Climatic Research Unit https://crudata.uea.ac.uk/cru/data/lwt/

North Atlantic Oscillation (NAO) data maintained by the University of East Anglia Climatic Research Unit https://crudata.uea.ac.uk/cru/data/nao/

National Tidal and Sea Level Facility UK National Tide Gauge Network (owned and operated by the Environment Agency) https://ntslf.org/data/uk-network-real-time

Scottish Avalanche Information Service annual reports of the winter season https://www.sais.gov.uk/sais-annual-reports/

UK Health Security Agency heat mortality monitoring reports https://www.gov.uk/government/publications/heat-mortality-monitoring-reports

Weather at Oxford monthly and annual reports https://www.geog.ox.ac.uk/research/climate/rms/reports.html

WMO Annual Bulletin on the Climate in region VI (Europe and Middle East) https://www.dwd.de/EN/ourservices/ravibulletinjahr/ravibulletinjahr.html

WMO guide to climatological practices https://library.wmo.int/index.php?lvl=notice_display&id=5668

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AUTHOR INDEX

WILEY

