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State of the UK Climate 2023

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The Royal Meteorological Society Journal of Climate Science

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Cover Images:

Left: Flooding in the Exe valley near Stoke Canon, Devon on 12 January 2023. The South-West main-line railway is in the foreground. The previous day several raingauges in the upper catchment of the River Exe on Exmoor recorded daily totals of 70 to 80mm or more, and more than 40 properties were flooded. Image: Matt Clark, Met Office.

Right: Storm Agnes – the first named storm of the 2023-24 season - approaches the UK on 27 September 2023. The brown area to the south-west of the storm centre is smoke from Canadian wildfires. Image: Met Office, NOAA, NASA.

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SPECIAL ISSUE ARTICLE

International Journal of Climatology RMetS

State of the UK Climate 2023

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Success is by no means a necessary result of efforts to secure it. Although, therefore, with each consecutive year I have adopted additional precautions against any errors either of observation or computation creeping into this work, it by no means follows that I shall continue to be as successful in keeping them out as I have hitherto been; in fact, in spite of every care, it is hardly reasonable to hope for a continuance of such remarkably small tables of errata as there have been of late years.

G. J. Symons 62, Camden Square, N. W. April 27, 1874 (British Rainfall Organization, 1874).

INTRODUCTION

This report provides a summary of the UK's weather and climate through the calendar year 2023, alongside the historical context for a number of essential climate variables. This is the tenth in a series of annual 'State of the UK Climate' publications, published in the International Journal of Climatology (IJC) since 2017, and an update to the 2022 report (Kendon et al., 2023). 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 and sea-level are also presented, and in addition there is a short section on phenology that 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 maintain the observation networks, in particular the UK land weather station network, into the future. This is vital if the UK's climate monitoring capability is to be 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). County-level statistics are also provided in some sections. 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 A–C.

The report presents summary statistics for the most recent year 2023 and the most recent decade 2014–2023 against the 30-year standard climate normal period 1991–2020 and the baseline period 1961–1990, following World Meteorological Organization climatological best practice (WMO, 2017). 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 2014–2023 provides a 10-year 'snapshot' of the most recent experience of the UK's climate and how it compares to historical records. Differences between 2014 and 2023, 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 2014–2023) changes every year, while the most recent 30-year reference period (currently 1991–2020) changes every decade. The reference period 1991–2020 does not overlap with 1961–1990.

Throughout the report's text the terms 'above normal' and 'above average' and so on refer to the 1991–2020 reference period unless otherwise stated. The majority of maps in this report show the year 2023 relative to 1991–2020—that is, they are anomaly maps that show the spatial variation in this difference from average. Some anomaly maps relative to 1961–1990 are also included. Maps of actual values are in most cases not displayed because these are dominated by the underlying climatology, which is strongly influenced, for example, by elevation and distance from the coast. For this report, this 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.

Corrections to State of UK Climate 2022

The executive summary and main text in the report stated: 'The most recent decade 2013–2022 has had 4%/7% fewer days of air and ground frost per year compared with 1991–2020 and 15%/23% fewer than 1961–1990'. These were incorrectly reported as percentages instead of actual days. The corrected sentence is 'the most recent decade 2013–2022 has had 4/7 fewer days of air and ground frost per year compared with 1991–2020 and 15/23 fewer than 1961–1990'.

The main text stated '… 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)'. The corrected text is '… representing substantial changes in the UK's climate with the number of air and ground frosts decreasing by around 2 and 3 weeks, respectively (Figure 21)'.

The correct percentage values (not reported) were 7%/7% and 23%/20%. Figure 21 and caption were correct as presented and the main report conclusions are unaffected.

This correction is published alongside the State of UK Climate 2022 report (references; Anon 2024).

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.
- Observations show that extremes of temperature in the UK have been affected much more than average temperature.
- The UK has warmed at a rate consistent with the observed change in global surface air temperature over land.

- The UK's second warmest year of 2023, the warmest June and the September heatwave were all made more likely by climate change.

Land temperature

- 2023 was the second warmest year on record for the UK in the series from 1884, with only 2022 warmer. 2023 was 0.83°C above the 1991–2020 average and 1.66°C above 1961–1990.
- February, May, June and September 2023 were all ranked in the top-ten warmest months for the UK in the monthly series from 1884.
- Six years in the most recent decade (2014–2023) have been within the top-ten warmest in the UK series from 1884, with all 10 warmest years occurring in the 21st century.
- The most recent decade (2014–2023) has been on average 0.42°C warmer than the 1991–2020 average and 1.25°C warmer than 1961–1990. This is the warmest 10-year period in both the UK series from 1884 and CET series from 1659.
- The last three decades (1994–2023) include more than half of all top-ten warmest monthly values, over two thirds of top-ten warmest seasonal values and over 90% of top-ten warmest annual values in temperature series for all counties of the UK from 1884.
- The number of 'pleasant' days (daily maximum 20°C) has increased by 41% for the most recent decade (2014–2023) compared with 1961–1990. The number of 'warm' days (25°C) has increased by 63%; the number of 'hot' days (28C) has more than doubled and 'very hot' days (30°C) more than trebled over the same period.

Air and ground frost

- The number of air frosts in 2023 was below the 1991–2020 average, while the number of ground frosts was the second lowest in the series from 1961.
- The most recent decade (2014–2023) has had almost a week fewer air frosts per year than the 1991–2020 average and over a fortnight fewer than 1961–1990.
- The most recent decade (2014–2023) has had over a week fewer ground frosts per year than the 1991–2020 average and almost a month fewer than 1961–1990.

Energy demand indices for heating, cooling and plant growth

- Heating and growing degree days in 2023 were third-lowest and second-highest, respectively, in series from 1960. Cooling degree days were above average but not exceptionally so.
- The most recent decade (2014–2023) has had 5% fewer heating degree days per year on average than 1991–2020 and 14% fewer than 1961–1990.
- The most recent decade (2014–2023) has had 30 cooling degree days per year for England compared with 22 for 1991–2020 and 14 for 1961–1990, that is, more than doubling from 1961 to 1990.
- The most recent decade (2014–2023) has had 6% more growing degree days per year on average compared with 1991–2020 and 21% more than 1961–1990.

Near-coast sea-surface temperature

- For the second successive year, 2023 was the warmest year for UK near-coast sea-surface temperature (SST) in a series from 1870.
- The most recent decade (2014–2023) has been on average 0.3°C warmer than the 1991–2020 average and 0.9°C warmer than 1961–1990 for UK near-coast SST.
- Six years of the most recent decade (2014–2023) for UK near-coast SST are within the top-ten warmest in the series.

Precipitation

- 2023 was the seventh wettest year on record for the UK in the series from 1836, with 113% of the 1991–2020 average. Large areas of the UK exceeded 125%.
- March, July, October and December 2023 were all top-ten wettest months in the UK monthly rainfall series from 1836; the first year this has happened for four separate months.
- Five of the 10 wettest years for the UK in the series from 1836 have occurred in the 21st century.
- The most recent decade (2014–2023) has been 2% wetter than 1991–2020 and 10% wetter than 1961–1990.
- UK winters for the most recent decade (2014–2023) have been 9% wetter than 1991–2020 and 24% wetter than 1961–1990, with smaller increases in summer and autumn and none in spring.
- For rainfall series for all counties of the UK from 1836, the number of top-ten wettest annual values is markedly higher in each of the last three decades (1994–2023) compared with earlier decades. However, the increase in top-ten wettest values is much less apparent in the respective monthly and seasonal series.
- There has been a slight increase in heavy rainfall across the UK in recent decades.

Snow

- While there were some snow events in 2023 (and several recent years were less snowy), overall this was still

a much less snowy year than most other years since the 1960s.
- In recent years, widespread and substantial snow events have occurred in 2009, 2010, 2013, 2018 and 2021, but their number and severity have generally declined since the 1960s.

Sunshine

- 2023 sunshine for the UK was 102% of the 1991–2020 average.
- June was the sunniest month of the year and the UK's sunniest calendar month since May 2020 with 245 h. December was especially dull with only 28 h.
- The most recent decade (2014–2023) has had for the UK on average 4% more hours of bright sunshine per year than the 1991–2020 average and 9% more than 1961–1990. 2014–2023 is the sunniest 10-year period in the UK series from 1910.
- For the most recent decade (2014–2023) UK winters have been 4% sunnier than 1991–2020 and 15% sunnier than 1961–1990. UK springs have been 7%/16% sunnier.

Wind

- The 2023–2024 storm season had its most active start with respect to the number of named storms since storm naming was introduced in 2015, with seven named storms (Agnes to Gerrit) from September to December.
- Even so, overall 2023 was comparable in storminess with other years in recent decades in terms of occurrences of max gust speeds exceeding 40/50/60 Kt.
- There have been fewer occurrences of max gust speeds exceeding 40/50/60 Kt in the last two decades compared with the 1980s and 1990s.
- The UK annual mean wind speed for 2023 was slightly below the 1991–2020 average.
- The UK annual mean wind speed from 1969 to 2023 shows a downward trend, consistent with that observed globally.

Sea-level rise

- Data from the tide gauge at Newlyn, one of the longest available records around the UK, shows sea level is rising, with 2023 the highest year on record since 1916. Other sites around the UK also had their highest or second-highest year on record.
- The rate of sea level rise is increasing, with highest estimates of 4.6 ± 0.9 mm/year (1993–2023), indicating acceleration.
- Newlyn monthly mean sea levels showed exceptionally high periods in 2023 especially in the second half of the year.
- There were 16 extreme storm-surge events in 2023, of which 13 were associated with named storms.
- The highest skew surges of the year were during storm Pia on 21 December (1.2 m at Cromer, Norfolk, 1.5 m at Lowestoft, Suffolk, 1.4 m at Harwich, Essex, 1.2 m at Sheerness, Kent and 1 m at Dover). Models show surges >1 m were widespread across the North Sea.
- The highest sea levels in most of south and south-west England and Wales were due to the combination of a spring tide and sustained period of high sea levels throughout late October and early November.

Significant weather

- The UK recorded its warmest June on record by a wide margin in a series from 1884, with a major North Atlantic marine heatwave a significant contributing factor.
- 30°C was recorded in September in the UK on seven consecutive days, for the first time on record.
- Scotland had its wettest 2-day period on record on 6–7 October in a daily series from 1891.
- Storm Babet brought the UK's most impactful weather event of the year. England and Wales combined had its third wettest 3-day period on record on 18–20 October in a daily series from 1891.
- Winds from storm Ciarán on 2 November had the potential to be as severe as from the 'Great Storm' of 16 October 1987, but the strongest winds missed the UK to the south.
- The UK recorded its wettest September to December period since 2000 due to persistently wet and unsettled weather, including the sequence of named storms from Agnes to Gerrit.

Phenology

- Indicators for spring 2023 were generally near-average or later compared with the 1999–2022 baselines. Insect activity, in particular, appeared later. However, Hazel had its earliest flowering date in a series from 1999.
- Bare tree dates were a few days later than the 1999–2022 baseline due to warm September temperatures and a generally mild autumn.
- Overall, the 2023 leaf-on season was slightly longer than the 1999–2022 baselines, although the shorter lawn-cutting season might be attributed to a complex mixture of low temperatures in early March inhibiting

growth and wet grass in autumn discouraging late cutting.

1 | SYNOPTIC SITUATION

1.1 | Atmospheric circulation

Figure 1 shows monthly mean sea-level pressure anomalies for the 12 months of 2023 relative to the 1991–2020 average, using the ERA5 reanalysis (Hersbach et al., 2020). This provides an indication of atmospheric circulation patterns for each month overall. Pressure anomalies on the charts are scaled equally across all 12 months for consistency; however, winter months typically have larger pressure anomalies than summer months. Figure 2 shows HadUK-Grid UK monthly mean sea-level pressure anomalies relative to 1991–2020 for the most recent decade 2014–2023 (120 months). These charts and the time series illustrate the characteristic large variability in atmospheric circulation patterns in the UK's climate, which tend to be masked out on a seasonal scale—although inevitably the monthly charts will also mask out daily variability too, since changes in weather type do not neatly coincide with calendar months and each month will usually comprise a mixture of weather types.

A large high-pressure anomaly was centred over the UK in February and the UK monthly mean sea level pressure anomaly (12.6 hPa above the 1991–2020 February average) was the highest for any calendar month since February 2012. Pressure was also higher than normal in April, May and June with a high pressure anomaly extending from eastern Europe and Scandinavia to the UK. In February, May and June in particular the weather was often settled and dry. Pressure was lower than normal for the other months of the year, most notably in March, July and October to December, each of these months seeing a low-pressure anomaly extending from eastern Europe to the UK, and in March including much of the north Atlantic. During these months, the jet stream was often stronger and shifted further south than normal, bringing unsettled weather and stormy at times. In summary, the second half of the year was much more unsettled, with fewer spells of fine-settled weather than the first half.

The lowest pressure anomalies for any month of the most recent decade 2014–2023 were, by far, January and February 2014 (−15.7 and −21.7 hPa, respectively). These 2 months had the lowest average UK pressure anomalies of any month in the series from 1961; very much lower than any month in 2023 (Figure 2). These 2 months formed part of the exceptionally stormy and wet winter of 2013–2014 (Kendon and McCarthy 2015)—this being the UK's wettest winter on record in the series from 1836.

1.2 | NAO index

Figure 3 shows the winter North Atlantic Oscillation (WNAO) index from 1850 to 2023 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.

The WNAO index for 2023 was negative, although not markedly so (−0.6), one of only two WNAO negative winters of the most recent decade 2014–2023, the other being 2021 (−1.0). Other earlier winters in the series have been much more negative, especially winter 2010 (−3.1). A WNAO negative winter would tend to be associated with a cold, dry winter. Winter 2023 was slightly milder than average (anomaly +0.2°C) and drier than average (anomaly 85%). February 2023 was very dry in the south of the UK with blocked weather patterns (Figure 1). The UK has experienced a run of mild, wet winters in the most recent decade, consistent with a positive phase of the WNAO, including the very wet winters of 2014, 2016 and 2020—but not 2023 (Figure 39). Overall, the WNAO index shows a large annual variability but also decadal variability with periods of mainly positive phase (e.g., the 1910s–1920s, 1990s and 2010s) and negative phase (e.g., the 1960s) which are represented by the smoothed trend line in Figure 3.

Figure 4 shows the summer North Atlantic Oscillation (SNAO) index from 1850 to 2023 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.

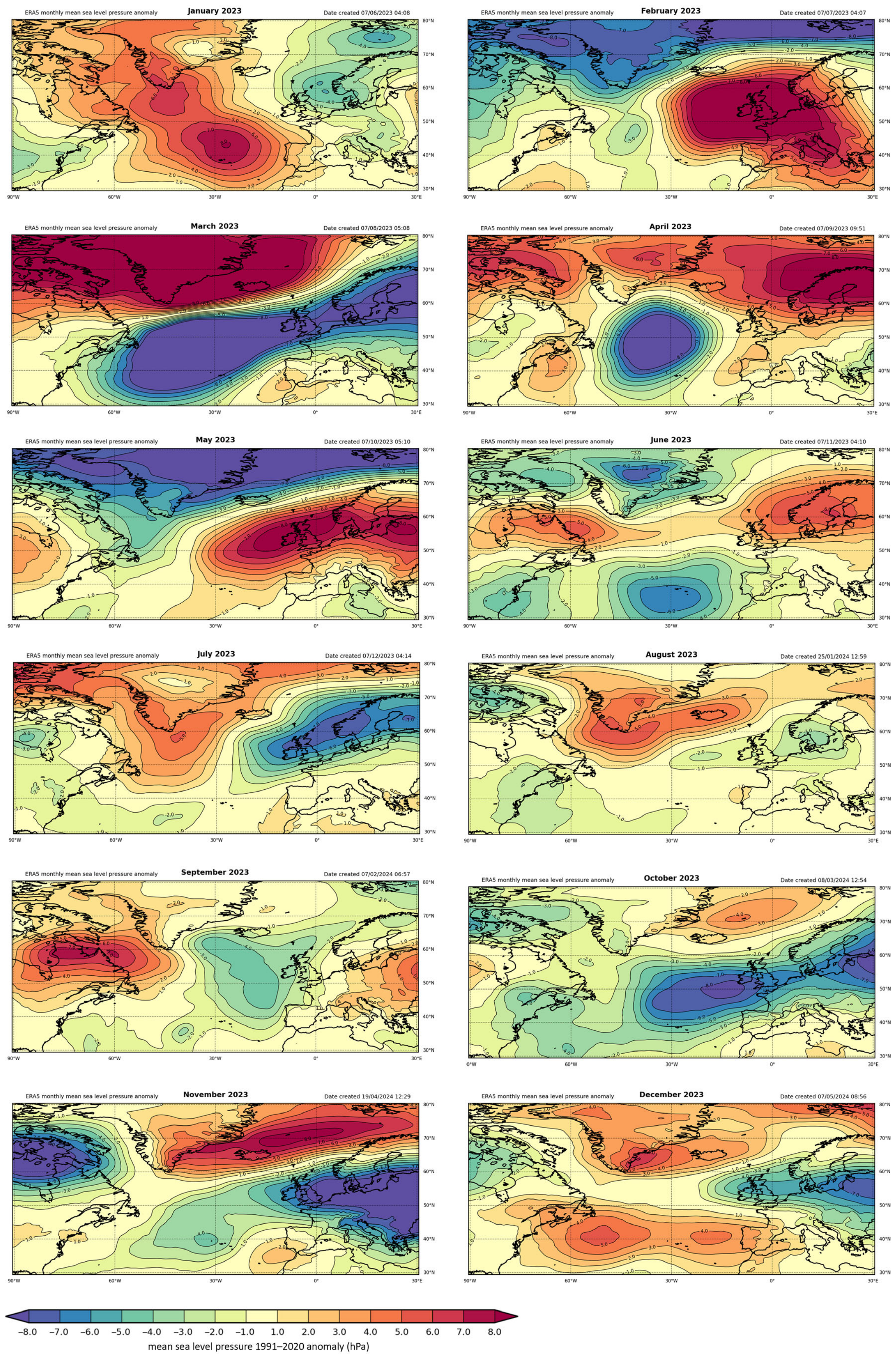


FIGURE 1 2023 monthly mean sea-level pressure anomalies relative to 1991–2020 using the ERA5 reanalysis (Hersbach et al., 2020).

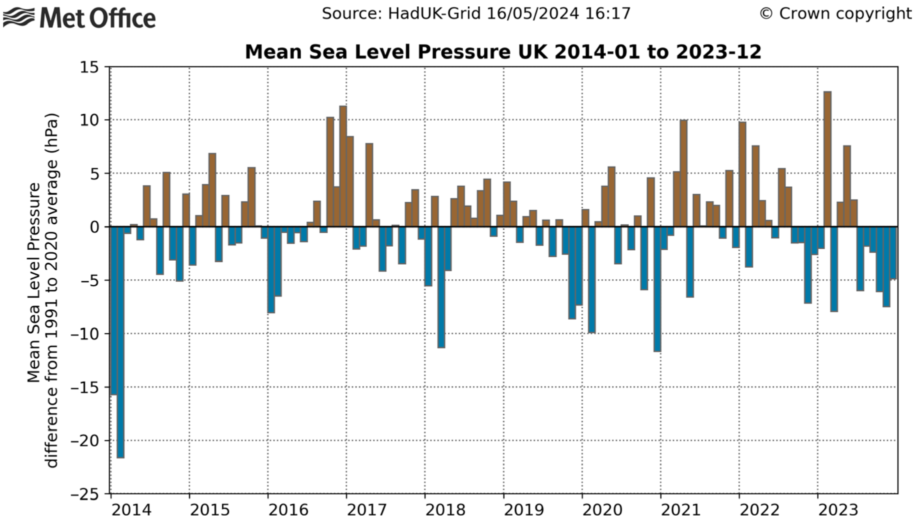


FIGURE 2 UK monthly mean sea-level pressure anomalies relative to 1991–2020 for the most recent decade 2014–2023 (120 months) based on the HadUK-Grid dataset (Hollis et al., 2019).

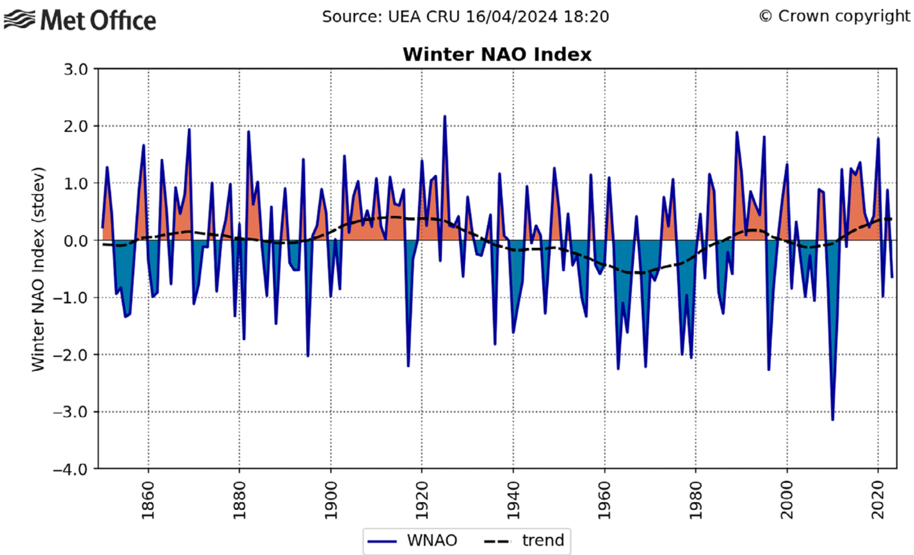


FIGURE 3 Winter NAO index based on the standardized monthly mean pressure difference between stations in Gibraltar and south-west Iceland. Winter 2023 refers to the period December 2022 to February 2023.

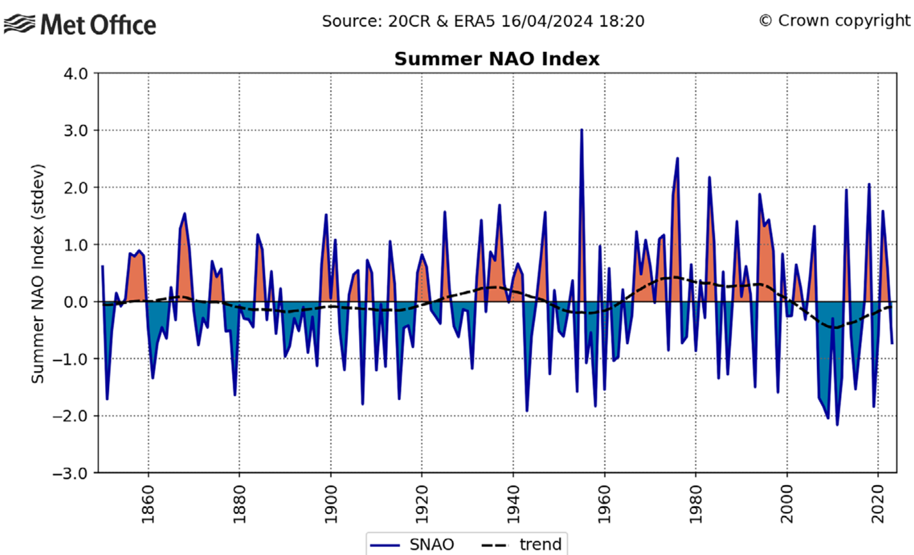


FIGURE 4 Summer NAO index based on the standardized monthly mean pressure difference using the 20th century reanalysis (Slivinski et al., 2019) and extended to the present day using the ERA5 reanalysis (Hersbach et al., 2020). Summer refers to the period June to August.

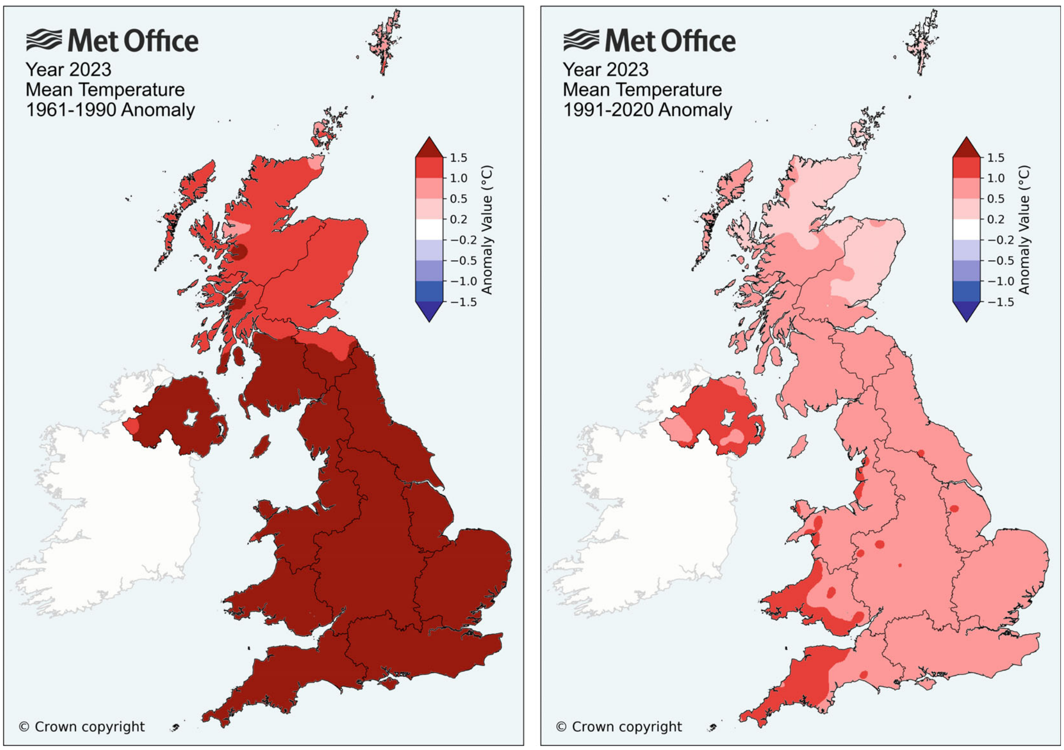
The SNAO index for 2023 was also marginally negative, (−0.7). A SNAO-negative summer would tend to be associated with lower temperatures and higher rainfall. Summer 2023 was warmer than average (anomaly 0.8°C) and wetter than average (anomaly 113%). June was fine and settled but July and August generally unsettled. Recent notably negative summers include 2015 (−1.5) and 2019 (−1.8) and positive summers 2018 (2.1) and 2021 (1.6). 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 a run of wet SNAO negative summers from 2007 to 2012. The recent large fluctuations in the SNAO reflect some markedly contrasting summers—illustrating the UK's large annual variability in the weather and atmospheric circulation patterns.

Importantly, neither the WNAO or SNAO can fully explain the variability of UK winters or summers because of the complexity of weather types and associated temperature and rainfall patterns through the season across the UK's relatively small spatial scale.

2 | TEMPERATURE

2.1 | Annual, seasonal and monthly temperature

The UK mean temperature (T_{mean}) for 2023 was 9.97°C, which is 0.83°C above the 1991–2020 long-term average. 2023 was the second warmest year on record in the UK series from 1884 behind only 2022 (10.03°C). The highest anomalies, exceeding 1.0°C relative to 1991–2020, were across Northern Ireland and western England and Wales. The UK mean temperature was 1.66°C above the 1961–1990 baseline long-term average (Figure 5). This was the warmest year on record for both Wales and Northern Ireland, the second warmest for England and third warmest for Scotland. The Republic of Ireland also had its warmest year in a national series from 1900 (Met Éireann, 2023). While many western counties had their warmest year on record, further east for the majority of England and Scotland the warmest year remains 2022, with other record years 2003, 2006 and 2014 confined to



2023	1961–1990	1991–2020
UK	1.66	0.83
England	1.84	0.92
Wales	1.80	0.99
Scotland	1.29	0.60
Northern Ireland	1.73	1.03

FIGURE 5 (a,b) Mean temperature anomalies relative to 1961–1990 and 1991–2020 for year 2023. The table shows anomaly values for the UK and countries (°C).

the far north and west (Figure 6a,b). Appendix A8 describes these county areas.

The UK annual mean daily maximum temperature (T_{max}) for 2023 was also the second highest on record, behind 2022, whereas it was the UK's warmest year on record for annual mean daily minimum temperature (T_{min}) (6.32°C, 0.79°C above the 1991–2020 average, next warmest 2014, 6.26°C). Annual T_{max} and T_{min} temperature anomalies across the UK were similar, but with slightly lower anomalies across Scotland for T_{min} (Figure 7).

Figures 8 and 9 show seasonal and monthly T_{mean} anomalies for the UK for 2023. Table 1 shows monthly, seasonal and annual actual and anomaly values and ranks for the UK and countries for 2023. Figure 10 shows UK monthly mean temperature anomalies for the most recent decade 2014–2023.

Eight of the 12 months of the year were warmer than average, with anomalies in June and September (+2.5°C and +2.2°C) the highest for the UK since December 2015. Four months of the year were in the top-ten warmest for the UK overall (for T_{mean}) in series from 1884—February (ranked 5th), May (8th), June (1st) and September (equal-1st)—although this is also true for 2006 and 2017, and compares to 6 months in 2022. All countries of the UK had their warmest June, while England and Wales also had their warmest September. Unusually, June was the warmest month of the year; the last time this happened was in 1966 (in 1970 June and August were equal-warmest). 1890 is the only year in the UK series where September was the warmest month.

Three months of the year were slightly cooler than average, with the most negative anomaly a modest −0.3°C in July. All other years in the most recent decade have had at least 1 month with a significantly more negative anomaly than this (Figure 10).

While winter and spring temperatures were near average overall, summer and autumn were notably warm (ranked 8th and 6th warmest, respectively), although for both seasons 2022 was warmer overall. Autumn anomalies were particularly high in the south, exceeding 1.5°C.

Table 2 shows monthly, seasonal and annual T_{mean} anomaly values for the UK and countries for the most recent decade 2014–2023 against both 1961–1990 and 1991–2020. The most recent decade 2014–2023 has been 0.42°C warmer than 1991–2020 and 1.25°C warmer than 1961–1990, with the most warming across England, then Wales, and slightly less across Scotland and Northern Ireland. Comparing the most recent decade 2014–2023 to 1961–1990, all months have warmed for the UK by between +0.9°C for October and +1.7°C for February, with the greatest warming in England for February (+1.9°C) and the least in Scotland for October (+0.5°C). These statistics reflect annual and decadal variability in

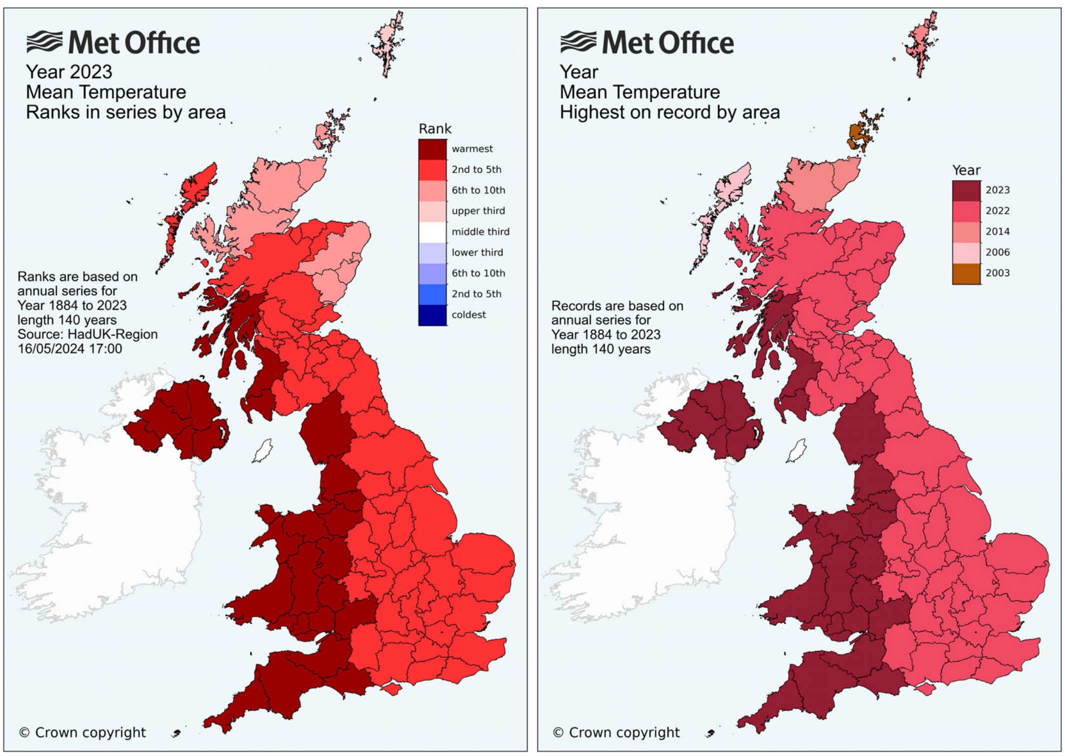


FIGURE 6 The rank of 2023 annual mean temperature for all counties of the UK (a, left) and the warmest year on record all counties of the UK (b, right) based on series from 1884.

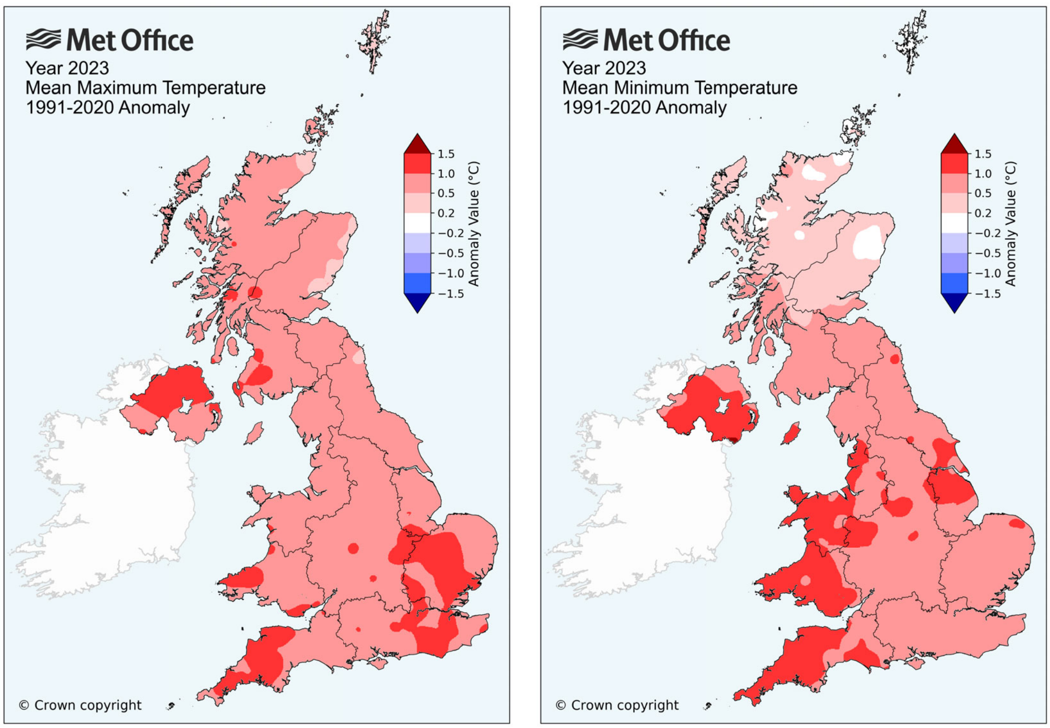
the UK's climate in addition to the ongoing warming due to climate change.

Figure 11 shows a time series of annual T_{mean} anomalies for the UK from 1884 to 2023 inclusive, and shows that the main period of warming for the UK has been from the 1980s onward at a rate of ~0.25°C per decade (1°C in 40 years, i.e., two grid lines along for every one grid line up on the graph.) The two warmest years in the series are 2022 and 2023. Six of the 10 years 2014 to 2023 have been within the top-ten warmest for the UK overall (2014, 2017, 2018, 2020, 2022 and 2023), and this is the warmest 10-year period in the UK series. All top 10 warmest years in the UK T_{mean} series have occurred in the 21st century; none of the top 10 coldest years has occurred in this century, the most recent of these being 1963. 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.

Thirty years ago, the warmest year in the UK series from 1884 to 1993 was 1990. Half of the years since then (i.e., for the period 1994 to 2023) have subsequently been warmer than 1990.

Figure 12 shows annual mean maximum and minimum temperatures for the UK from 1884 to 2023 as anomalies relative to 1991–2020. These series are highly correlated (R^2 0.83). Warming is slightly higher for T_{max} than T_{min} with the most recent decade (2014–2023) 1.41°C warmer than 1961–1990 for T_{max} and 1.09°C for T_{min}. The UK average diurnal temperature range (DTR, $T_{max} - T_{min}$) is ~7°C. There has been a small recent increase in the average DTR but to levels similar to those observed before the mid-20th Century (Figure 13).

Figure 14 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 2014–2023 has seen 16 seasons out of 40 in the top-ten warmest in their seasonal series (more than one in three): five in winter



2023	T_{max}	T_{min}
UK	0.87	0.79
England	0.93	0.92
Wales	0.92	1.07
Scotland	0.72	0.45
Northern Ireland	1.00	1.06

FIGURE 7 2023 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).

(2014, 2016, 2019, 2020, and 2022); four in spring (2014, 2017, 2020, and 2022); three in summer (2018, 2022, and 2023); four in autumn (2014, 2021, 2022, and 2023)—whereas none have fallen in the top-ten coldest.

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

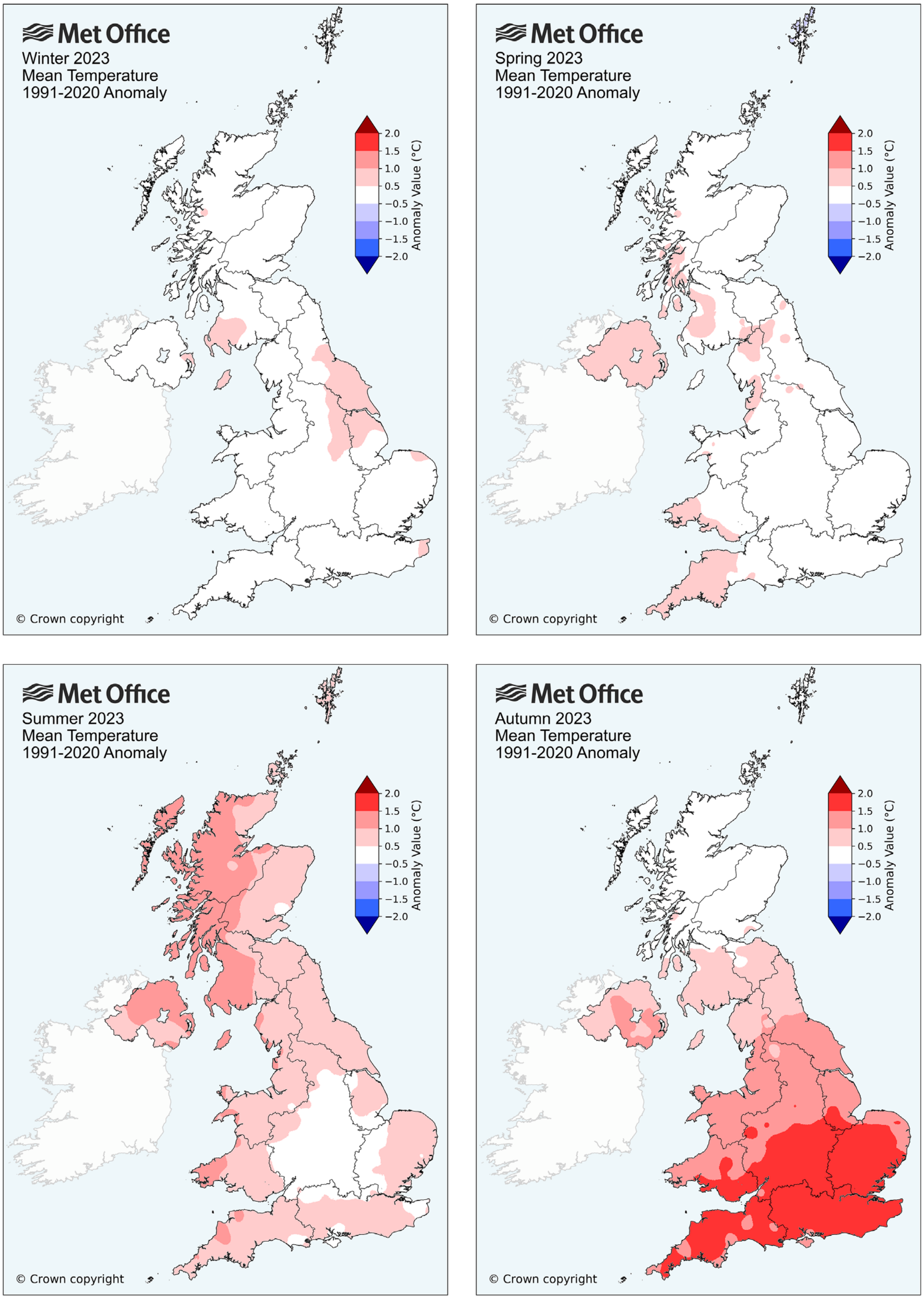


FIGURE 8 2023 seasonal mean temperature anomalies relative to 1991–2020. Winter refers to the period December 2022 to February 2023.

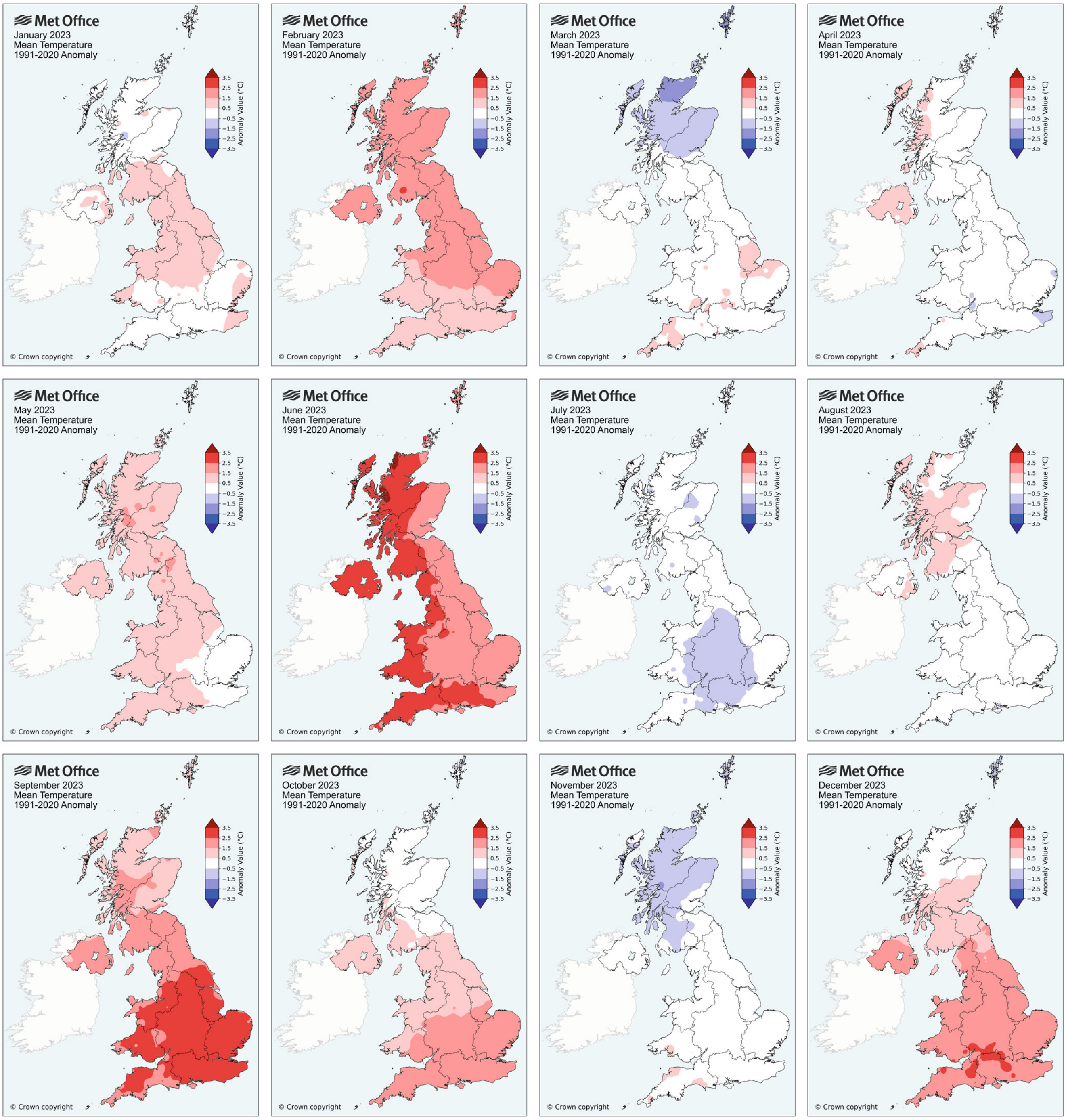


FIGURE 9 2023 monthly mean temperature anomalies relative to 1991–2020. The legend scale ranges from −3.5°C to +3.5°C.

error is <0.1°C and consequently the uncertainty is much smaller than the year-to-year variability. In this report monthly and seasonal temperature data are presented in tables to the nearest 0.1°C and annual temperature data to 0.01°C. More information relating to the uncertainties and how they are estimated is provided in Appendix B2.

A key illustration of the implications of the UK's warming climate is the increased number of high-temperature values which have occurred in monthly, seasonal and annual temperature series in recent years. This question was examined a decade ago (Kendon 2014) with a similar analysis repeated here. Monthly, seasonal and annual temperature values are often reported where they fall within the top-ten of the series at country, national, regional or county level. Figure 15a examines the frequency of occurrence of these values through each

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TABLE 1 Monthly, seasonal and annual mean temperature actual and anomaly values (°C) relative to 1991–2020 for the UK and countries for year 2023.

	UK Actual	UK Anomaly	England Actual	England Anomaly	Wales Actual	Wales Anomaly	Scotland Actual	Scotland Anomaly	Northern Ireland Actual	Northern Ireland Anomaly
January	4.4	0.5	4.9	0.5	5.0	0.6	3.3	0.3	4.9	0.5
February	5.8	1.7	6.2	1.5	5.8	1.3	5.1	2.0	6.7	2.0
March	5.7	0.0	6.8	0.4	6.2	0.3	3.6	−0.7	6.3	0.3
April	7.8	0.0	8.4	−0.2	8.1	0.0	6.6	0.1	8.6	0.6
May	11.6	0.9	12.3	0.7	11.9	1.0	10.3	1.2	11.8	1.3
June	15.8	2.5	16.7	2.3	16.2	2.7	14.3	2.7	16.0	3.0
July	15.0	−0.3	16.1	−0.4	14.9	−0.3	13.2	−0.2	14.4	−0.3
August	15.3	0.2	16.2	−0.1	15.2	0.1	13.8	0.5	14.9	0.4
September	15.2	2.2	16.6	2.7	15.6	2.5	12.8	1.5	14.2	1.6
October	10.7	1.0	12.1	1.5	11.5	1.4	8.3	0.1	10.9	1.2
November	6.3	−0.2	7.2	0.1	7.3	0.3	4.4	−0.8	6.8	0.0
December	5.8	1.6	6.8	2.1	7.0	2.1	3.6	0.6	6.5	1.8
Winter	4.3	0.2	4.8	0.2	4.7	0.1	3.3	0.3	4.9	0.3
Spring	8.4	0.3	9.2	0.3	8.7	0.4	6.9	0.2	8.9	0.7
Summer	15.4	0.8	16.3	0.6	15.4	0.8	13.8	1.0	15.1	1.0
Autumn	10.7	1.0	12.0	1.4	11.5	1.4	8.5	0.3	10.6	1.0
Annual	9.97	0.83	10.89	0.92	10.40	0.99	8.29	0.60	10.17	1.03

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 below. The series lengths are 1884–2023 (140 years) except winter which is 1885 to 2023 (139 years).

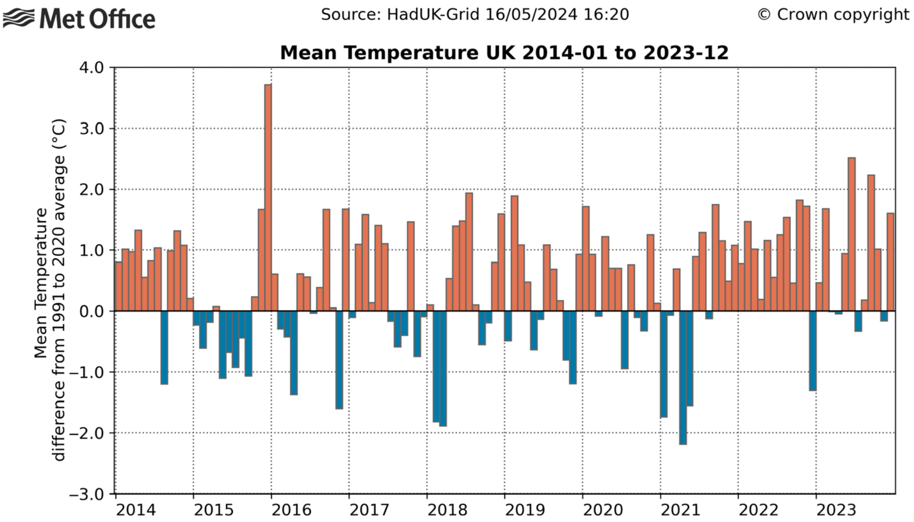


FIGURE 10 UK monthly mean temperature anomalies relative to 1991–2020 for the most recent decade 2014–2023 (120 months).

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 2014–2023.

	UK		England		Wales		Scotland		Northern Ireland	
	61–90	91–20	61–90	91–20	61–90	91–20	61–90	91–20	61–90	91–20
January	1.1	0.2	1.2	0.2	1.2	0.3	0.9	0.1	0.9	0.1
February	1.7	0.5	1.9	0.7	1.8	0.6	1.4	0.3	1.2	0.3
March	1.3	0.3	1.5	0.4	1.2	0.2	1.0	0.2	0.9	0.1
April	1.2	0.0	1.3	0.0	1.3	0.1	1.0	0.0	1.0	0.1
May	1.2	0.3	1.3	0.3	1.2	0.3	1.1	0.4	1.3	0.4
June	1.4	0.8	1.5	0.8	1.5	0.8	1.3	0.8	1.4	0.8
July	1.3	0.4	1.5	0.5	1.1	0.4	1.1	0.3	1.0	0.3
August	1.0	0.1	1.1	0.2	0.9	0.1	0.8	0.1	0.8	0.1
September	1.2	0.5	1.3	0.6	1.2	0.5	1.2	0.5	1.0	0.3
October	0.9	0.6	1.1	0.7	0.9	0.6	0.5	0.4	0.6	0.4
November	1.3	0.3	1.4	0.4	1.2	0.3	1.1	0.2	1.1	0.2
December	1.3	1.0	1.6	1.1	1.6	1.1	0.8	0.7	1.0	0.8
Winter	1.4	0.6	1.5	0.6	1.5	0.7	1.1	0.4	1.0	0.4
Spring	1.2	0.2	1.4	0.2	1.3	0.2	1.0	0.2	1.1	0.2
Summer	1.2	0.4	1.4	0.5	1.2	0.4	1.1	0.4	1.1	0.4
Autumn	1.1	0.5	1.3	0.6	1.1	0.5	1.0	0.4	0.9	0.3
Annual	1.25	0.42	1.41	0.49	1.25	0.45	1.02	0.32	1.02	0.32

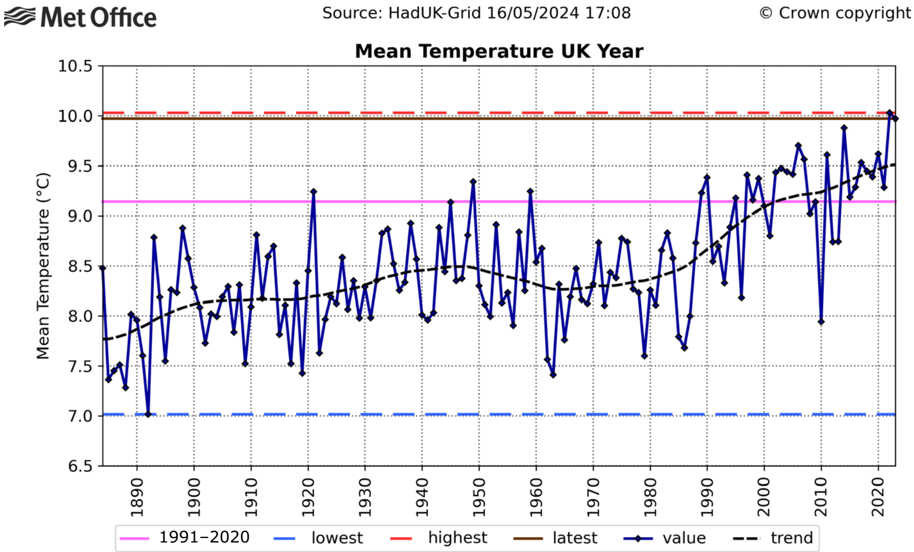
Key: <−0.95°C | −0.95°C to −0.45°C | −0.45°C to −0.25°C | −0.25°C to 0.25°C | 0.25°C to 0.45°C | 0.45°C to 0.95°C | >0.95°C

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

decade of the monthly, seasonal and annual mean temperature time series across 97 county areas of the UK. These county areas are described in Appendix A8 and shown in Figure A6. Although these areas vary in size, they are useful for monitoring at this spatial scale. The figure counts the total number of such values across all counties by decade throughout the monthly, seasonal and annual series, converted to a percentage of all monthly, seasonal and annual top-ten values (which is the same as the percentage of the total number of records for each decade).

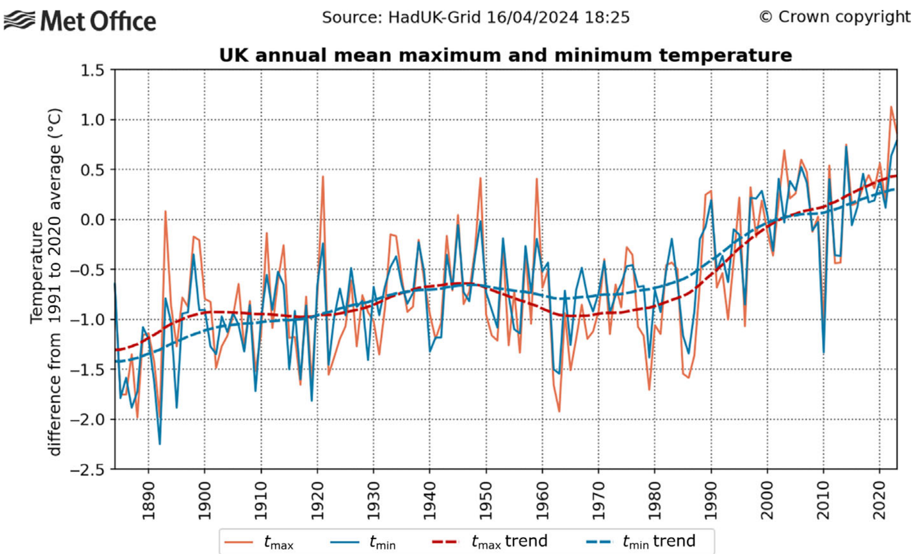
The average across the 14 decades of the 140-year series is 7.1% per decade (100/14, that is, what would be expected on average if these values were evenly spaced).

FIGURE 11 Annual mean temperature for the UK, 1884 to 2023. The table shows actual values for the UK and countries (°C).



	1961–1990	1991–2020	2014–2023	2023
UK	8.32	9.14	9.56	9.97
England	9.04	9.96	10.45	10.89
Wales	8.61	9.41	9.86	10.40
Scotland	6.99	7.69	8.02	8.29
Northern Ireland	8.44	9.13	9.46	10.17

FIGURE 12 Annual mean maximum and minimum temperature for the UK, 1884 to 2023 as anomalies relative to 1991–2020. The table shows actual values for the UK (°C).



	1961–1990	1991–2020	2014–2023	2023	2014–2023 anom wrt 1961–1990	2014–2023 anom wrt 1991–2020
T_{max}	11.87	12.79	13.28	13.66	1.41	0.49
T_{min}	4.80	5.53	5.88	6.32	1.09	0.35

However, as a consequence of the UK's warming climate, the occurrence of top-ten warmest values in the series is dominated by the last three decades, which together account for 52% of all top-ten warmest monthly values, 70% of all top-ten warmest seasonal values and 93% of all top-ten warmest annual values. The most recent decade alone accounts for 25%/33%/50% monthly/seasonal/annual values. So, overall, a quarter of all months, a third

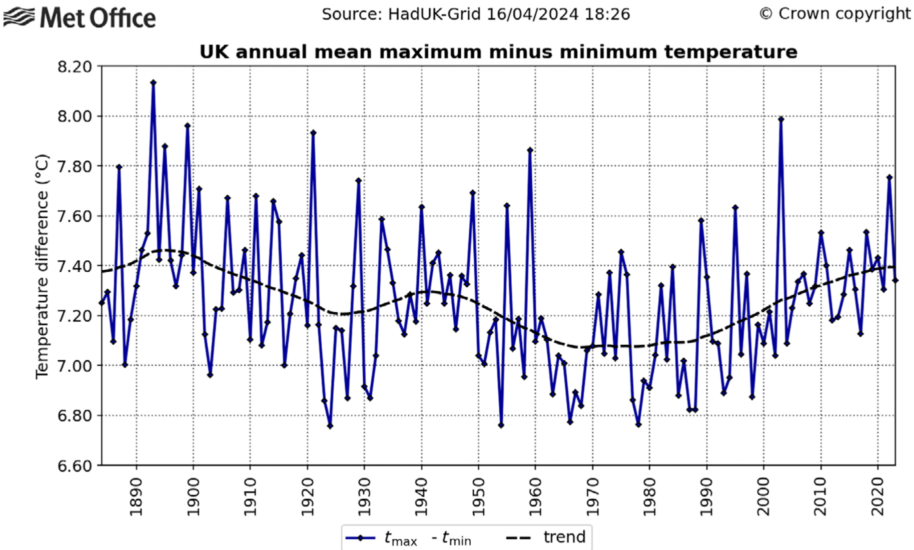


FIGURE 13 Annual mean maximum temperature minus mean minimum temperature (diurnal temperature range, DTR) for the UK, 1884–2023.

of all seasons and half of all years of the most recent decade 2014–2023 have been in the top-ten warmest in their respective monthly, seasonal or annual series (e.g., in the top-ten warmest Januaries, etc.), or an alternative framing, based on the observational series, is that the chance of any year of the most-recent decade 2014–2023 falling within the top-ten warmest in the series is one in four for each month, one in three for each season and one in two for each year.

The UK's climate is dominated by natural variability, with the warming trend becoming increasingly apparent as the data are averaged over time, due to the 'signal-to-noise' ratio—warming trend versus variability—increasing. This is because each season comprises three constituent months, and each year four constituent seasons. Although the separate months will not be completely independent, the variability will tend to reduce and the climate change signal will be retained when averaging over these 3-month and 12-month periods. The signal-to-noise ratio is, therefore, increased because the noise (i.e., the variability) is reduced. In statistics this effect is known as the Central Limit Theorem (Fischer 2011). The increased proportion of top-ten annual values compared with seasonal and monthly values in the most recent decades is a direct consequence of this effect.

Figure 15b similarly explores the frequency of the top-ten coldest values in the county mean temperature series, with the last three decades together accounting for <3% of monthly and seasonal values and <0.5% of annual values, and the occurrence of these values much more prominent in the early decades of the series. No seasons or years of the most recent decade 2014–2023 have been in the top-ten coldest in their respective series for any county area of the UK, and virtually no months (4 values out of 11,640 records [0.03%]). Taken together, these figures show the dramatic consequence of the UK's changing climate on occurrences of both warmest and coldest monthly, seasonal and annual top-ten temperature values.

2.2 | Central England temperature

Figure 16 shows annual T_{mean} for the CET series from 1659 and for England from 1884 to 2023. CET represents a region bounded by Hertfordshire, Worcestershire and Lancashire. The temperature trends in the HadUK-Grid dataset shown in Figure 11 are confirmed by the close consistency with the CET series. 2023 was the second warmest year in the CET series with an annual T_{mean} of 11.13°C, 0.89°C warmer than the 1991–2020 average with only 2022 warmer (11.18°C). Six of the 10 years in the most recent decade, 2014–2023, in the CET series have been in the top-ten warmest: 2014, 2017, 2018, 2020, 2022 and 2023—the same years as the UK series. 2023 was the second warmest year in the CET T_{max} series also behind 2022, but the equal-warmest year (with 2006) in the CET T_{min} series with an annual T_{min} of 7.30°C (both series from 1878).

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 17). When comparing the early 21st century (2001–2023) to previous centennial averages, the annual T_{mean} difference is +0.9°C compared with 1901–2000, +1.3°C compared with 1801–1900 and 1701–1800, and +1.8°C compared with 1659–1700—with some seasonal variations (Table 3). The most recent decade (2014–2023) has been the warmest 10-year

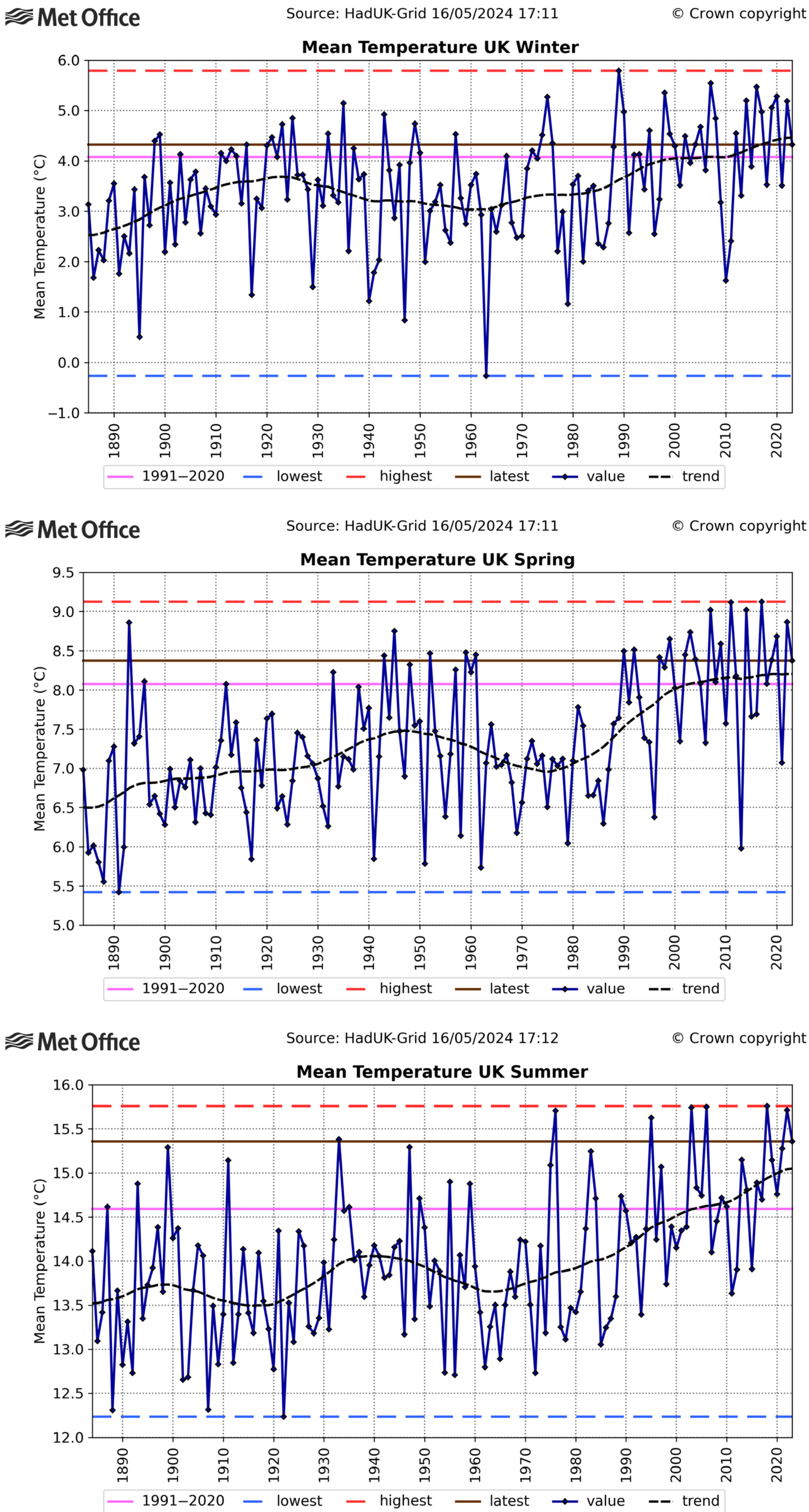


FIGURE 14 Seasonal mean temperature for the UK for (a) winter, (b) spring, (c) summer, and (d) autumn - (overleaf) 1884–2023 (winter 1885–2023). Note the *y*-axis gridline spacing differs between the figures.

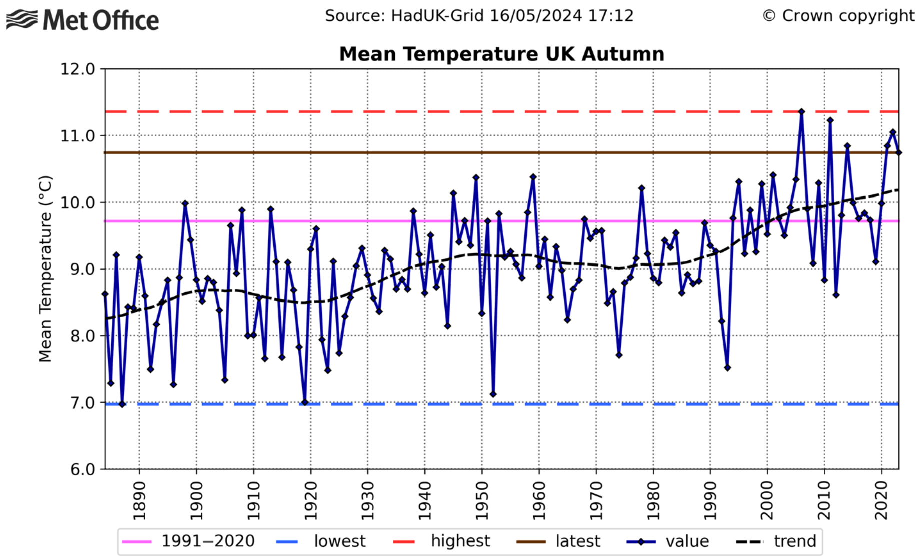


FIGURE 14 (Continued)

FIGURE 15 (a,b) Number of monthly, seasonal and annual top-ten temperature values by decade for the 14 decades of the 140-year HadUK-Grid monthly mean temperature series 1884–2023. The figure counts the number of values in the top-ten warmest (a) and top-ten coldest (b) in the series across 97 counties of the UK. There are $97 \times 12 \times 10 = 11{,}640$ monthly values, $97 \times 4 \times 10 = 3880$ seasonal values and $97 \times 10 = 970$ annual values for each of the top-ten warmest and top-ten coldest spread across all the decades. Each decade also comprises 11,640/3880/970 monthly/seasonal/annual values in total from which these top-ten/bottom-ten subsets of values are taken. Counts are converted to the percentage of all monthly, seasonal and annual top-ten values, with an average of 7.1% per decade. The first decade is one winter short, that is, 1885–1893.

period in the CET series, and 2023 was the first year in the series in which every calendar month was warmer than the 1961–1990 long-term average.

The CET and England series are very highly correlated (R^2 value of 0.99 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 B2. 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 16 the England series anomalies are slightly lower than the CET series before the 1991–2020 period. The slightly greater warming for England compared with CET warrants further investigation since the cause of this difference cannot be confidently attributed at present. However, this difference is small compared with the overall warming trend common to both series.

2023 was also the second warmest year on record at the Oxford Radcliffe Meteorological station in a series from 1814, with 11.85°C, behind 2022 (12.14°C). The next warmest year was 2014 (11.79°C).

2.3 | Comparison with global mean surface temperature

Figure 18 plots annual T_{mean} for the UK from 1884 to 2023 from HadUK-Grid alongside global mean surface temperature (land surface air temperature and sea surface temperature) based on the 'best estimate' time-series from the HadCRUT5 dataset (Morice et al., 2021) and the global land surface only from the CRUTEM5 dataset (Osborn et al. 2021). All three series are plotted as anomalies relative to the baseline reference period 1961–1990. The annual variability in UK T_{mean} is very much larger than HadCRUT5 and CRUTEM5, as the UK covers only a small fraction (~1/2000) of the Earth's surface.

Globally, 2023 was the warmest year in the HadCRUT5 series from 1850, exceeding the previous warmest year, 2016, by 0.17°C. It was also the warmest year for the global land surface only. Based on HadCRUT5, 2023 was 1.10°C warmer than 1961–1990. Global average surface temperatures are commonly reported with reference to a 'pre-industrial' baseline period of 1850–1900. 2023 was 1.46°C warmer than 1850–1900. This 'pre-industrial' baseline is not available for the UK since the monthly series start in 1884. Globally, June to December 2023 were each the warmest such month on record in the HadCRUT5 series. On top of long-term warming, this was in part due to a transition into El Niño conditions in the latter part of the year, further elevating temperatures. El Niño is part of a pattern of climate variability in the tropical Pacific that imparts warmth to the global atmosphere, temporarily adding up to 0.2°C to the temperature of an individual year. This stands in contrast to the reverse pattern of climate variability, La Niña, which suppressed global average temperatures in 2021 and 2022. El Niño/ La Niña is just one example of a mode of variability affecting the global climate.

Globally, warming is greater across high latitudes compared with the equator, and over land compared with the ocean (IPCC, 2021, Blunden and Boyer, 2022). The most recent decade 2014–2023 has been 1.25°C warmer than 1961–1990 for the UK, compared with 0.85°C for global mean surface temperature and 1.15°C for global land only. The UK's climate is subject to natural multi-annual to multi-decadal modes of variability which will super-impose on any longer-term trend. Taking this factor into consideration, the underlying warming observed for the UK is consistent with that observed globally over land. However, the details of any comparison will also depend on the choice of 1961–1990 as the baseline.

2.4 | Daily temperature

Figure 19a,b shows daily maximum and minimum temperature anomaly maps relative to the 1991–2020 monthly averages for each day of 2023. In the UK's climate, daily maximum and minimum temperature anomalies are mostly 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 20a,b shows the UK area average daily maximum (T_{max}) and minimum (T_{min}) temperatures through the year.

In common with most recent years, in 2023 the number of days where the UK average daily maximum and minimum temperatures were above the 1991–2020 monthly averages exceeded the number of days below: 2023 comprised 230/135 days above/below for maximum and 218/147 days above/ below for minimum temperature. The most recent year where the number of days below average exceeded days above was 2016 for T_{max} and 2015 for T_{min}. By far the most significant spells of above-average temperature in 2023 were in June and early September (these events are described in Sections 9.1 and 9.2), while much of December was also very mild. There were significant cold spells in mid-January, early March and late November to early December, although despite this no months of the year saw temperature anomalies well below the 1991–2020 average (Figure 10, Table 1).

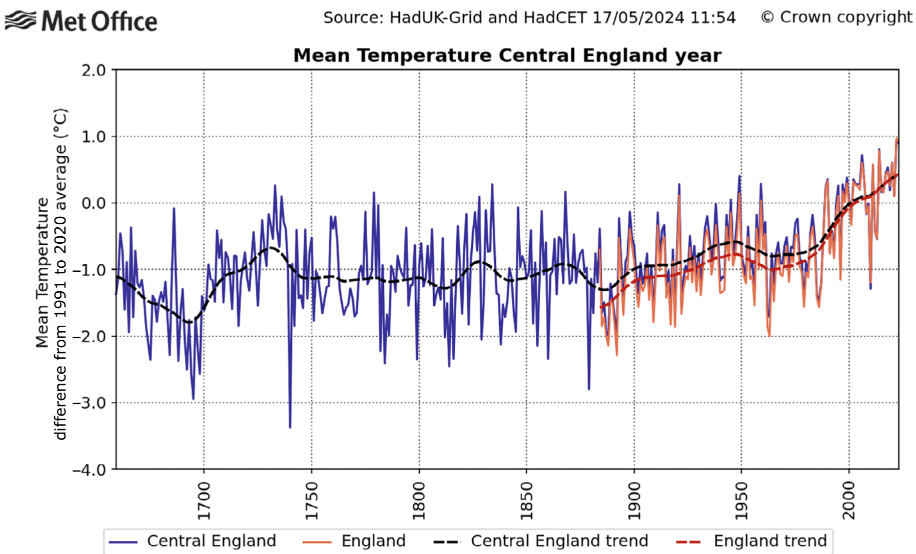
Figure 21a,b shows the UK's highest daily maximum and lowest daily minimum temperatures for each calendar day of 2023 based on the HadUK-Grid dataset. These are point values—the location of which will vary on a daily basis depending on where in the UK that daily extreme happens to be located—so they differ from Figure 20a,b which is 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 in 2023 and from 1960 to 2023—that is, defining the envelope of UK climate observations—as they do not include spatial averaging.

With high pressure and clear skies, the cold spell in January saw widespread hard frosts for around a week, including across London (e.g., −8.4°C at Heathrow on 23rd). Early March saw some notably low temperatures across northern Scotland (widely −10°C to −15°C) due to a cold plunge of Arctic air and lying snow cover; temperatures struggled to rise above freezing at times (e.g., a maximum of −0.9°C at Pennerley, Shropshire on 8th). The cold snap in late November to early December again saw widespread hard frosts (−6.8°C at Exeter Airport on 2nd December). Maximum temperatures were fairly suppressed during the spring, not reaching 25°C until late May, but June was exceptionally warm with 30°C reached from 10th to 13th and again on 25th. After a fine June, July and August were generally cool and unsettled: maximum temperatures in July were particularly suppressed, often struggling to reach 20°C. 30°C was reached locally on only 1 day in July (7th in west London) and none at all in August—but on seven consecutive days in September. Nine of the UK's 10 warmest days of the year 2023 (based on UK average daily mean temperature) were in June or September.

A long-standing curious statistic of UK climatology was that 13 June was the only June date that had never previously recorded temperatures in excess of 30°C (Webb and Meaden, 2000). This quirky fact was finally broken in 2023, with 30.8°C at Porthmadog (Gwynedd).

A notable spell of warmth affected southern England from 7 to 10 October, with temperatures reaching 25°C in London and parts of the south-east. This was the most significant spell of October warmth since 2011. After the first few days, much of December was very mild, especially for average daily minimum temperatures. For example, on Christmas Day, daily minimum temperatures fell no lower than 11°C or 12°C widely across southern England and Wales. The UK recorded its highest daily minimum temperature on record on Christmas Day with 12.4°C at Exeter Airport and East Malling, Kent.

Further details for each month of the year and each day of the month are provided within the Met Office Monthly Climate Summaries and Daily Weather Summaries available from the Met Office Digital Library and Archive.



	1961–1990	1991–2020	2014–2023	2023
Central England	9.47	10.23	10.72	11.13
England	9.04	9.96	10.45	10.89

FIGURE 16 Annual mean temperature for Central England (CET), 1659–2023, and England, 1884 to 2023, as anomalies relative to 1991–2020. The table shows actual values (°C).

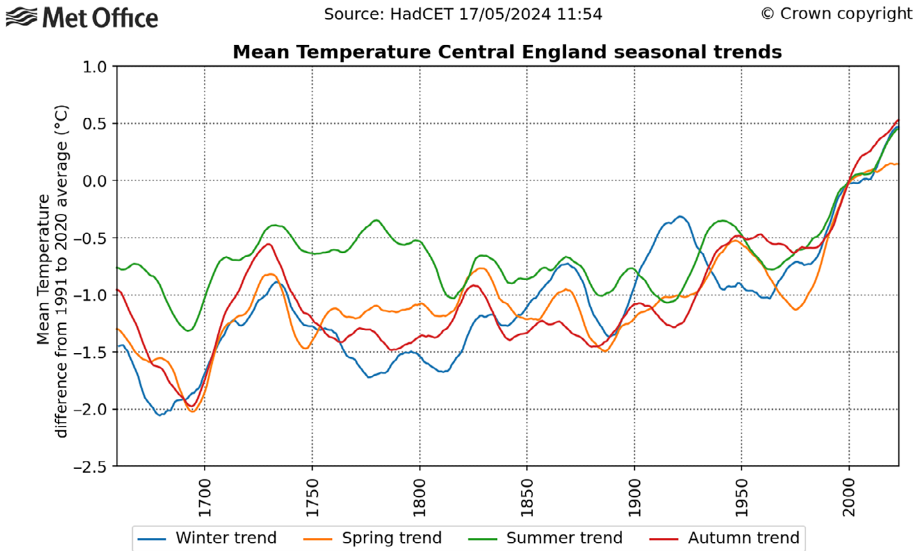


FIGURE 17 Seasonal mean CET trends 1659–2023 (winter 1660–2023), as anomalies relative to 1991–2020, showing the smoothed trends for each series using a weighted kernel filter described in Appendix B1.

TABLE 3 Centennial averages for CET (°C) 1659–2023 (winter from 1660 to 2023).

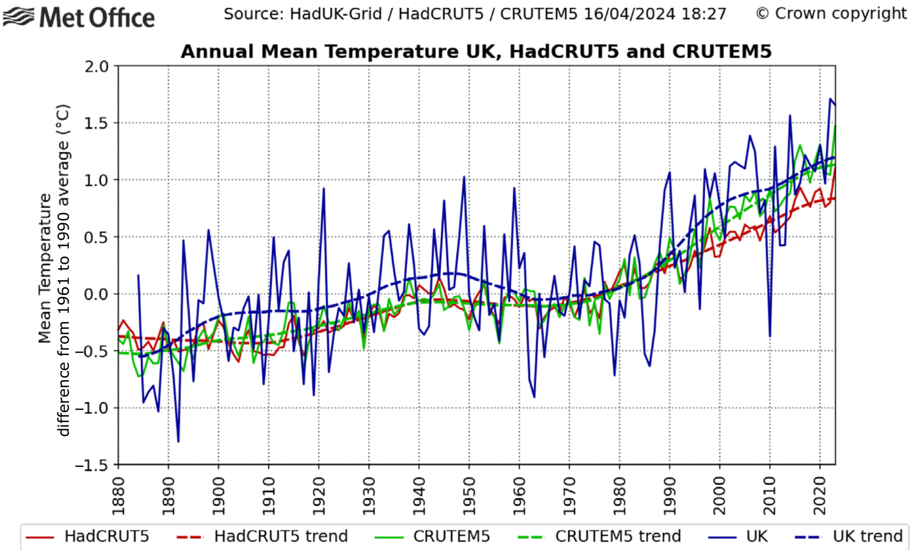
Season	1659–1700	1701–1800	1801–1900	1901–2000	2001–2023
Year	8.67	9.18	9.15	9.52	10.45
Winter	2.96	3.51	3.65	4.19	5.00
Spring	7.53	8.07	8.12	8.42	9.34
Summer	14.95	15.46	15.20	15.35	16.22
Autumn	9.14	9.59	9.51	10.02	11.12

Tables 4 and 5 show highest, lowest and percentiles of the annual distribution of UK mean daily maximum and mean daily minimum temperature as averages for 1961–1990, 1991–2020 and the most recent decade 2014–2023, and actual values for year 2023. These give an indication of how these daily temperature distributions have changed over time, providing more information than a simple annual mean, with changes in the extremes of the distribution of particular interest. For the most recent decade 2014–2023, the median T_{max} (50th percentile) has warmed by 1.2°C relative to 1961–1990 whereas the 99th T_{max} percentile (3 days of the year would be hotter than this) has warmed by 2.0°C, and the hottest day by 2.8°C. The median T_{min} has warmed by 0.9°C relative to 1961–1990 whereas the 1st percentile (3 days of the year would be cooler than this) has warmed by 1.7°C and the coldest day by 2.2°C. Some caution is needed interpreting these statistics but overall they suggest that extremes of temperature are changing faster than the mean.

Figure 22a–c present the results of an alternative analysis based on an absolute threshold approach. These show an average count of the number of days per year for 97 county areas of the UK in which the highest daily maximum temperature on that day *anywhere* within that county (i.e., the highest grid point value) has reached 20°C, 25°C and 28°C, respectively—for the periods 1961–1990, 1991–2020, the most recent decade 2014–2023 and actual counts for year 2023. These thresholds could be described as 'pleasant', 'warm' and 'hot' days, with the analysis also repeated for 'very hot' days reaching 30°C and 'extremely hot' days exceeding 32°C.

The spatial variability on these maps is generally greatest for the most recent year 2023 and greater for the most recent decade 2014–2023 than for 1991–2020 and 1961–1990 since these compare 1-year actual counts and 10-year average counts against 30-year average counts. The scale on the maps varies: 20°C—up to 140 days (20 weeks); 25°C—up to 50 days (~7 weeks); 28°C—up to 20 days (~3 weeks), these days being most likely to occur during the climatologically warmest months. The *highest* maximum is defined as *anywhere* within that county-level reaching that threshold at 1 km grid-point resolution. On some days, the majority of grid points within that county may exceed the threshold. On others, it may be just a few points—although temperature tends to be a relatively smoothly varying field—with the most likely locations tending to be the climatologically warmest areas within each county, depending on weather patterns on that particular day.

The *highest* maximum is chosen, rather than the *average* maximum because the latter metric would be much more influenced by elevation and proximity to the coast.



	1991–2020	2014–2023	2023
UK	0.83	1.25	1.66
HadCRUT5	0.54	0.85	1.10
CRUTEM5	0.74	1.15	1.47

FIGURE 18 Annual mean temperature for the UK from HadUK-Grid, 1884–2023, plotted alongside global annual mean temperature based on the HadCRUT5 dataset and global land only based on the CRUTEM5 dataset as anomalies relative to 1961–1990. The table shows anomaly values relative to 1961–1990 (°C).

Since the majority of the UK's population tends to live at lower elevations within each county, the highest maximum is arguably judged as being more population-relevant. In Scotland, for example, a relatively high proportion of land area is at high elevation (above 500 masl) and mostly uninhabited.

The maps show that the highest counts for all thresholds occur across the climatologically warmest areas of the south-east, but with the red colours expanding markedly across the map from 1961–1990 to 1991–2020 to 2014–2023. For example, for 1961–1990 only Kent and Essex recorded between 100 and 120 days ≥20°C on average per year, but for 1991–2020 this area has expanded to cover most south-east counties from Devon to Norfolk, and for the most recent decade 2014–2023 it has expanded again as far Lincolnshire, Nottinghamshire and Powys (east Wales), with most south-east counties from Hampshire to Suffolk recording between 120 and 140 days. The expansion of the area of darker shades is a common feature across all the maps (≥20°C, ≥25°C, ≥28°C) and illustrates how the number of 'pleasant', 'warm' and 'hot' days each year has increased across all geographic regions of the UK (i.e., Wales, Scotland and Northern Ireland as well as England).

Table 6 presents summary statistics for all five thresholds, summed across all 97 county areas, with the last two columns the 2014–2023 percentage of 1991–2020 and 1961–1990. 'Pleasant' days for the most recent decade have increased by 10% compared with 1991–2020 and by 41% compared with 1961–1990. 'Warm' days have increased by 18% and 63% respectively, and 'hot' days by 42% and 150%. These results show that while the number of 'pleasant', 'warm', 'hot', 'very hot' and 'extremely hot' days have all increased markedly, the increases are much more dramatic for the higher thresholds—with the number of 'hot' days more than doubling compared with 1961–1990 and the number of 'very hot' and 'extremely hot' days more than trebling. These results illustrate how the warming climate has the greatest implications for extremes of temperature, rather than average temperature, and this is particularly noteworthy because it is the extremes of temperature that usually have the greatest impacts (e.g., on human health). Table 6 also includes years 1976 and 2022 for comparison with 2023. Each of these years saw far higher counts of 'hot', 'very hot' and 'extremely hot' days overall compared with 2023, with the highest numbers of 'warm', 'hot' and 'very hot' days in 1976, reflecting the large spatial extent and long duration of the major heatwave in the UK that year.

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 2023 was 45 days, 8 days below the 1991–2020

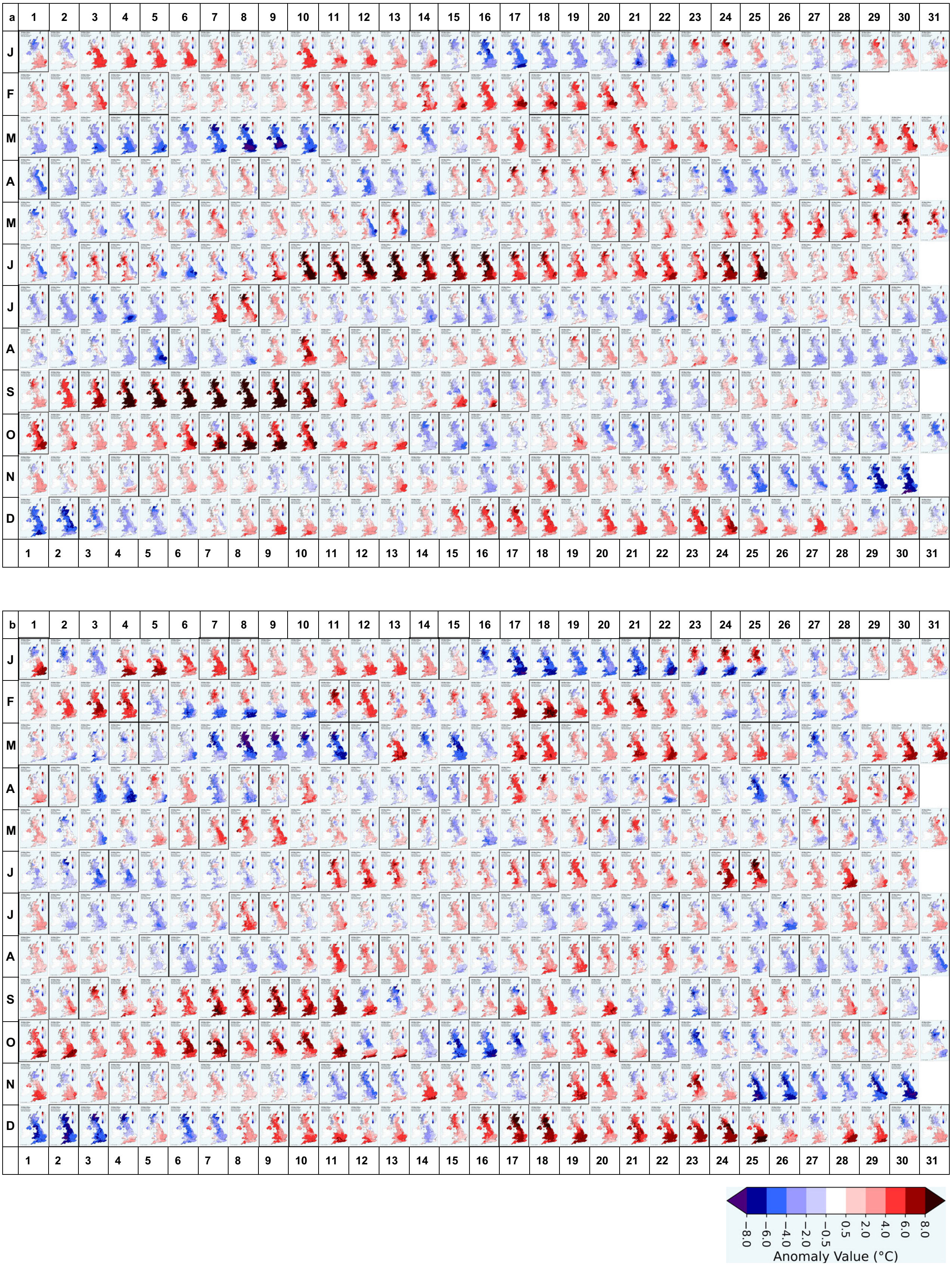


FIGURE 19 2023 daily anomalies relative to 1991–2020 monthly averages by month (top to bottom) and day (left to right) for (a) maximum and (b) minimum temperature. Weekends are displayed with a black border. The anomaly shading covers +8°C to −8°C.

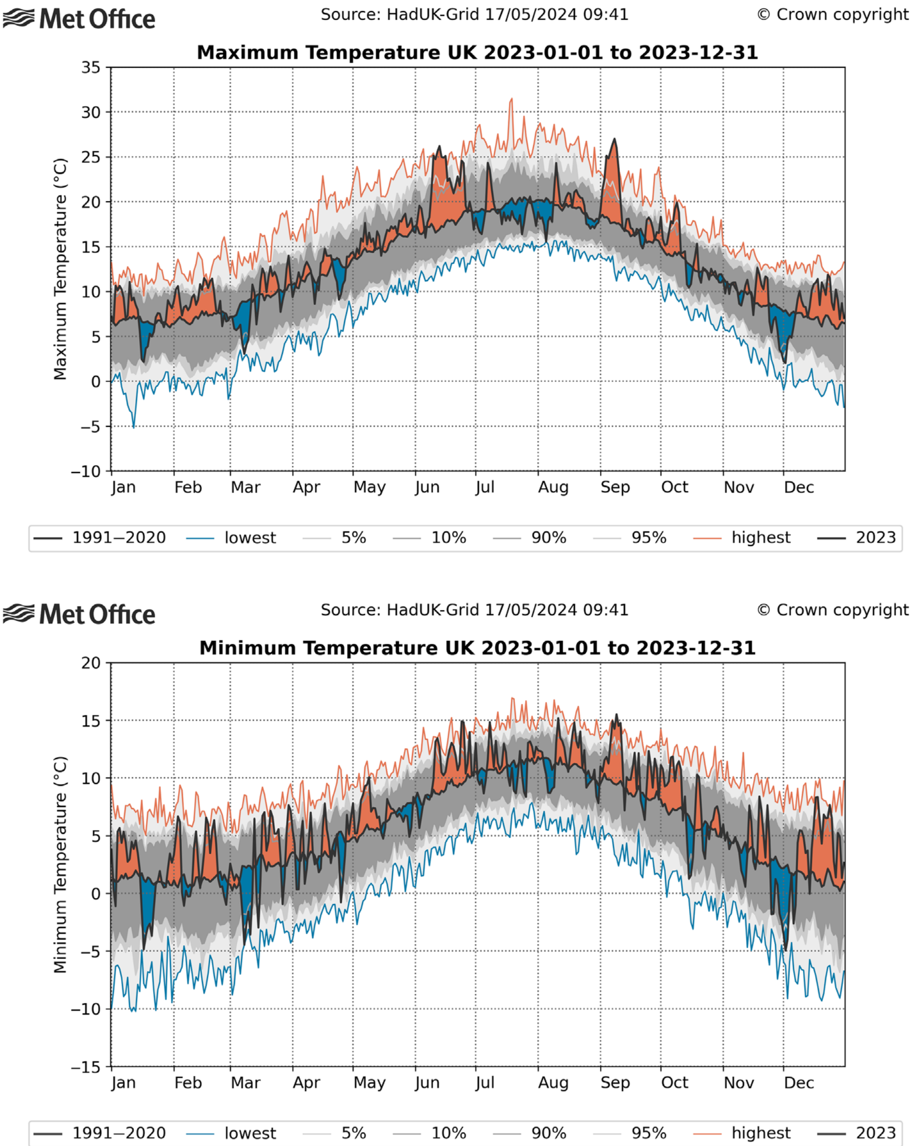


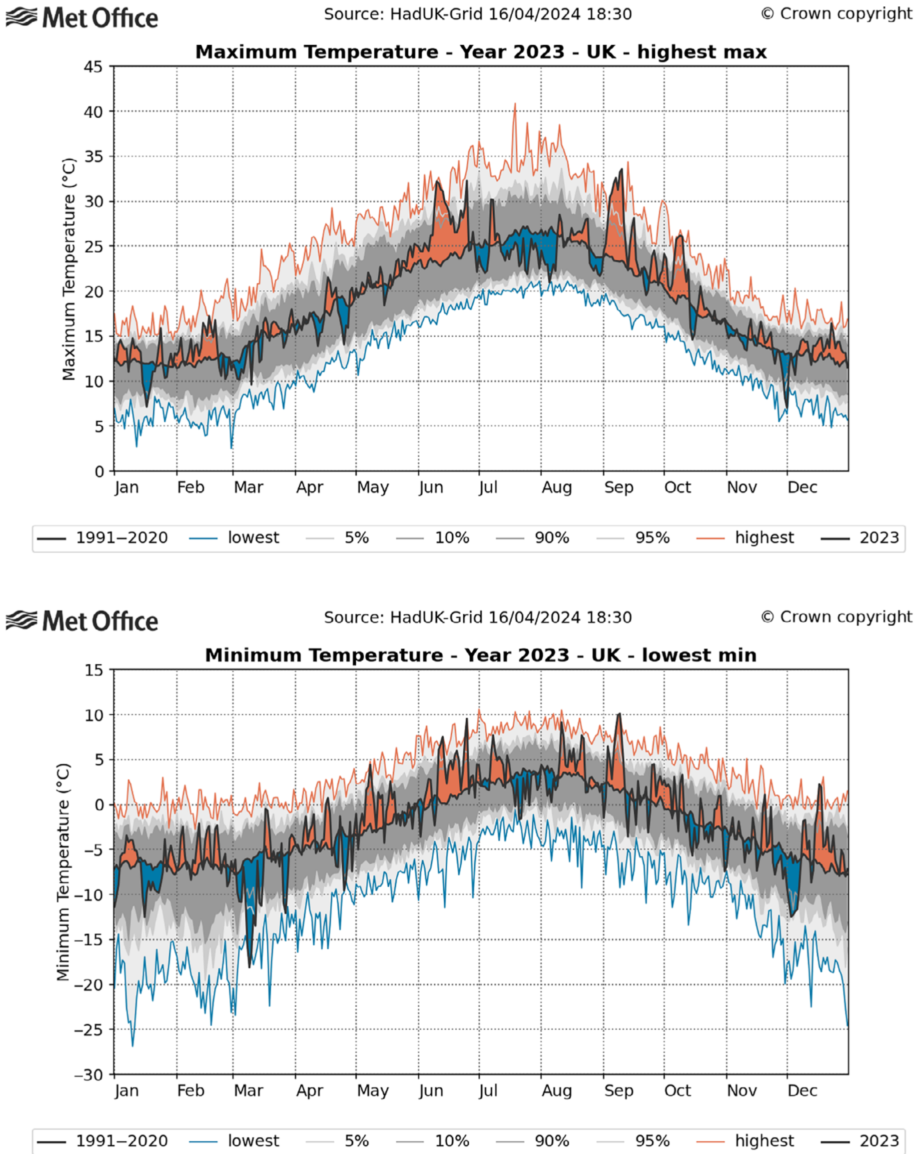
FIGURE 20 Daily anomalies for (a) UK mean maximum and (b) UK mean minimum temperature for each calendar day of the year 2023. The central black line shows the 1991–2020 average for each calendar day; the outermost red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1960 to 2023 inclusive.

average, with a typically variable spatial pattern broadly similar across all countries (Figure 23a). The average number of days of ground frost for the UK was 79 days, 23 days below the 1991–2020 average, and more than 40 days below for some western and northern areas (Figure 23b). Air frosts were slightly above average in both March and November, but well below in February and December (Figure 24a), with these anomalies related to the timing of the spells of wintry weather in 2023 (mid-January, early March, late November to early December), and their relative absence through February and most of December (Figure 20b). After the first week of December, many stations in southern England recorded no further air frosts until January 2024. Ground frosts were near or below average for all months (Figure 24b).

The number of ground frosts in 2023 was second lowest in the series from 1961, behind 2014, whereas the number of air frosts, while below normal, was not especially so for the series back to 1960 (Figure 25). The relative difference in the rank of 2023 between these two series might potentially be explained by fewer days with daily minimum temperatures in the 0°C–3°C category compared with other years (i.e., where there is a ground frost but not an air frost), but this has not been analysed.

The most recent decade 2014–2023 has had 6/11 fewer days of air/ground frosts compared with 1991–2020 and 17/28 days fewer than 1961–1990, the latter corresponding to more than 2 and 4 weeks, respectively. Remarkably, Wales and Scotland have effectively recorded a month fewer days of ground frost per year for the most recent decade 2014–2023 compared with 1961–1990. More than two-thirds of individual months in the most recent decade have seen fewer air and ground frosts than the 1991–2020 average (Figure 24).

FIGURE 21 Daily anomalies for (a) UK highest maximum and (b) UK lowest minimum temperature for each calendar day of the year 2023. The central black line shows the 1991–2020 average for each calendar day; the outermost 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 to 2023 inclusive.



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 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 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 growing degree days and in this report these are derived from daily temperature grids which extend back to 1960. They 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 heating degree days (HDD), cooling degree days (CDD) and growing degree days (GDD) are 15.5°C, 22°C and 5.5°C, respectively, and the formulae used are described in Appendix A5 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

TABLE 4 Highest, lowest and percentiles of annual distributions of UK mean daily maximum temperature (°C), averaged for 1961–1990, 1991–2020, 2014–2023 and actual values for 2023.

	1961–1990	1991–2020	2014–2023	2023	2014–2023 diff from 1961 to 1990	2014–2023 diff from 1991 to 2020
Min	0.1	1.1	1.5	2.0	1.5	0.4
1%	1.5	2.3	2.8	2.8	1.2	0.4
5%	3.4	4.4	5.1	5.5	1.8	0.7
10%	4.7	6.0	6.6	6.9	1.8	0.6
25%	7.6	8.6	9.0	9.4	1.4	0.4
50%	11.8	12.6	13.0	12.8	1.2	0.4
75%	16.2	17.1	17.6	17.8	1.3	0.5
90%	18.9	19.7	20.0	20.7	1.1	0.3
95%	20.3	21.3	21.7	23.4	1.3	0.4
99%	22.8	23.7	24.8	25.8	2.0	1.1
Max	24.7	25.6	27.6	27.0	2.8	2.0

TABLE 5 Highest, lowest and percentiles of annual distributions of UK mean daily minimum temperature (°C), averaged for 1961–1990, 1991–2020, 2014–2023 and actual values for 2023.

	1961–1990	1991–2020	2014–2023	2023	2014–2023 diff from 1961 to 1990	2014–2023 diff from 1991 to 2020
Min	−7.0	−5.4	−4.8	−5.0	2.2	0.6
1%	−4.9	−3.7	−3.2	−3.8	1.7	0.5
5%	−2.5	−1.6	−1.1	−1.6	1.4	0.5
10%	−1.0	−0.4	0.2	0.3	1.2	0.6
25%	1.4	2.1	2.4	3.2	1.1	0.4
50%	4.9	5.5	5.8	6.5	0.9	0.3
75%	8.5	9.1	9.5	10.1	1.0	0.3
90%	10.6	11.3	11.7	12.3	1.1	0.3
95%	11.5	12.3	12.7	13.2	1.2	0.4
99%	13.0	13.9	14.2	14.9	1.2	0.3
Max	14.0	15.0	15.6	15.5	1.6	0.6

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 2023 were below the 1991–2020 average for the UK (90%) and third lowest in the series from 1960 to marginally above 2022, the second lowest, and 2014, the lowest (Figure 26). There were three significant cold spells in which the UK average daily mean temperature fell below 0°C in in mid-January, early March and early December 2023 and these would have made the greatest contribution to the annual HDD total. The lowest 10 HDD years for the UK in this series from 1960 have all occurred in the 21st Century of which five have been in the most recent decade 2014–2023. For the UK, the most recent decade 2014–2023 has had an annual average HDD 5% lower than 1991–2020 and 14% lower than 1961–1990, with these 10 years all below the 1991–2020 average. However, earlier years in the 21st century such as 2010, 2012 and 2013 show that above average HDD years are still possible.

Figure 27 shows average HDD for each county area of the UK for 1961–1990, 1991–2020, 2014–2023 and 2023. These charts illustrate the general contraction of HDD to the climatologically coldest northern parts of the UK, this widespread reduction in HDD being common across all counties of the UK as the climate continues to warm. A comparison between two example areas illustrates the

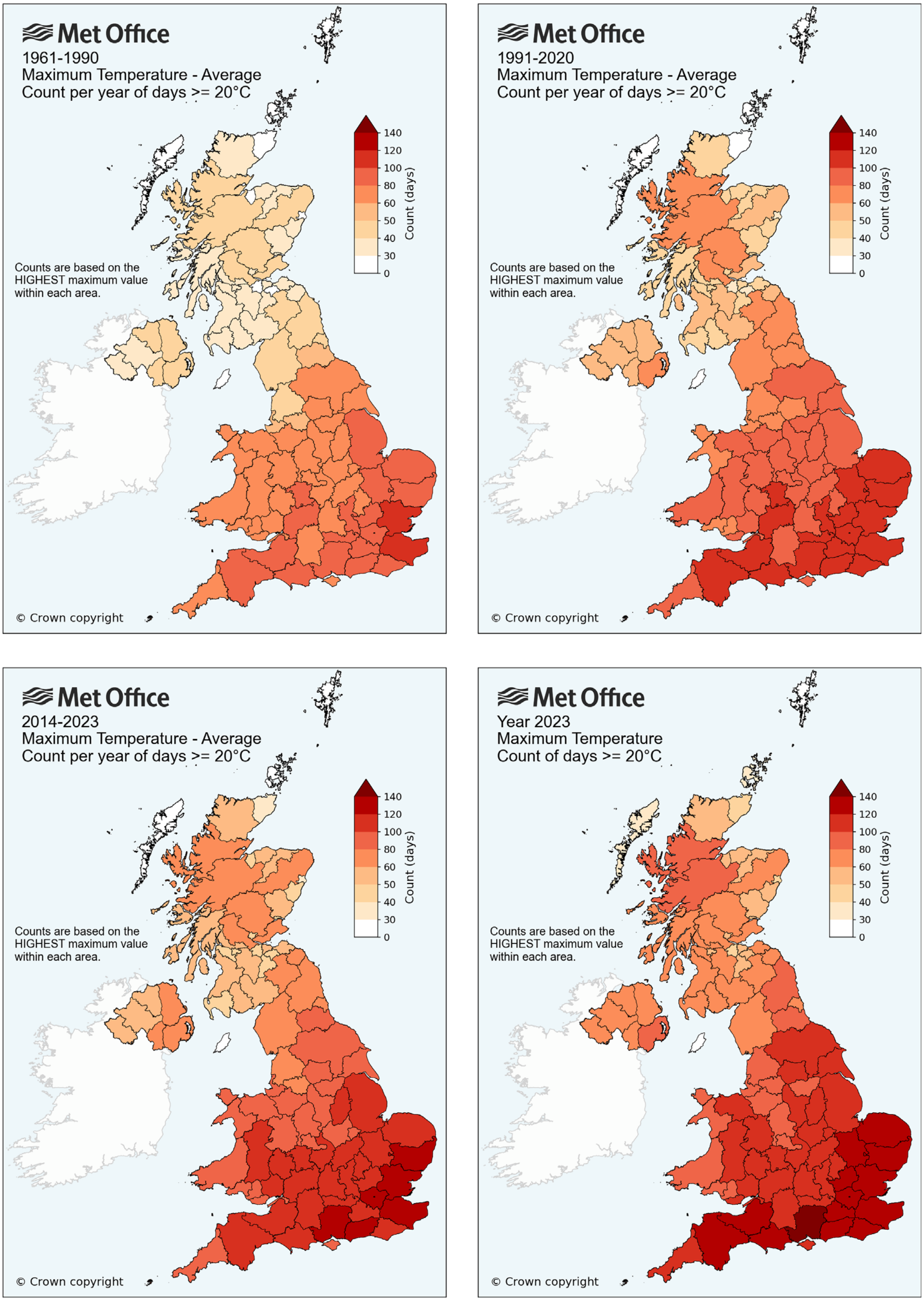


FIGURE 22 (a) Average count of the number of days per year in which the highest maximum temperature for each county of the UK has exceeded 20°C—indicating a 'comfortable' temperature—covering the periods 1961–1990, 1991–2020, 2014–2023 and actual counts for year 2023. The scale extends to 140 days. (b) As for Figure 22 exceeding 25°C—indicating a 'warm' day. The scale extends to 50 days. (c) As for Figure 22 exceeding 28°C—indicating a 'hot' day. The scale extends to 20 days.

geographic extent of this change in HDD; Lincolnshire (a relatively low-lying and largely rural county ~200 km to the north of London), and Greater London (the warmest part of the UK for average annual mean temperature). HDD for Lincolnshire were 2505 HDD for 1961–1990, 2208 HDD for 1991–2020 and 2063 HDD for 2014–

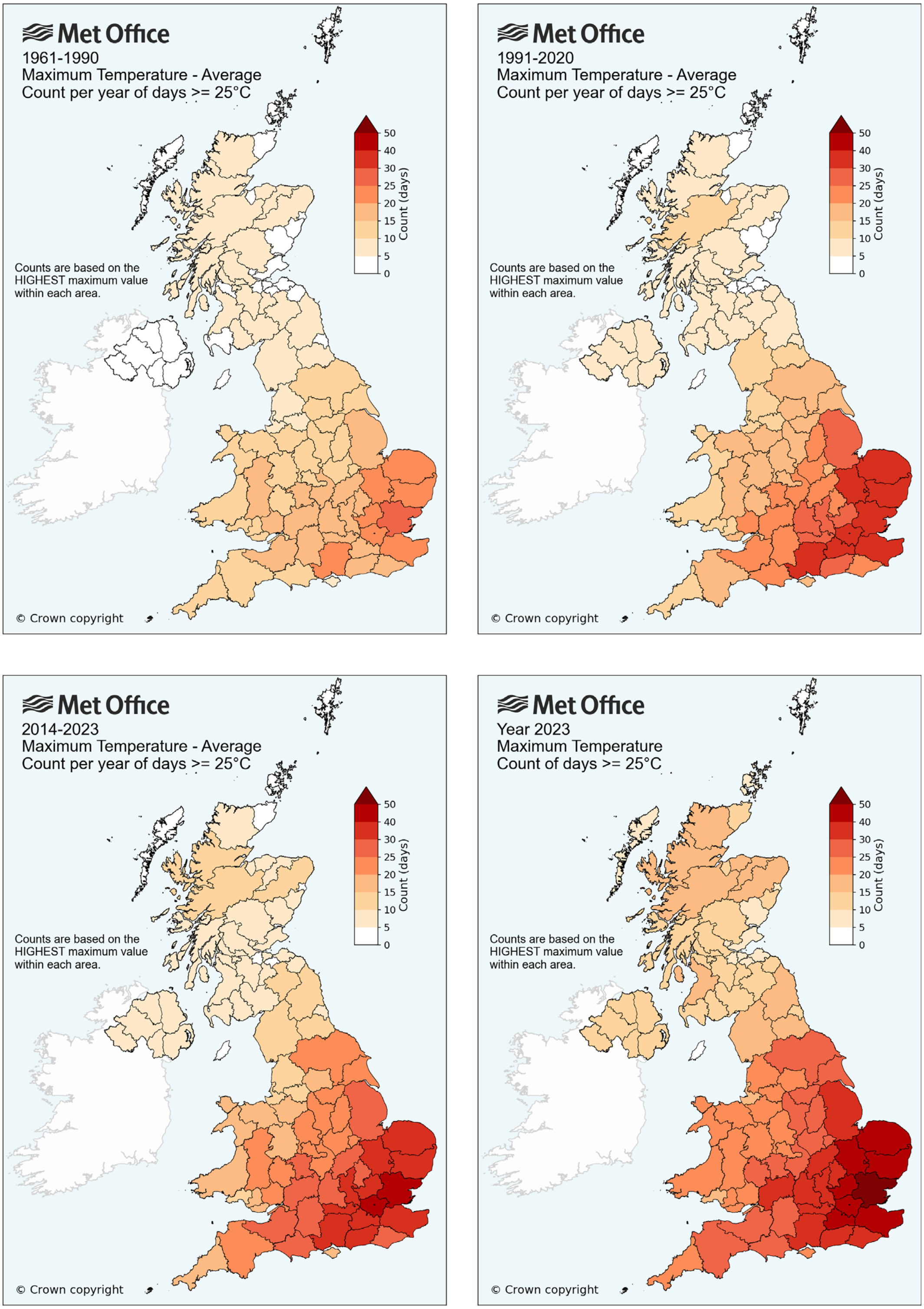


FIGURE 22 (Continued)

2023, representing an 18% reduction from 1961–1990 to 2014–2023. HDD for Lincolnshire for the most recent decade 2014–2023 were significantly lower than HDD for Greater London for 1961–1990 (2150 HDD).

CDD were well above the 1991–2020 average for all countries of the UK, but particularly England (34 CDD compared with 22 CDD) and Wales (18 CDD compared with 10 CDD). The UK value for 2023 was 23 CDD, tenth highest in the series from 1960 (Figure 28). The most significant spells of heat were in June and September (Figure 20a)—with around a week in each month of temperatures widely exceeding 28°C. Despite the fact that

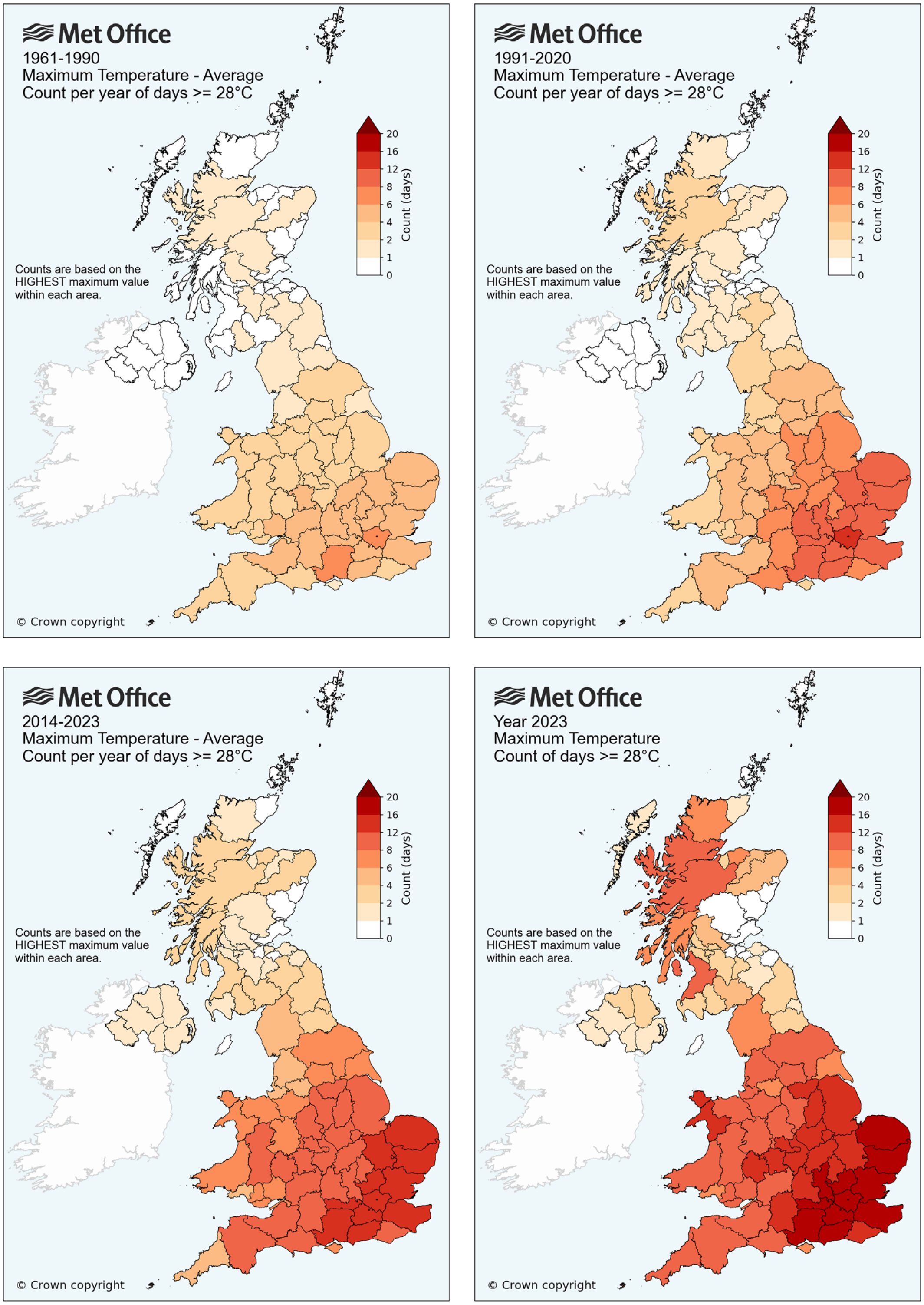


FIGURE 22 (Continued)

there were no notably hot spells (i.e., reaching 28°C widely) in either July or August (the climatologically warmest months of the year), CDD were still relatively high overall.

The UK CDD series is dominated by annual variability, to a much greater extent than either the HDD series (Figure 26) or GDD series (Figure 30). HDD and GDD are very highly correlated with the UK annual T_{mean} series (Figure 11) (R^2 values 0.98 and 0.90, respectively). In contrast, the CDD correlation is much weaker (R^2 value 0.34) and this series is more closely correlated with the summer T_{mean} series (R^2 values 0.78). Significant peaks in CDD coincide with significant summer heatwaves (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. In 1976 and 1995, temperatures peaked at 35.6°C and 35.2°C respectively, relatively modest in the context of the last two decades. Both these summers saw prolonged periods of fine, warm weather, and it is this persistence of warmth, rather than any extremes of temperature, that make 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 with mean temperature, there is still an underlying rising trend since 1960. For England, the most recent decade has had 7 CDD more than 1991–2020 and 16 more than 1961–1990—representing a doubling of CDD over this period.

Figure 29 shows average CDD for each county area of the UK for 1961–1990, 1991–2020, 2014–2023 and 2023. These charts illustrate the general expansion of CDD from the climatologically warmest south-east parts of the UK. Taking the same two illustrative areas as for HDD, average CDD for Lincolnshire were 15 CDD for 1961–1990, 27 CDD for 1991–2020 and 35 CDD for 2014–2023, representing a more than doubling in CDD from 1961–1990 to 2014–2023. As a consequence, CDD for Lincolnshire for the most recent decade 2014–2023 were significantly higher than CDD for Greater London for 1961–1990 (30 CDD).

GDD for 2023 were around 114% of average across the UK and the second highest in the series, behind 2022 (Figure 30). The 10 highest GDD years for the UK in this series from 1960 have all occurred since 1995, of which six have been in the most recent decade 2014–2023. The most recent decade has had an annual GDD 6% higher than 1991–2020 and 21% higher than 1961–1990. 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.

As for CDD, the maps for GDD show the similar general expansion of GDD from 1961–1990 to 1991–2020 to 2014–2023 (Figure 31). Taking the same two illustrative areas again, average GDD for Lincolnshire were 1706 GDD for 1961–1990, 1980 GDD for 1991–2020 and 2115 GDD for 2014–2023, representing a 24% increase from 1961–1990 to 2014–2023. As a consequence, GDD for Lincolnshire for the most recent decade 2014–2023 were significantly higher than GDD for Greater London for 1961–1990 (2059 GDD).

2.7 | Coastal waters

The annual mean sea-surface temperature (SST) for 2023 for near-coast waters around the UK was 1.3°C above the 1961–1990 long term average making this the UK's warmest year for near-coast SST in a series from 1870 for the second successive year (Figure 32). See Appendix A11 for details of the UK near-coast SST series. The most recent decade 2014–2023 has been 0.3°C warmer than the 1991–2020 long term average and 0.9°C warmer than 1961–1990. This compares to the most recent decade being 0.42°C warmer than 1991–2020 and 1.25°C warmer than 1961–1990 over UK land (Table 2), with the greater warming over land than sea observed around the UK consistent with that observed globally (IPCC, 2021, see also Section 2.3). Six years of the most recent decade (2014–2023) for UK near-coast SST are within the top-ten warmest in the series, and all top-ten warmest years in the series have occurred in the 21st Century. The warming trend around the UK is not uniform but greatest across the southern North Sea and least in the Atlantic to

TABLE 6 Average count of the number of days per year in which the highest maximum temperature for each county of the UK has exceeded 20°C, 25°C, 28°C, 30°C and 32°C, as a sum across all 97 counties—covering the periods 1961–1990, 1991–2020, 2014–2023 and actual counts for year 2023.

	1961–1990	1991–2020	2014–2023	1976	2022	2023	2014–2023% of 1961–1990	2014–2023% of 1991–2020
20°C—comfortable	5544	7093	7806	7698	8430	8604	141	110
25°C—warm	1002	1387	1634	3229	2397	2070	163	118
28°C—hot	223	393	558	1379	1006	755	250	142
30°C—very hot	72	144	240	700	580	226	332	167
32°C—extremely hot	24	39	87	305	316	28	364	223

Note: Actual counts for years 2022 and 1976 are also included for comparison with year 2023.

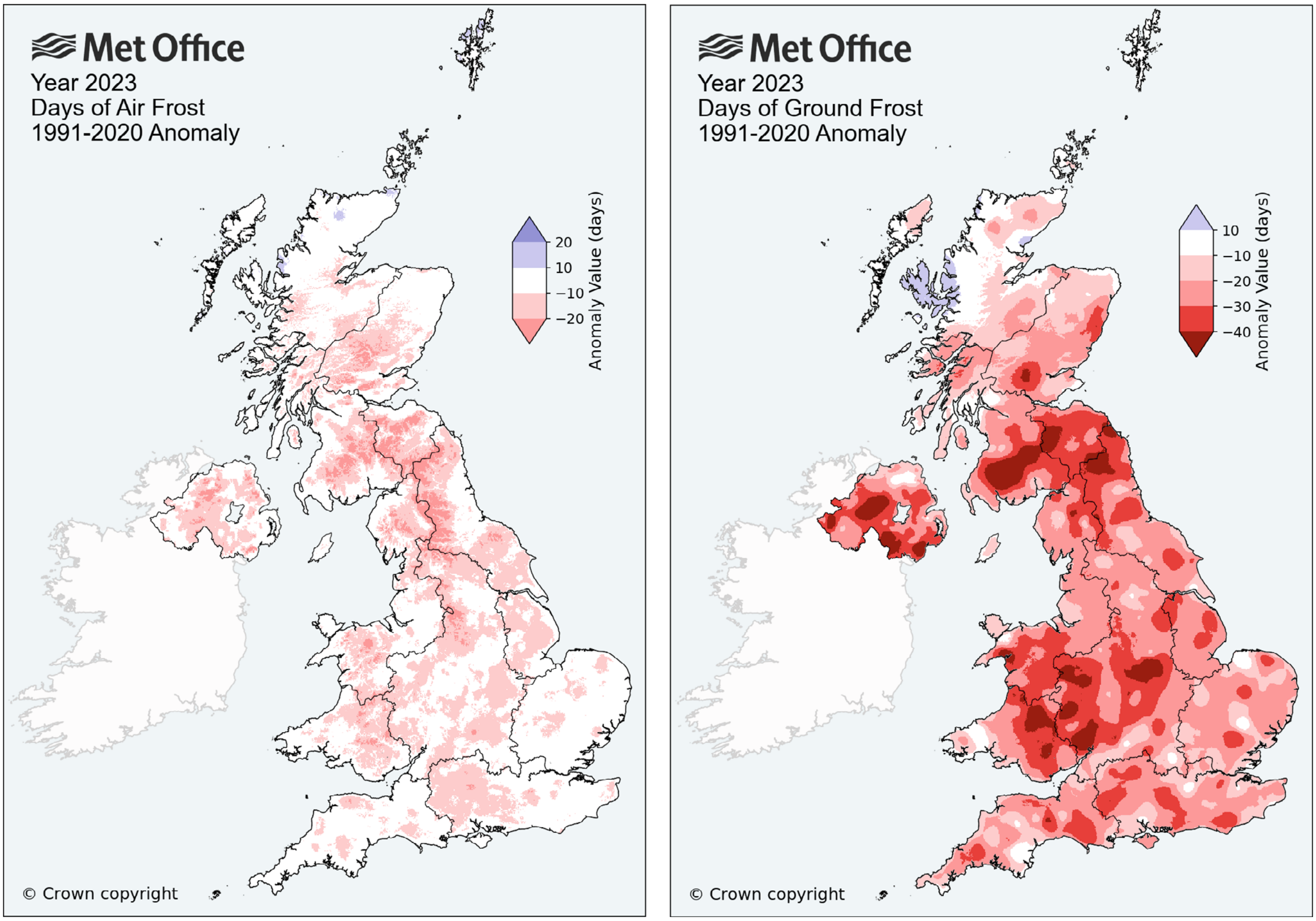
the west of the UK (Cornes et al., 2023). Section 9.1 on the record warm June provides more detail of monthly UK near-coast SST for the most recent decade 2014–2023.

Near-coast SST is highly correlated with the land observations (R^2 value 0.86, see Appendix B4) with a root mean square difference of <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 32, 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.

3 | PRECIPITATION

3.1 | Annual, seasonal and monthly rainfall

The UK rainfall total for 2023 was 1319 mm, 113% of the 1991–2020 average. This was the seventh wettest year for



2023	Airfrost	Groundfrost
UK	-8	-23
England	-9	-26
Wales	-10	-28
Scotland	-6	-17
Northern Ireland	-10	-29

FIGURE 23 Days of (a) air frost and (b) ground frost for year 2023 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.

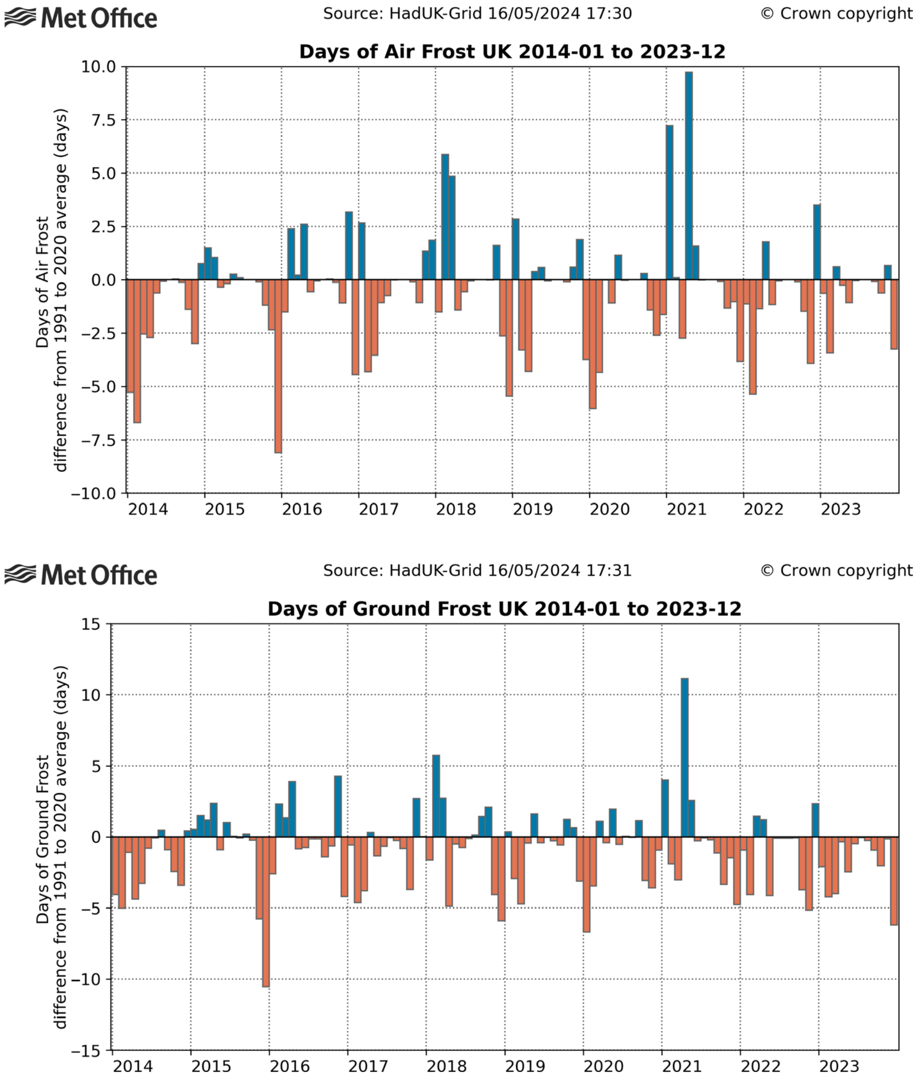


FIGURE 24 UK monthly days of (a) air frost and (b) ground frost anomalies relative to 1991–2020 for the most recent decade 2014–2023 (120 months).

the UK in the series from 1836 (2020 was the only wetter year in the most recent decade 2014–2023). Rainfall totals were above average across all the UK except western Scotland, with much of eastern Scotland, the southern half of Northern Ireland, a swathe of northern England to East Anglia and parts of central southern England recording 125% or more (Figure 33). The year was ranked in the top-ten wettest for many counties in these areas (Figure 34a) and was the fourth wettest year for England, ninth wettest for Wales and third wettest for Northern Ireland. A few rain-gauges recorded over 150% of average (e.g., parts of Wiltshire and the Isle of Wight).

Figure 34b shows the wettest year on record for the 97 counties of the UK. Across most of the UK, the wettest year on record is 1872. However, this is not true across all parts of the UK, with recent years such as 2011, 2012 and 2015 the wettest on record for some counties. Despite the wet year overall, there were no individual counties where 2023 was the wettest year on record. In terms of annual totals, the wettest locations in 2023 were in the Cumbrian fells with several rain-gauges recording over 4000 mm (e.g., 4436 mm/4234 mm 118%/119% of the 1991–2020 average at Honister Pass and Seathwaite, respectively). The driest locations in Kent and Suffolk recorded less than 600 mm (e.g., 567.3 mm/577.1 mm at Scarhouse, Suffolk and Dartford, Kent although these were nevertheless still slightly wetter than average with 108%/104%, respectively).

Figures 35 and 36 show seasonal and monthly rainfall anomalies for the UK for 2023. Table 7 shows monthly, seasonal and annual actual and anomaly values and ranks for the UK and countries for 2023. Figure 37 shows UK monthly rainfall anomalies for the most recent decade 2014–2023.

These figures illustrate the large spatial and temporal variability in UK rainfall—as is typically the case. March, July, September, October and December were much wetter than average with substantial areas of the UK recording more than twice the normal rainfall. Four months were in the top-ten wettest for the UK: March (sixth

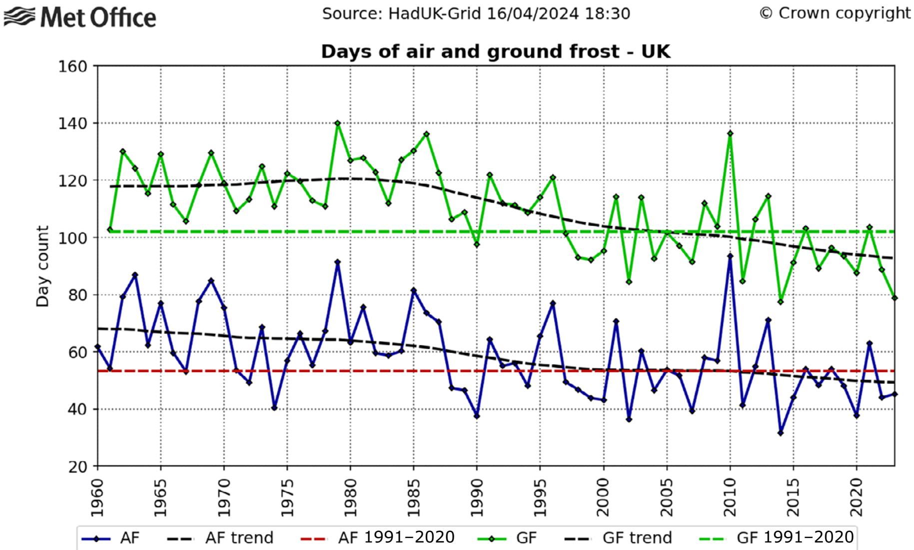


FIGURE 25 Annual days of (a) air and (b) ground frosts for the UK, 1960–2023 and 1961–2023, respectively. The tables show actual values for the UK and countries (days), with anomaly values for 2014–2023 (days).

Air Frost	1961–1990	1991–2020	2014–2023	2023	2014–2023 anom wrt 1961–1990	2014–2023 anom wrt 1991–2020
UK	64	53	47	45	−17	−6
England	56	45	38	36	−19	−7
Wales	54	45	38	35	−17	−7
Scotland	83	72	67	66	−16	−5
Northern Ireland	54	41	37	32	−17	−5

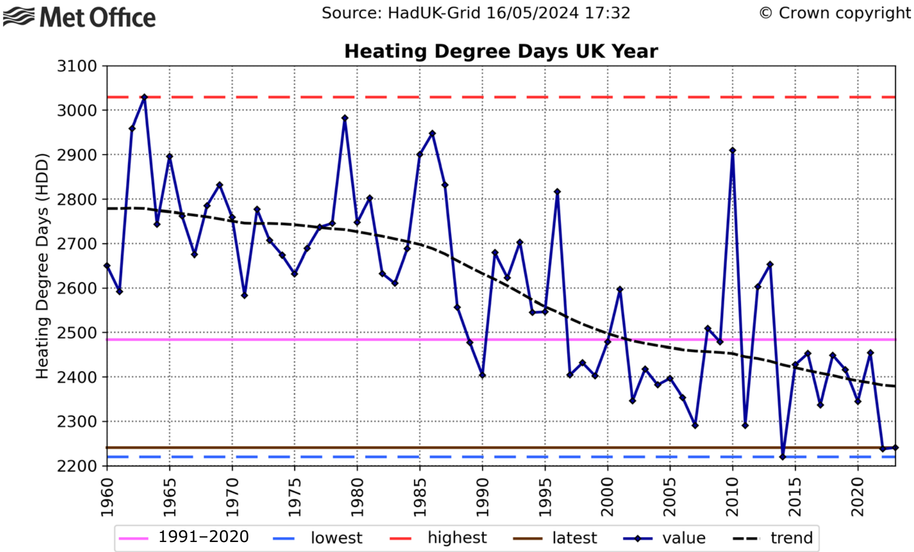
Ground Frost	1961–1990	1991–2020	2014–2023	2023	2014–2023 anom wrt 1961–1990	2014–2023 anom wrt 1991–2020
UK	119	102	91	79	−28	−11
England	111	96	86	71	−25	−10
Wales	110	92	79	64	−31	−14
Scotland	136	116	104	99	−32	−12
Northern Ireland	111	93	84	64	−27	−10

wettest, 158% of the 1991–2020 average), July (sixth wettest, 172%), October (sixth wettest, 145%) and December (equal-seventh wettest, 149%), the first year where this has happened for 4 months in the UK series from 1836.

While the wet March offset a dry February, and a wet July offset a dry June, overall, a general characteristic of the year was that the second half was wetter and more unsettled than the first half consistent with the monthly mean sea level pressure anomalies (Figure 2). The period July to December was the wettest second half of the year on record for the UK a series from 1836 (for Northern Ireland by a very wide margin). The fact that the wettest areas in October and December tended to coincide (e.g., in eastern Scotland and parts of northern England) had consequences for flooding (see Section 9). The driest months relative to average were February, May and June. England recorded its eighth driest February, while the consecutive dry months of May and June caused some impacts, for example, water scarcity issues in western Scotland.

With a slightly negative WNAO index (Section 1.2), winter was comparatively dry overall. Spring saw a marked north/south contrast in rainfall anomalies, and summer was wetter than average for most areas. Autumn was particularly wet across parts of Northern Ireland, eastern Scotland and eastern England, with the UK recording its equal-eighth wettest autumn (with 2022).

Table 8 shows monthly, seasonal and annual rainfall anomaly values for the UK and countries for the most recent decade 2014–2023 against both 1961–1990 and 1991–2020. The most recent decade 2014–2023 has been 2% wetter than 1991–2020 and 10% wetter than 1961–1990. UK winters have been 9% wetter than 1991–2020 and 24% wetter than 1961–1990. Increases have been less in summer and autumn, while spring overall has been slightly drier. February has seen the largest increase, with the most recent decade 15% wetter than 1991–2020 and 45% wetter than 1961–1990 (55% wetter than 1961–1990 for Scotland). April has seen the largest decrease, with



	1961–1990	1991–2020	2014–2023	2023	2014–2023 % of 1961–1990	2014–2023 % of 1991–2020	2023 anom % of 1961–1990	2023 anom % of 1991–2020
UK	2739	2484	2358	2241	86	95	82	90
England	2521	2247	2108	1985	84	94	79	88
Wales	2620	2362	2228	2066	85	94	79	87
Scotland	3149	2923	2818	2740	89	96	87	94
Northern Ireland	2655	2425	2326	2114	88	96	80	87

FIGURE 26 Annual heating degree days for the UK, 1960–2023. The table shows actual values for the UK and countries (HDD) with percentage of average values for 2014–2023 and 2023.

the most recent decade being 26% drier than 1991–2020 and 20% drier than 1961–1990. Although the UK's climate is getting wetter overall, the large annual and decadal variability in the UK's precipitation means that caution is needed when interpreting trends over relatively short time periods, since averages may be strongly influenced by extreme years.

The UK annual precipitation time-series from 1836 to 2023 shows the large annual variability inherent in the UK's climate. There has been an increase from the 1970s and 1980s onwards (Figure 38). The wettest year for the UK overall is 1872 (124% of average) and the driest 1855 (68%). Two years in the most recent decade 2014–2023 have been in the top-ten wettest (2020 and 2023); five have occurred in the 21st Century (2000, 2008, 2012, 2020 and 2023)—but none of the 10 driest years.

Figure 39 shows seasonal rainfall series for the UK from 1836 to 2023 (for winter 1837–2023). Similar to the annual series, the seasonal series are dominated by large inter-annual variability with some decadal variability. There has been a marked increase in winter rainfall in the last few decades. In the most recent decade 2014–2023, the winters of 2014, 2016 and 2020 have each been 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 since the relative high of the 1980s and 1990s, and autumn rainfall has increased slightly (see also Table 8). Since 2000, the UK has recorded its wettest February (2020), April (2012), June (2012), November (2009) and December (2015)—five out of 12 months, the wettest winter (2014) and autumn (2000), and the driest September (2014).

Figure 40a,b repeat the previous analysis shown in Figure 15 of the occurrence of monthly, seasonal and annual top-ten wettest and top-ten driest values for the 97 county areas of the UK. The average across the near 19 decades of the 188-year series from 1836 is 5.3% per decade (100/18.8, that is, what would be expected on average if these values were evenly spaced). Annual variability relative to the long term trend is much greater for UK rainfall compared with temperature, and rainfall also has a very much larger spatial variability. So, compared with temperature, the influence of climate change on the occurrence of these top-ten values in the rainfall series is as a consequence very much less pronounced. To illustrate this, for the UK overall, 16 months in the most recent decade 2014–2023 have been in the top-ten wettest of their respective monthly series compared with 31 in the top-ten warmest, five seasons have been in the top-ten wettest compared with 16 in the top-ten warmest, and two years in the top-ten wettest compared with six in the top-ten warmest.

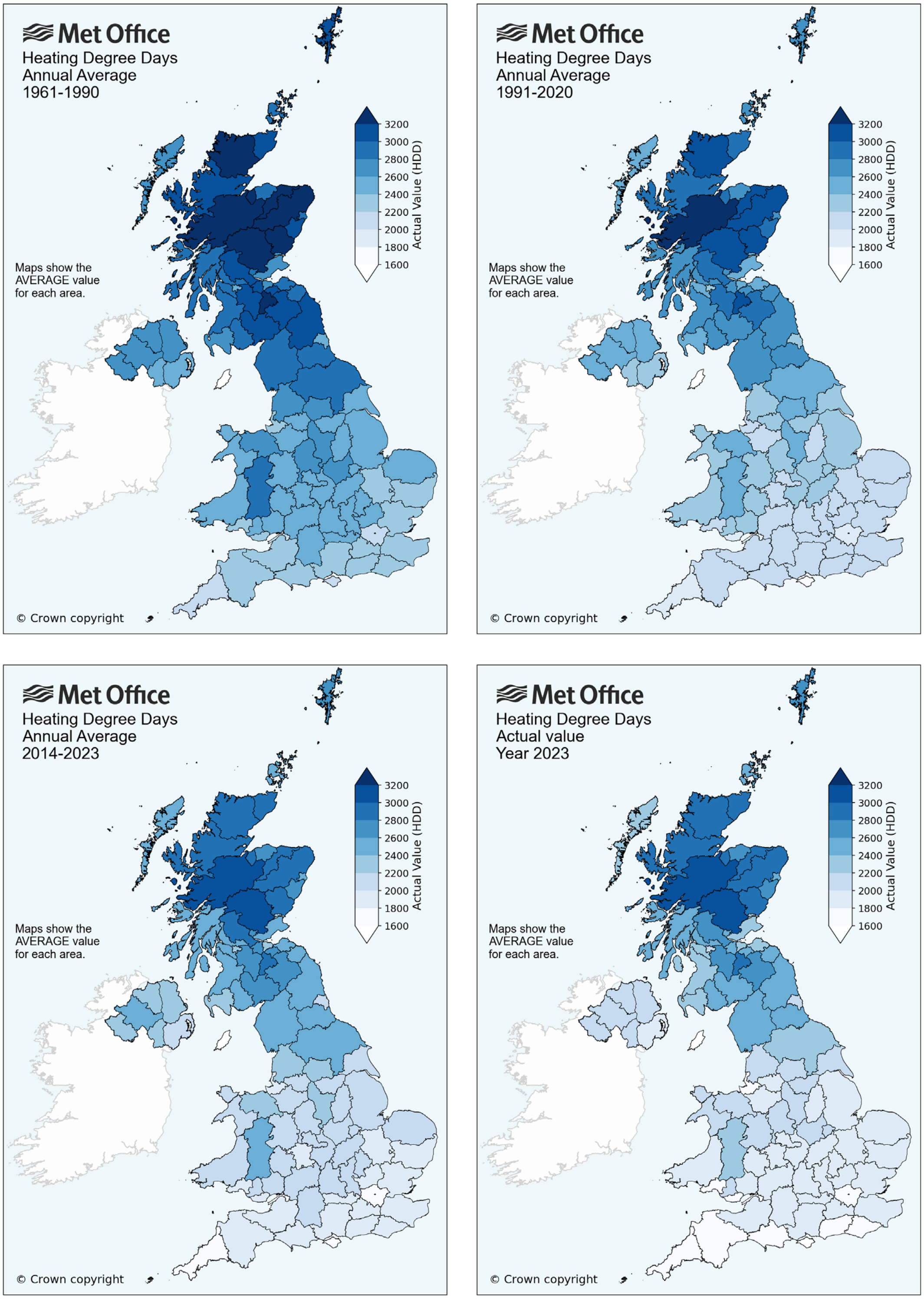


FIGURE 27 Annual average heating degree days per year for 1961–1990, 1991–2020 and 2014–2023 and annual actual heating degree days for 2023, as an average for each county of the UK.

Nevertheless, each of the last three decades 1994–2023 has still seen more monthly and seasonal top-ten wettest rainfall values than would be expected on average. These three decades together account for 23%/27% of all top-ten wettest monthly/seasonal values, respectively (16% would be expected). Most notable, however, is the marked increase in the number of top-ten wettest annual values with the last three decades accounting for 41%, and the last decade 2014–2023 alone over 15%, three times what would be expected. So, overall, while the occurrence of top-ten wettest monthly and seasonal values at county level is still predominantly associated with the variability of the UK's climate, it is particularly when averaging temporally to an annual timescale that the recent increased number of these values becomes apparent.

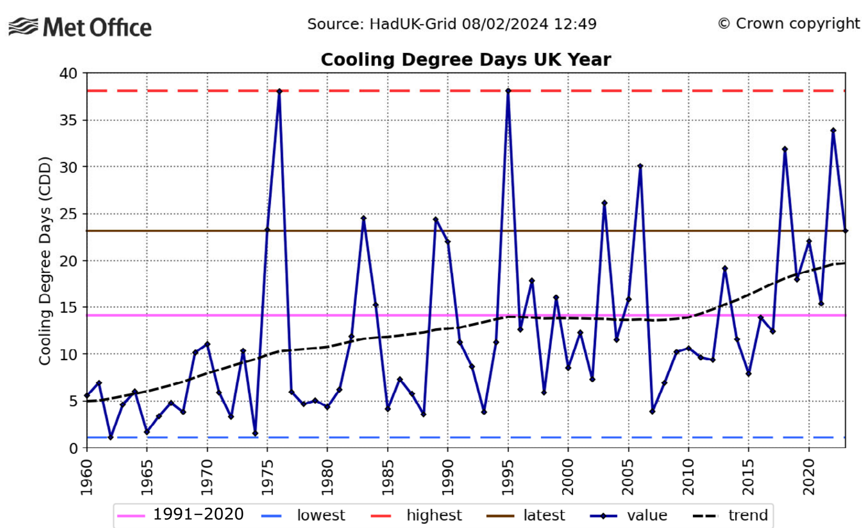
There is no obvious reducing trend in the occurrence of top-ten driest monthly, seasonal or annual values in the last three decades, although the number of annual values for the most recent decade (2014–2023) is notably low. Early decades in the series have generally higher counts of top-ten driest values.

3.2 | England and Wales precipitation

The annual rainfall total for 2023 in the long running England and Wales precipitation (EWP) series was 1194 mm, which is 123% of the 1991–2020 average (Figure 41). This was the seventh wettest year in this series from 1766 and the wettest year since 2012. 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 2014–2023 is 3% wetter than 1991–2020 and 10% wetter than 1961–1990. Importantly, the England and Wales areal rainfall series based on 1 km resolution gridded data is very 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 sampling of stations used for the EWP series and the gridding method used for the England and Wales areal series.

Figure 42 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. In the winter series to 2023, winter 2014 is the wettest winter on record, 2021 is ranked seventh wettest, 2016 ranked ninth wettest and 2020 ranked 12th wettest (Winter 2024—December 2023 to February 2024—is not included in this report but was provisionally ranked 6th wettest. The inclusion of this winter would also change the ranks for 2021, 2016 and 2020). Before 1900, EWP winter rainfall was substantially lower than autumn rainfall, but the increase in winter rainfall has meant that



	1961–1990	1991–2020	2014–2023	2023	2014–2023 anom wrt 1961–1990	2014–2023 anom wrt 1991–2020	2023 anom wrt 1961–1990	2023 anom wrt 1991–2020
UK	9	14	19	23	10	5	14	9
England	14	22	30	34	16	7	20	12
Wales	8	10	14	18	6	4	10	8
Scotland	3	3	4	8	2	1	6	5
Northern Ireland	3	4	6	9	3	2	6	5

FIGURE 28 Annual cooling degree days for the UK, 1960 to 2023. The table shows actual values for the UK and countries (CDD) with anomaly values for 2014–2023 and 2023 (CDD). Anomalies are presented as difference from average (instead of a percentage). This is because CDD are close to zero over much of Highland Scotland.

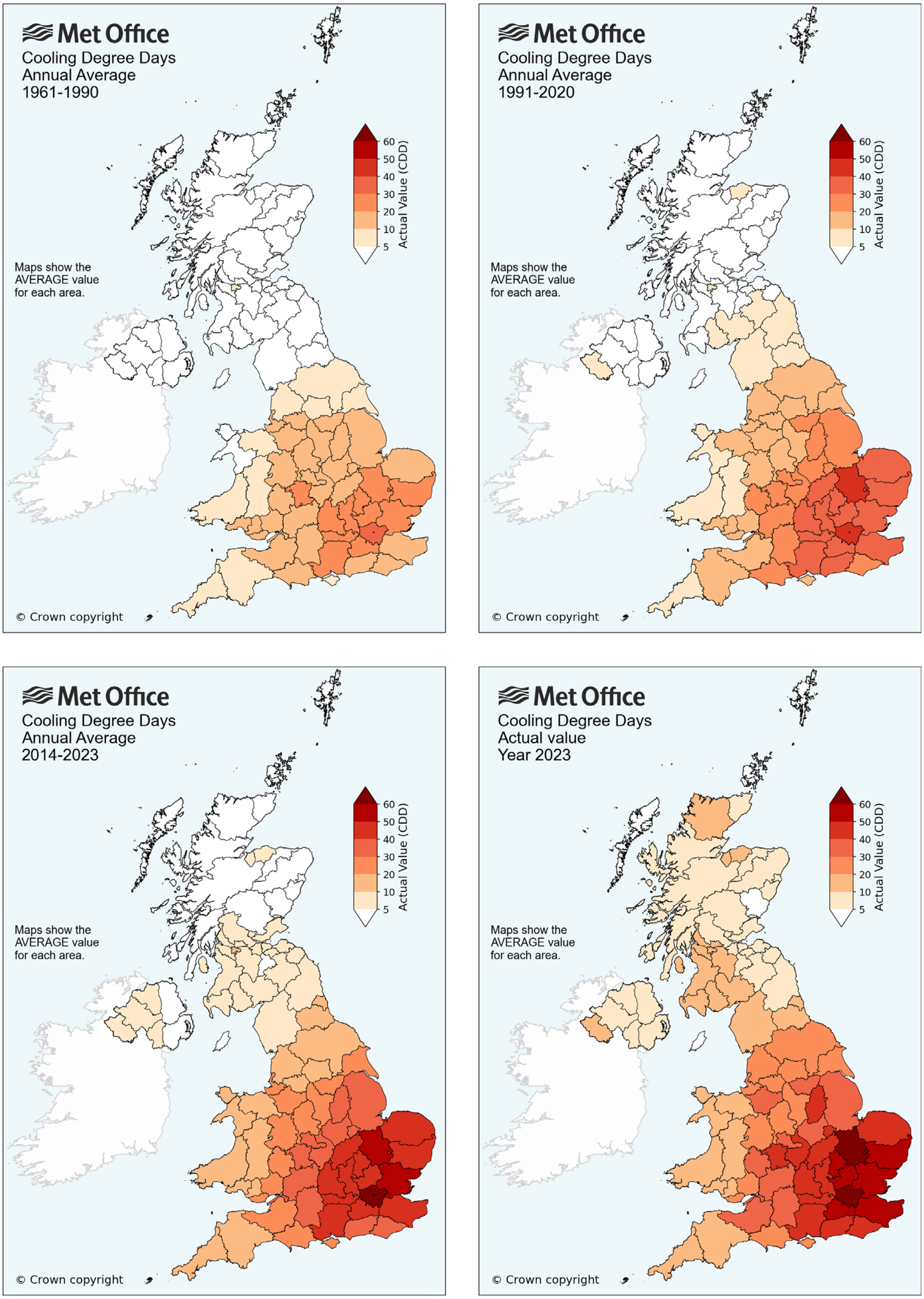


FIGURE 29 Annual average cooling degree days per year for 1961–1990, 1991–2020 and 2014–2023 and annual actual cooling degree days for 2023, as an average for each county of the UK.

from the early 20th Century onwards autumn and winter rainfall have been broadly comparable. However, autumn rainfall has also recently increased, with autumn 2000 the wettest autumn on record, autumn 2019 ranked fifth wettest and autumn 2023 ranked 12th wettest in this series. There has been a slight reduction in summer rainfall, while spring rainfall has remained fairly steady.

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

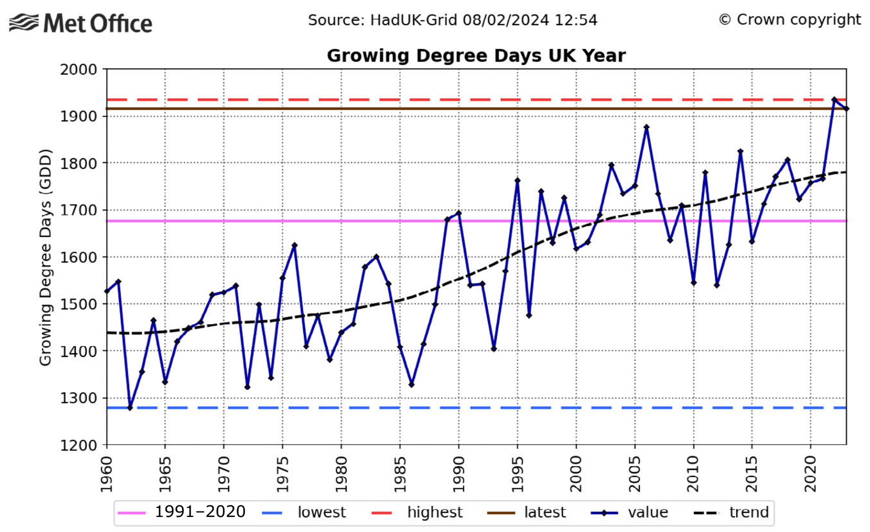


FIGURE 30 Annual growing degree days for the UK, 1960–2023. The table shows actual values for the UK and countries (GDD) with percentage of average values for 2014–2023 and 2023.

	1961–1990	1991–2020	2014–2023	2023	2014–2023 % of 1961–1990	2014–2023 % of 1991–2020	2023 anom % of 1961–1990	2023 anom % of 1991–2020
UK	1471	1676	1785	1915	121	106	130	114
England	1677	1920	2047	2182	122	107	130	114
Wales	1517	1723	1836	2003	121	107	132	116
Scotland	1124	1269	1348	1448	120	106	129	114
Northern Ireland	1424	1606	1692	1901	119	105	133	118

relating to the treatment of snow, before systematic meteorological observing networks were established, which could be associated with an underestimation (Murphy 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 over estimated (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 B2. 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.

2023 was the fifth wettest year at the Oxford Radcliffe Meteorological station in a series from 1767, with 929.5 mm (136% of the 1991–2020 long term average). The only wetter years in this 257 year series were 2012 (979.5 mm), 1960 (964.7 mm), 1852 (960.1 mm) and 1768 (932.7 mm).

3.3 | Daily rainfall

Figure 43 shows UK daily rainfall totals for each day of the calendar year 2023, and Figure 44 the time-series of UK area average daily rainfall. Figure 45 shows UK area average daily rainfall as an accumulation through the year. The most significant spells of dry weather (associated with high pressure bringing settled conditions) were in the second half of January and much of February, the second half of May, much of June, and early September, with rainfall deficits from the start of the year building up in early March, much of June and early July. In late May, the dry weather in the north and west of the UK led to concerns over wildfires (there was, e.g., a large scale wildfire at Cannich, near Inverness), and there were further wildfires in the West Highlands in mid-June, as well as water scarcity issues. For most of the UK the very wet second half to the year subsequently more than eliminated these deficits.

As occurs every year in the UK, there were various flood events during 2023. 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. Named storms are also described in Section 5. The two wettest days of the year for UK mean daily rainfall by a substantial margin were

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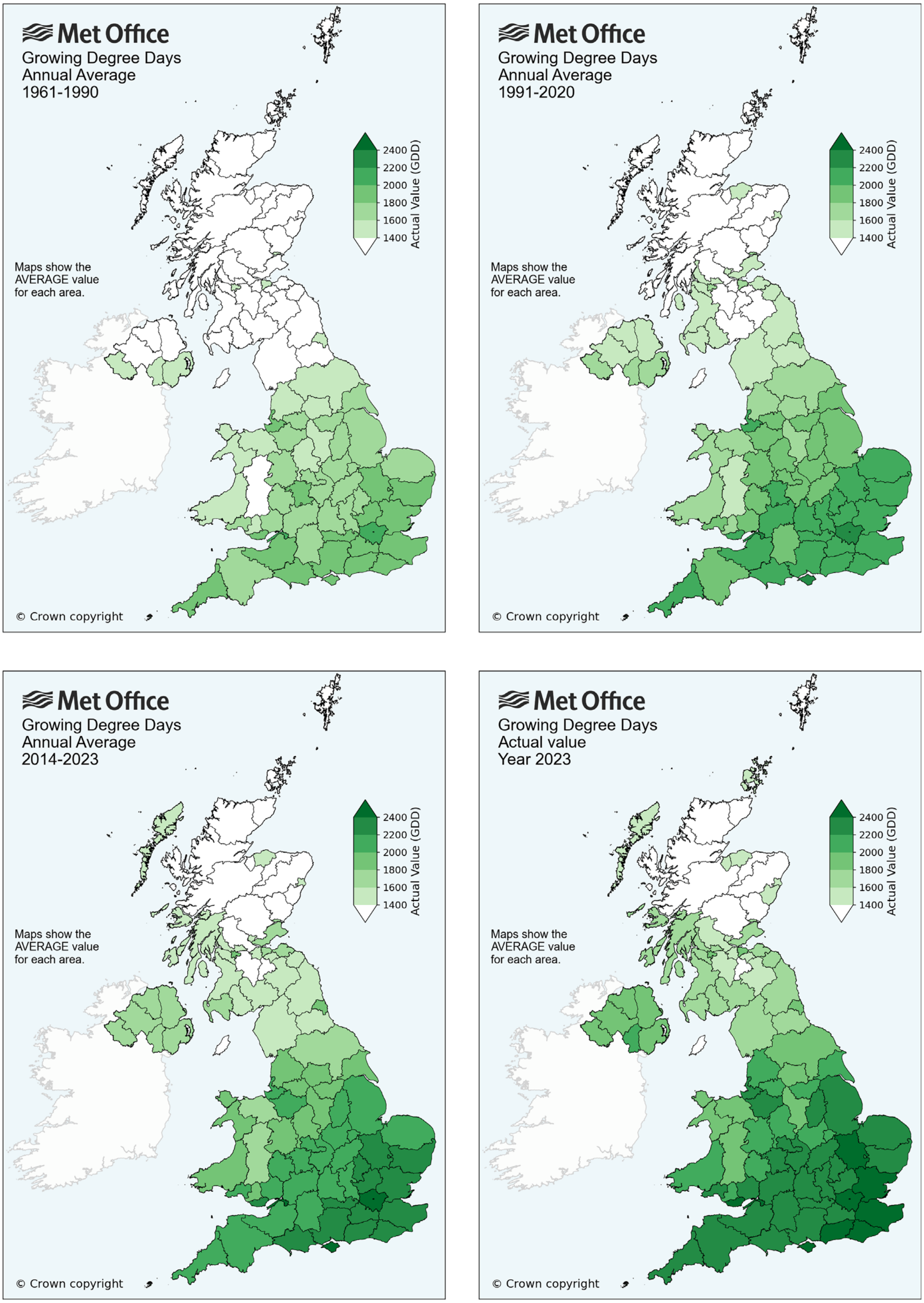
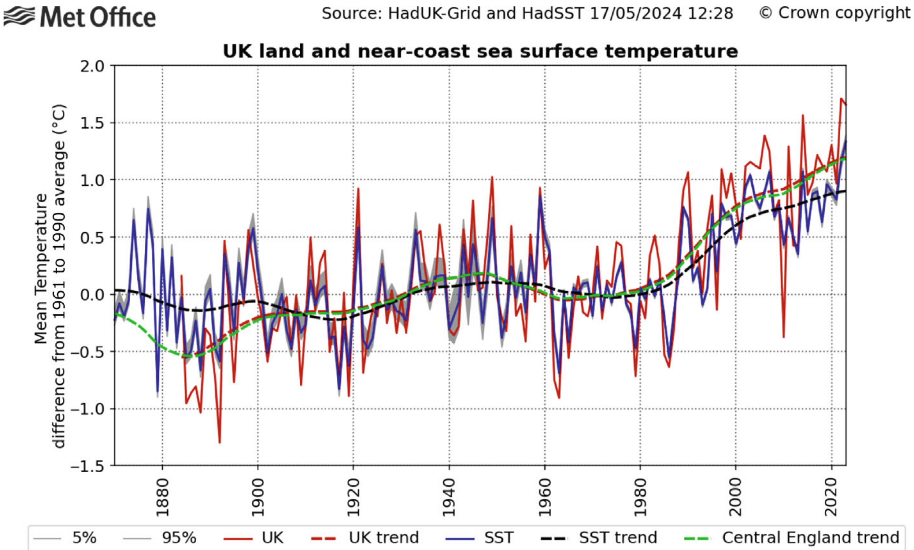


FIGURE 31 Annual average growing degree days per year for 1961–1990, 1991–2020 and 2014–2023 and annual actual growing degree days for 2023, as an average for each county of the UK.

19 October (20.1 mm storm Babet) and 27 December (17.2 mm storm Gerrit). The worst flooding of the year was for storm Babet (described in Section 9.4), and at a national scale this was the most significant flooding since storms Ciara and Dennis in February 2020. The sequence of named storms through the autumn and early winter, including storm Gerrit, is described in Section 9.6.

Unsettled weather in early January led to some flood impacts. Many locations in the Welsh uplands and on Exmoor recorded over 150% of the January 1991–2020



Area	1991–2020	2014–2023	2023
SST	0.6	0.9	1.3
UK	0.83	1.25	1.66
CET	0.76	1.25	1.66

FIGURE 32 UK annual mean temperature over land 1884 to 2023, CET trend and UK annual mean sea surface temperature across near-coastal waters around the UK 1870–2023 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).

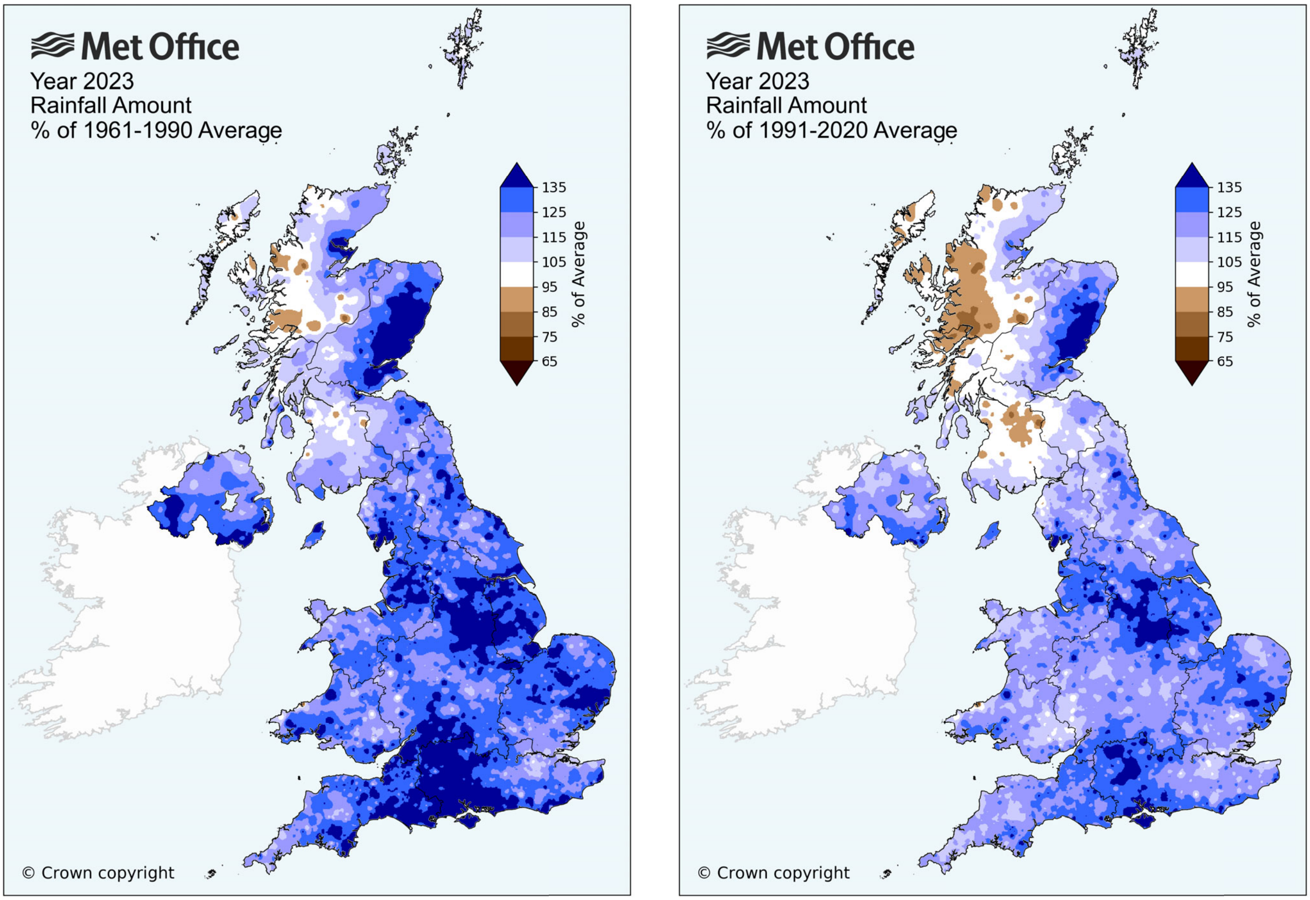
average rainfall in the first 2 weeks, and there were flooding problems, for example, across the Somerset Levels and from the River Severn and River Exe (see cover image). Any flood impacts after this were fairly limited until June, although heavy rain affected parts of South Yorkshire and Lincolnshire just after mid-March.

The warmth of June triggered thunderstorms, leading to fairly widespread impacts from flash flooding, large hail and lightning strikes, for example, from 10th to 13th and 16th to 23rd. Unseasonably wet and unsettled weather in July also caused various flooding problems, for example, closure of the West Coast Main Line. July included a succession of particularly wet weekends with low pressure dominating (15th to 16th, 22nd to 23rd, 29th to 30th)—disappointingly poor weather at the height of summer after the promising start in June.

Storm Antoni in early August brought heavy rain and strong winds to Wales and the south-west, with some transport disruption and a number of events cancelled (with many people on holiday at this time of year). Parts of Merseyside and north Cheshire were affected by surface water flooding from 25 to 27 August and there were two fatalities when a car was submerged at a rail underpass in Liverpool. There was a thundery breakdown to the spell of hot weather in early September. On the 10th, thousands of runners taking part in the Great North Run (Newcastle upon Tyne) were stranded after the event due to major disruption to the transport network, with the South Shields Metro station closed while water was cleared from the tracks.

The period from late September to December saw numerous flood impacts associated with persistent unsettled weather and Atlantic low pressure systems. Flash flooding on 17–18 September affected Devon and Somerset (with flooding at Exeter Airport), and there was further flooding in North Wales and parts of Cumbia on 19th. Exceptionally wet weather on 6–7 October affected Scotland, followed by storm Babet on 18th to 21st. These events are described in Sections 9.3 and 9.4. After Babet, flooding problems continued for the remainder of the month, affecting southern and eastern England, for example, Hampshire and the Isle of Wight, Nottinghamshire and Norfolk, and eastern Scotland but, especially, southern and eastern parts of Northern Ireland. There were major problems in counties Antrim, Armagh and Down, with numerous flooded properties and communities affected. From 18 to 31 October, County Down recorded an average rainfall total of 236 mm, twice the 1991–2020 October whole-month average, with 131 mm of this falling in the last 4 days alone. In this fortnight, Trassey Slievenaman in the Mourne Mountains recorded 489 mm, almost three times the October 1991–2020 average and equivalent to almost 35 mm/day.

The main impacts from storm Ciarán on 1–2 November were across the south of the UK from the strong winds, but this storm also brought flooding problems across East Anglia and south-west England. Across southern England and South Wales, 30–50 mm of rain fell over the two rain-days 31 October to 1 November from both Ciarán and the previous low



2023	1961–1990	1991–2020
UK	122	113
England	130	123
Wales	124	117
Scotland	112	103
Northern Ireland	127	120

FIGURE 33 (a,b) Rainfall anomalies relative to 1961–1990 and 1991–2020 for year 2023. The table shows percentage of average values for the UK and countries.

pressure system, with 60 mm or more across parts of Cornwall and Devon. The prolonged wet weather also resulted in increasing concerns over groundwater flooding (e.g., in Dorset), with groundwater levels in many aquifers reported as exceptionally high for the time of year. November and December continued very unsettled, with further rain from storms Debi, Elin and Fergus and continuing flood impacts, followed by storms Pia and Gerrit on 21 and 27 December. The main flood impacts at this stage were as a result of the persistent wet weather from mid-September onwards, with flooding concerns for the River Severn, River Trent and River Ouse, culminating in significant flooding in early 2024 after the arrival of storm Henk on 2 January (see Section 9.6).

3.4 | Days of rain and rainfall intensity

The number of days of rain greater than or equal to 1 mm (RR1, 'wet days') for the UK during 2023 was 172 days—that is, not far short of half the year across the UK on average. This was 13 days more than the 1991–2020 long term average and the highest since 2014 (Figure 46a). England and Northern Ireland recorded over a fortnight of wet days more than normal (the latter the most since 1998), and Wales over 3 weeks more (the most since 2000). The number of wet days for Scotland was near normal overall; more than average in the east and fewer in the west.

For the UK overall, there were fewer wet days than average in February, May and June, but more than

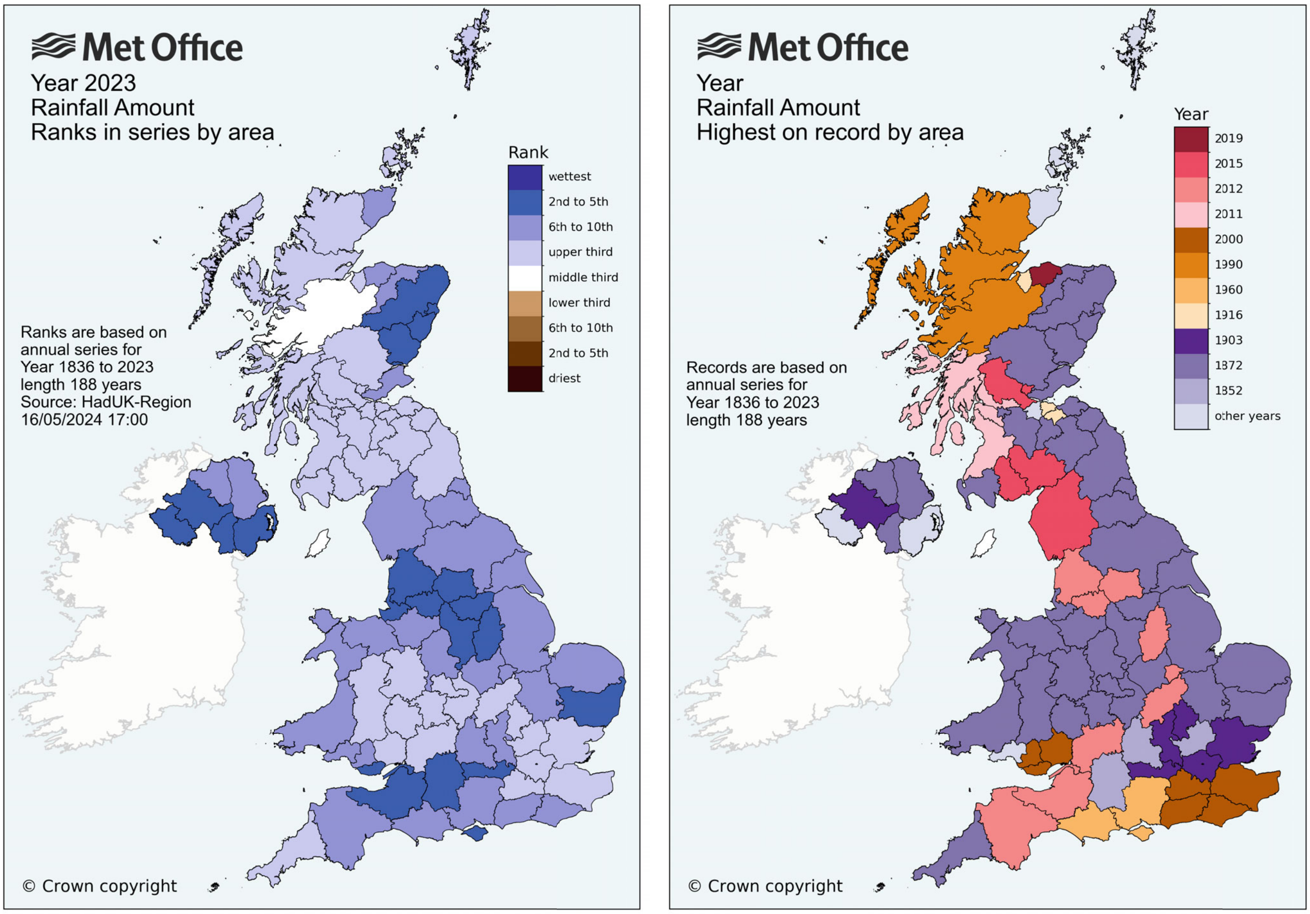


FIGURE 34 The rank of 2023 annual rainfall for all counties of the UK (a) and the wettest year on record all counties of the UK (b) based on series from 1836.

average for all other months—including July to December (Figure 47a). Monthly anomalies for wet days are fairly well correlated with monthly mean sea level pressure anomalies (Figure 2) with an R^2 value of 0.66. The peaks in the annual wet days series (1998, 2000, 2012, 2014, 2023) are all highly ranked in the UK annual rainfall series from 1836.

The number of days of rain greater than or equal to 10 mm (RR10, 'very wet days') for the UK during 2023 was 41 days, 6 days more than the 1991–2020 average and third highest in the series from 1961, behind 2000 and 2012 (Figure 46b). England, Wales and Northern Ireland all recorded over a week more very wet days. Monthly anomalies for very wet days were highest in July, October and December (Figure 47b).

The RR1 wet days series shows an increase from 154 days for 1961–1990 to 162 days for the most recent decade 2014–2023, and RR10 very wet days a similar increase from 31 days to 36. 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 48 shows an estimate of the areal-average rainfall intensity across the UK for each year from 1961 to 2023 (see Table A1 for definition). The figure is indicative of trends in rainfall intensity across the UK on wet days although, as with wet days and very wet days (RR1 and RR10), it neither provides a seasonal break-down, nor distinguishes between upland and lowland areas.

2023 was the fourth highest year for this metric, behind 2000, 2012 and 2020. As noted for the wet days series, these correspond to very wet years for the UK: 2000 (ranked 2 in the series from 1836), 2012 (rank 5), 2020 (rank 4) and 2023 (rank 7). There is a slight increase of 0.2 mm (~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 0.73), as would be expected because in years with a large number of very wet days (≥10 mm) the average rainfall intensity on wet days (≥1 mm) is higher. In

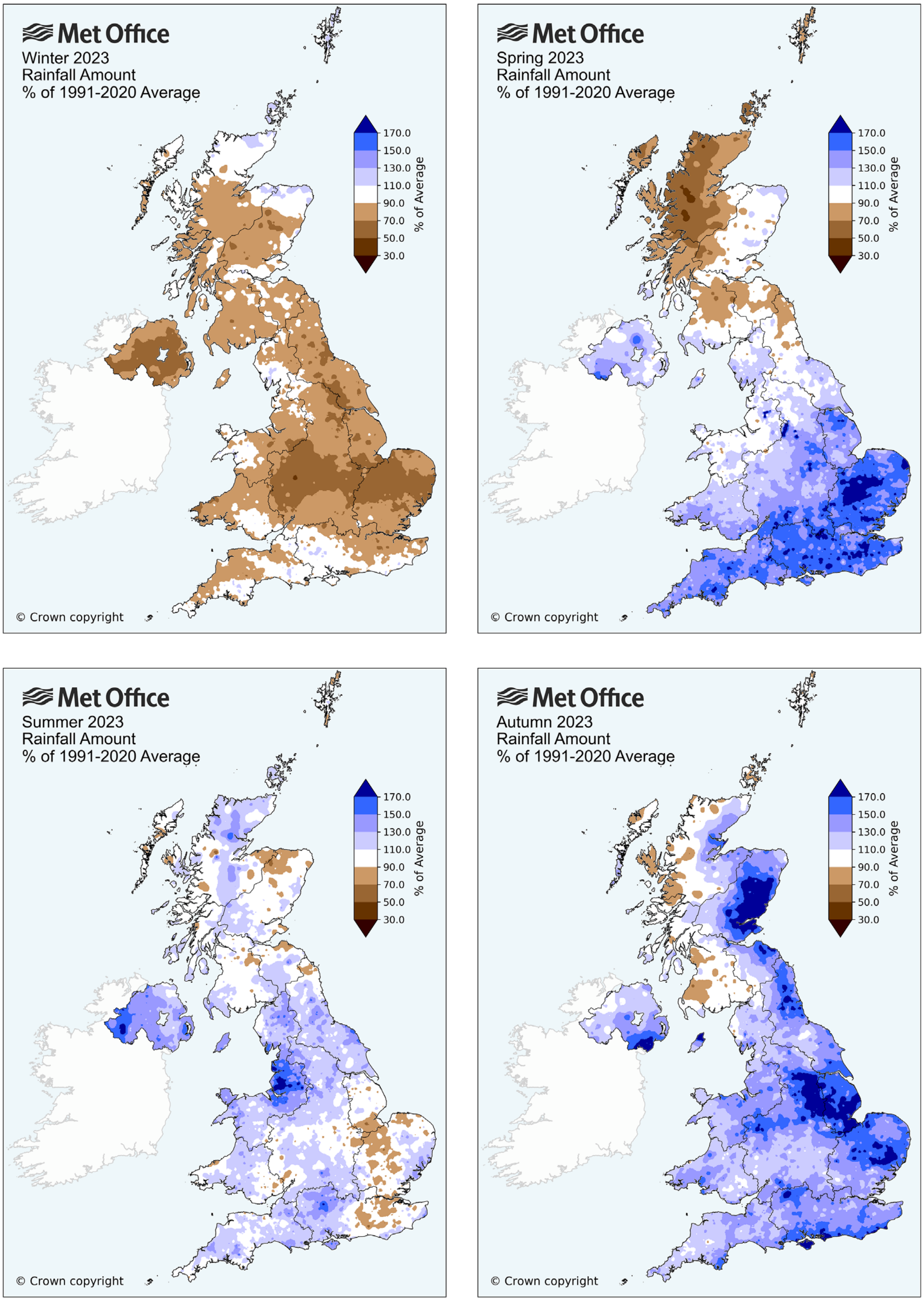


FIGURE 35 2023 seasonal rainfall anomalies relative to 1991–2020. Winter refers to the period December 2022 to February 2023.

contrast, there is low correlation between the rainfall intensity series and the RR1 series (R^2 value 0.23) because both these series use the same threshold (1 mm), and whereas RR1 simply relates to the number of days exceeding this threshold, rainfall intensity relates to the rainfall amounts on days exceeding this threshold.

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

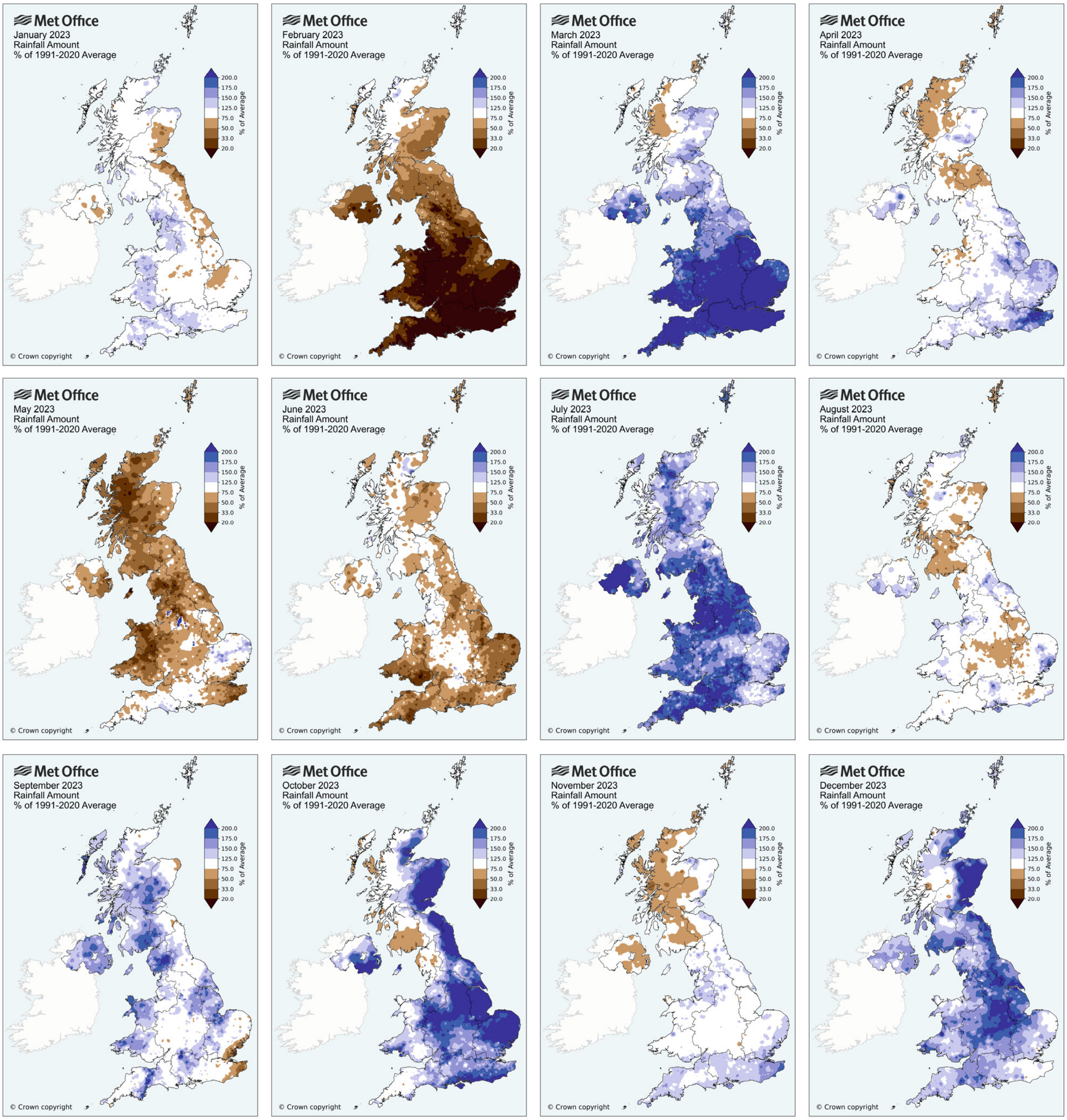


FIGURE 36 2023 monthly rainfall anomalies relative to 1991–2020. The legend scale ranges from 20% to 200%.

duration. These metrics adopt both 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, beginning only in 1961.

The limitation of the length of these series emphasizes in particular the importance of future work to digitize daily rainfall observations before 1961 in order to provide longer term context; especially given the very large variability in heavy rainfall events and the need to capture major rainfall events in earlier years. Nevertheless—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 49a,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 at each grid point based on rainfall totals

TABLE 7 Monthly, seasonal and annual rainfall actual values (mm) and percentage of average values relative to 1991–2020 for the UK and countries for year 2023.

	UK		England		Wales		Scotland		Northern Ireland	
	Actual	%	Actual	%	Actual	%	Actual	%	Actual	%
January	129	106	91	110	198	128	179	101	102	89
February	46	47	15	23	27	22	103	73	35	38
March	134	158	123	210	210	203	132	106	142	164
April	73	102	68	121	84	95	76	82	90	121
May	40	57	40	71	36	41	40	45	49	66
June	55	71	42	65	49	53	75	81	68	83
July	142	172	122	183	180	182	158	152	182	204
August	90	96	73	98	122	109	103	86	120	121
September	121	134	84	123	161	144	170	138	136	156
October	178	145	151	167	216	136	212	126	185	162
November	120	97	111	120	174	107	125	76	95	78
December	190	149	145	158	259	147	248	142	178	147
Winter	293	85	200	83	394	87	433	88	226	69
Spring	248	109	231	135	330	118	249	81	281	120
Summer	287	113	237	115	350	116	337	106	370	137
Autumn	419	125	345	138	551	128	507	111	416	128
Annual	1319	113	1066	123	1716	117	1622	103	1383	120

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 below. The series lengths are 1836–2023 (188 years) except winter which is 1837–2023 (187 years).

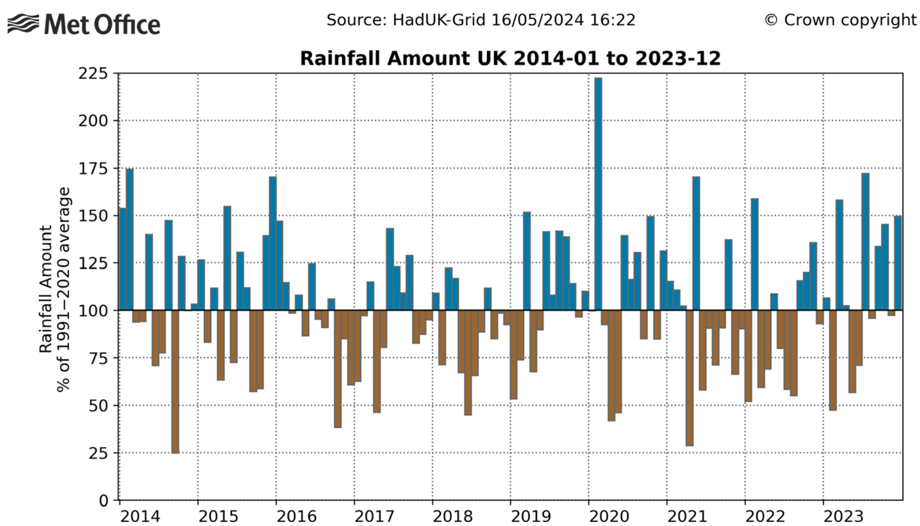


FIGURE 37 UK monthly rainfall anomalies relative to 1991–2020 for the most recent decade 2014–2023 (120 months).

over the period 1961–1990 on wet days—days exceeding 1 mm of rain; the UK value is the areal-average of the number of days calculated at each grid point. (Based on Figure 46a we would therefore expect about 5% of 154 = 7.7 days per year to exceed the 95th percentile for the period 1961–1990—which is indeed the case; 154 is the 1961–1990 UK average number of wet days).

As with rainfall intensity, this neither includes a seasonal breakdown, nor does it distinguish between orographically enhanced frontal rain and convective rain. This

TABLE 8 Monthly, seasonal and annual rainfall percentage of average values relative to 1961–1990 and 1991–2020 for the UK and countries for the decade 2014–2023.

	UK		England		Wales		Scotland		Northern Ireland	
	61–90	91–20	61–90	91–20	61–90	91–20	61–90	91–20	61–90	91–20
January	112	103	111	108	111	107	115	98	99	99
February	143	115	132	115	141	120	155	114	139	123
March	103	110	106	121	108	118	99	101	105	109
April	80	74	73	72	75	72	90	76	86	77
May	101	100	99	103	100	98	104	98	99	97
June	103	95	102	94	103	92	106	96	105	94
July	119	104	114	99	115	95	122	110	138	107
August	109	104	107	102	108	103	110	105	119	113
September	91	99	94	97	100	108	86	99	89	102
October	118	106	128	108	110	99	113	106	102	102
November	109	99	117	104	107	98	101	95	116	100
December	122	110	120	110	124	114	123	108	121	109
Winter	124	109	119	109	123	112	129	107	116	108
Spring	96	96	94	99	96	97	98	92	97	95
Summer	110	101	108	98	109	97	112	104	120	106
Autumn	106	102	114	104	106	101	101	100	103	102
Annual	110	102	110	103	110	103	110	101	110	103

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

Note: Colour coding corresponds to the % of average values as given in the key below.

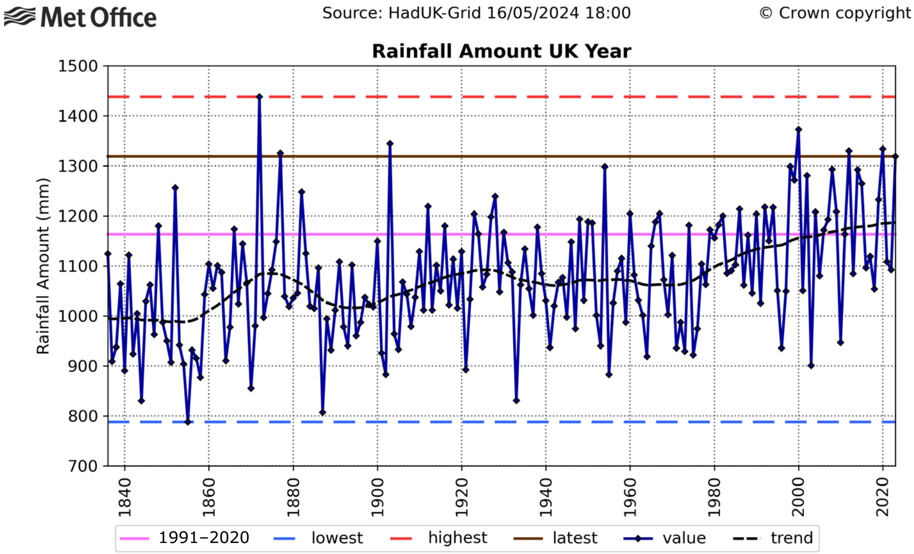
metric is based on a percentile approach with thresholds that vary geographically so that all parts of the UK will have an equal influence (the climatologically wetter parts of the UK in the north and west will have higher percentile thresholds than the drier parts in the south and east). This contrasts 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 B3).

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 9.1/1.9 days for the most recent decade 2014–2023. As with the annual series for wet days (RR1), very wet days (RR10) and rainfall intensity, the 2023 values for the 95th and 99th percentiles were both notably high. The 95th percentile for wet days is highly correlated with the annual RR10 series (R^2 value 0.81).

Table 9 shows percentiles of UK mean daily rainfall for 1961–1990, 1991–2020, 2014–2023 and 2023. Percentiles for the most recent decade 2014–2023 are only slightly higher than for 1991–2020 (with a slight reduction for 99th) but have increased for all percentiles compared with 1961–1990, except for the maximum (i.e., the UK's wettest day of the year). (An example of an annual maximum is 3 October 2020, the UK's wettest day on record and the only day exceeding 30 mm as a UK area average, see Kendon and McCarthy, 2021). The changes are highest for the 50th percentile, with the UK median daily rainfall for the most recent decade 2014–2023 5% higher than that for 1991–2020 and 16% higher than 1961–1990, broadly consistent with the UK's climate becoming wetter overall (Table 8). However, the absence of a notable increase in the 99th percentile and maximum reflect the fact that the annual variability of the UK's climate is still the predominant factor for extremes of UK mean daily rainfall.

Figures 50 and 51 show a count of the average number of days per year that have exceeded the 95th percentile and 99th percentile of 1961–1990 average rainfall for each county area of the UK (see Appendix A8) for 1961–1990, 1991–2020, 2014–2023 and actual days for 2023. This is an alternative approach which looks at how much the frequency of exceedance of a fixed percentile has changed, rather than how much the percentiles

FIGURE 38 Annual rainfall (mm) for the UK, 1836–2023. The table shows actual values for the UK and countries.



	1961–1990	1991–2020	2014–2023	2023
UK	1084	1163	1191	1319
England	820	870	898	1066
Wales	1380	1465	1513	1716
Scotland	1444	1573	1592	1622
Northern Ireland	1090	1156	1195	1383

themselves have changed. Since the baseline period is 1961–1990 the maps are uniformly shaded by definition with a value of 18.3 days (95th percentile) and 3.7 days (99th). (Note that this differs from the previous analysis in Figure 49 since it considers the percentile for *all* days, rather than the percentile for *wet days only*. If the latter were used, the average number of days exceeding the 95th percentile for 1961–1990 would not be uniform but greater across the climatologically wetter areas of the UK). Table 10 provides summary statistics for the 95th, 98th, 99th, 99.5th and 99.8th percentiles averaged across all county areas.

The average number of days in 2023 was around 30 to 40% higher than the 1991–2020 average and around 50% or more higher than 1961–1990 across all percentiles, that is, consistent with 2023 being a wet and unsettled year overall. The most days exceeding the 95th and 99th percentiles occurred across parts of southern, eastern and northern England, Northern Ireland and eastern Scotland. The number of days exceeding the 99th percentile is broadly consistent with the rank of 2023 annual rainfall for individual counties (Figure 34a). The maps and table show that the number of days exceeding the 1961–1990 percentile has increased overall for 1991–2020 and 2014–2023. The most recent decade has typically had around 20% more days exceeding these percentiles than 1961–1990. However, there is no obviously coherent spatial pattern on the maps (e.g., a greater increase across climatologically wetter parts of the UK), suggesting that although there has been a general increase in heavy rainfall events overall for the UK, at a county-area scale this is still dominated by annual and decadal variability. For higher percentiles, the sample size of the observations included in the analysis decreases which increases the overall variability—for example, the 99.8th percentile represents fewer than 1 day/year, on average (Table 10).

Figure 52 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 ≥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 between 2000 and 3000 gauges since the 2010s (see Figure A3).

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

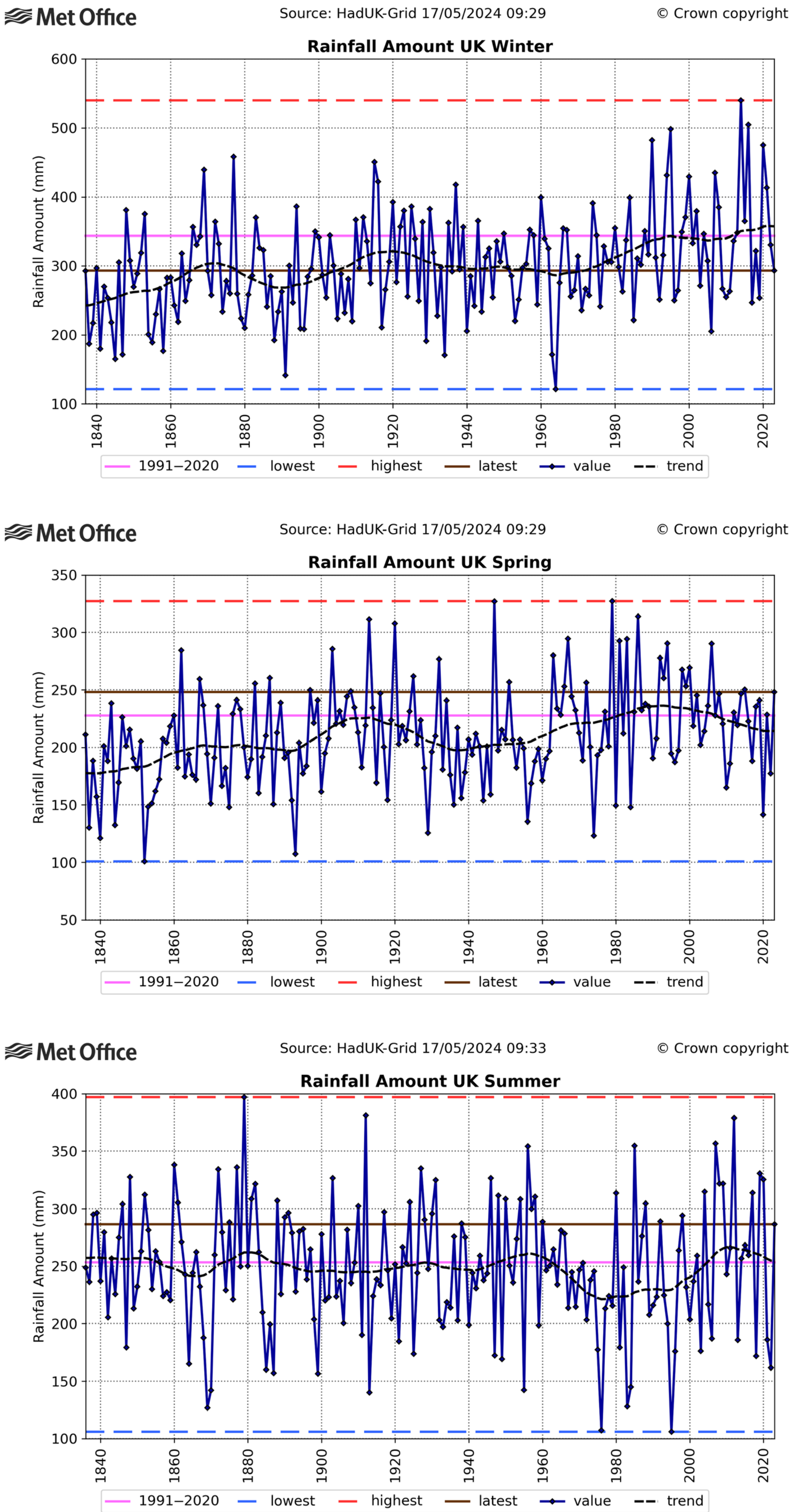


FIGURE 39 Seasonal rainfall (mm) for the UK for (a) winter, (b) spring, (c) summer (d) autumn - (overleaf) 1836–2023 (winter 1837–2023). Note the *y*-axis gridline spacing differs between the figures.

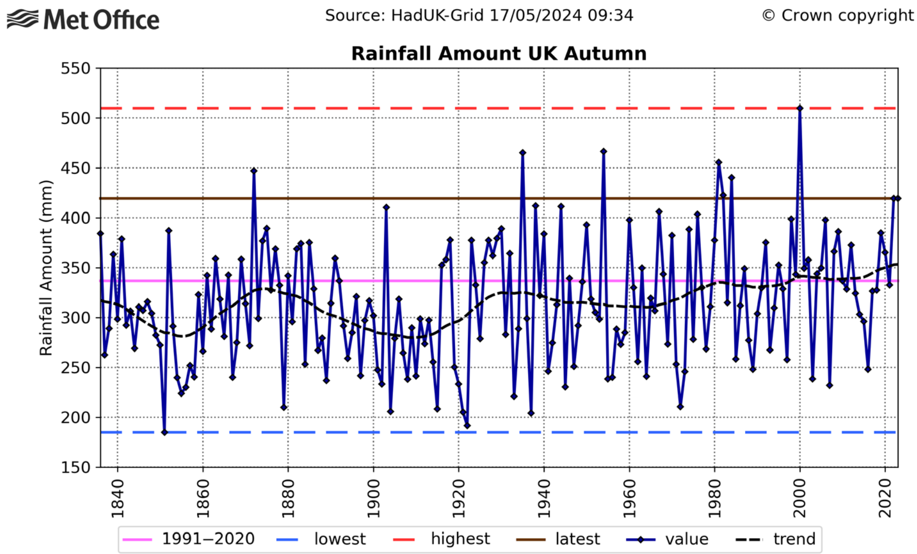


FIGURE 39 (Continued)

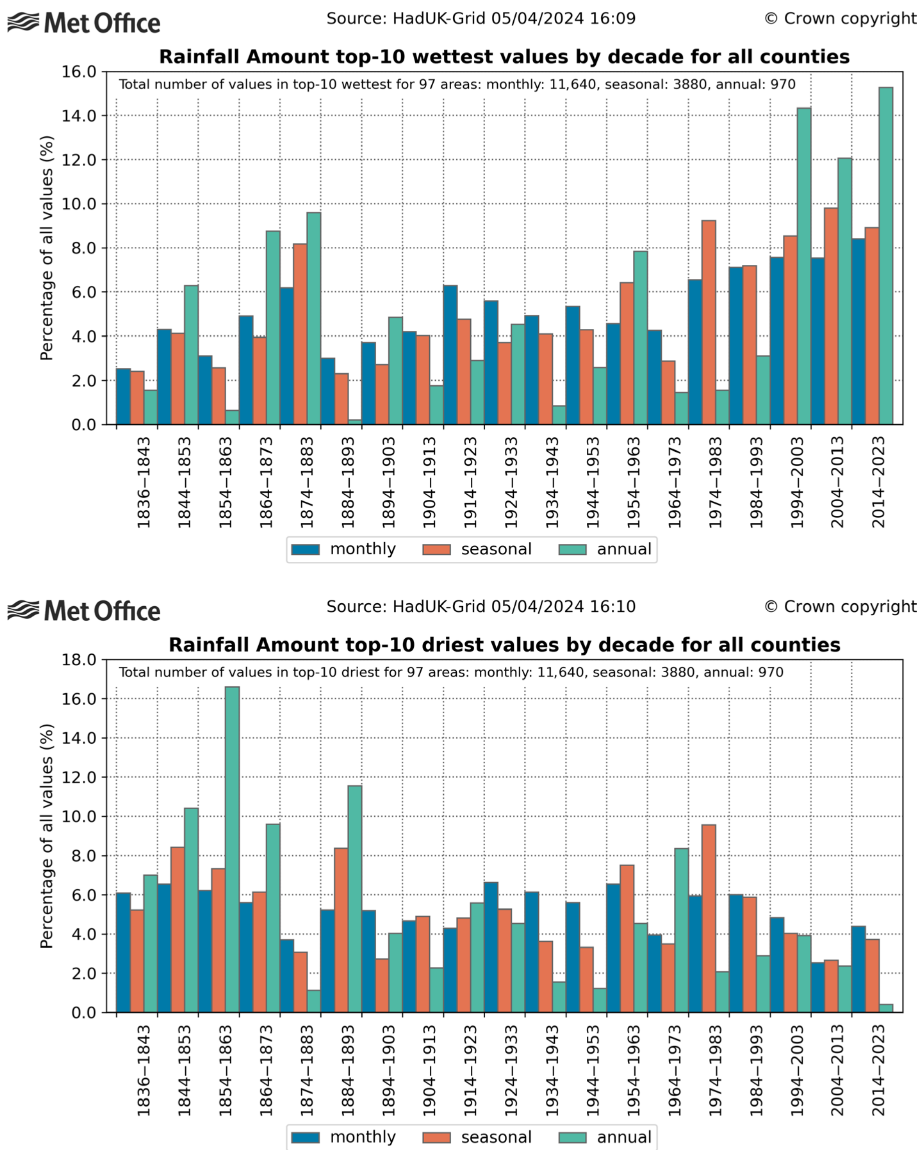
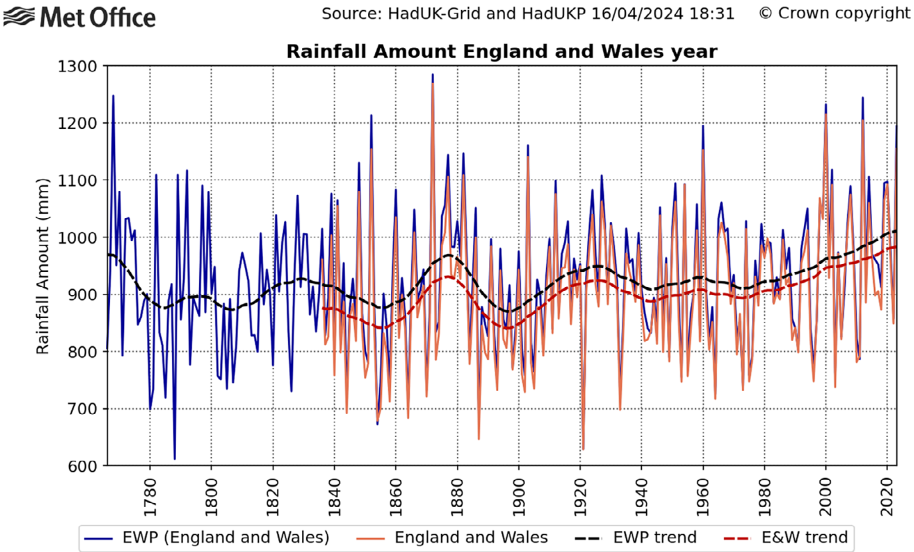


FIGURE 40 (a,b) Number of monthly, seasonal and annual top-ten rainfall values by decade for the near-19 decades of the 188-year HadUK-Grid monthly rainfall series 1836–2023 (the first 'decade' 1836–1843 comprises only 8 years). The figures count the number of values in each decade in the top-ten wettest (a) and top-ten driest (b) in the series across 97 counties of the UK. In total there are 97 × 12 × 10 = 11,640 monthly values, 97 × 4 × 10 = 3880 seasonal values and 97 × 10 = 970 annual values for each of top-ten wettest and top-ten driest spread across all the decades. Each decade also comprises 11,640/3880/970 monthly/seasonal/annual values in total from which these top-ten wettest/driest subsets of values are taken (except 1836–1843). Counts are converted to the percentage of all monthly, seasonal and annual values, with an average of 5.3% per decade.



	1961–1990	1991–2020	2014–2023	2023
EWP (England and Wales)	915	971	1012	1194
England and Wales	897	951	982	1155

FIGURE 41 Annual rainfall for England and Wales (EWP) 1766–2023, and England and Wales from HadUK-Grid dataset, 1836–2023. The table shows actual values (mm).

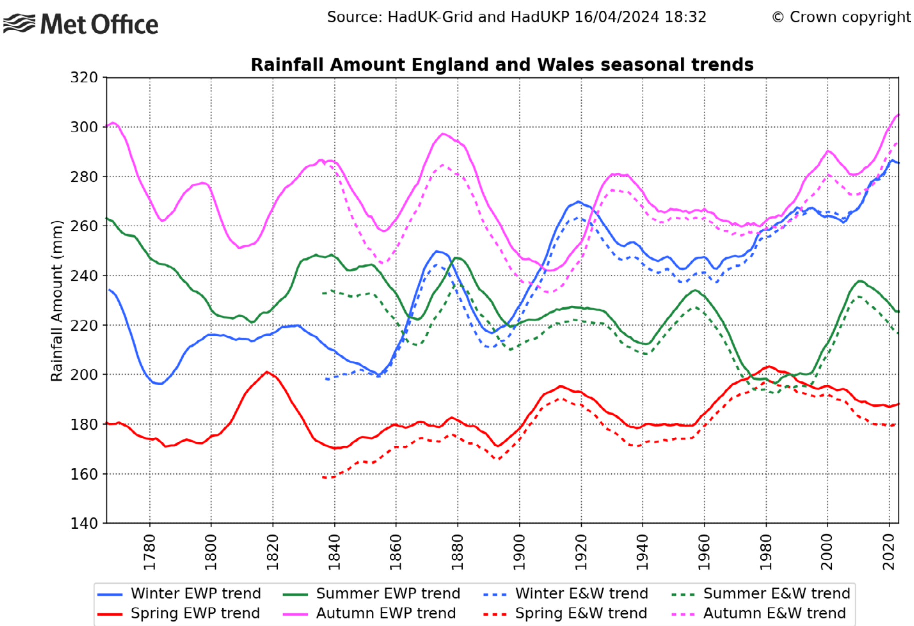


FIGURE 42 Seasonal EWP trends 1766–2023 (winter 1767–2023) showing the smoothed trends for each series using a weighted kernel filter described in Appendix B1. The equivalent England and Wales series (E&W) from the HadUK-Grid dataset are also shown dashed.

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, 2023 had a count of 1618 station-days, slightly above the long term trend and 117% of the 1991–2020 average. The majority of this total is accounted for by days with widespread frontal rainfall from Atlantic weather systems, in January, July, September, October and December. The most recent decade 2014–2023 has a count of station-days 9% higher than 1991–2020 and 46% higher than 1961–1990. Note however the important caveat above which may particularly affect the 1961–1990 period. There was a particular tendency in the raingauge network for spatial clustering of stations through these years—for example, in the London and Manchester areas—which may significantly affect the 1961–1990 count.

3.6 | Snow

Table 11 counts the number of stations across England, Wales, Scotland and Northern Ireland recording snow depths ≥5 cm by day through 2023. This provides an indication of the most notable spells of snow through the course of the year.

Scotland bore the brunt of impacts from snow from 17 to 19 January due to an influx of colder air from the north. Frequent snow showers led to disrupted rail services, road and school closures. Snow depths reached 34 cm on 18th and 19th at Loch Glascarnoch (Ross and Cromarty)—the UK's greatest depth of the year, while Northern Ireland was also affected. Snow showers off the

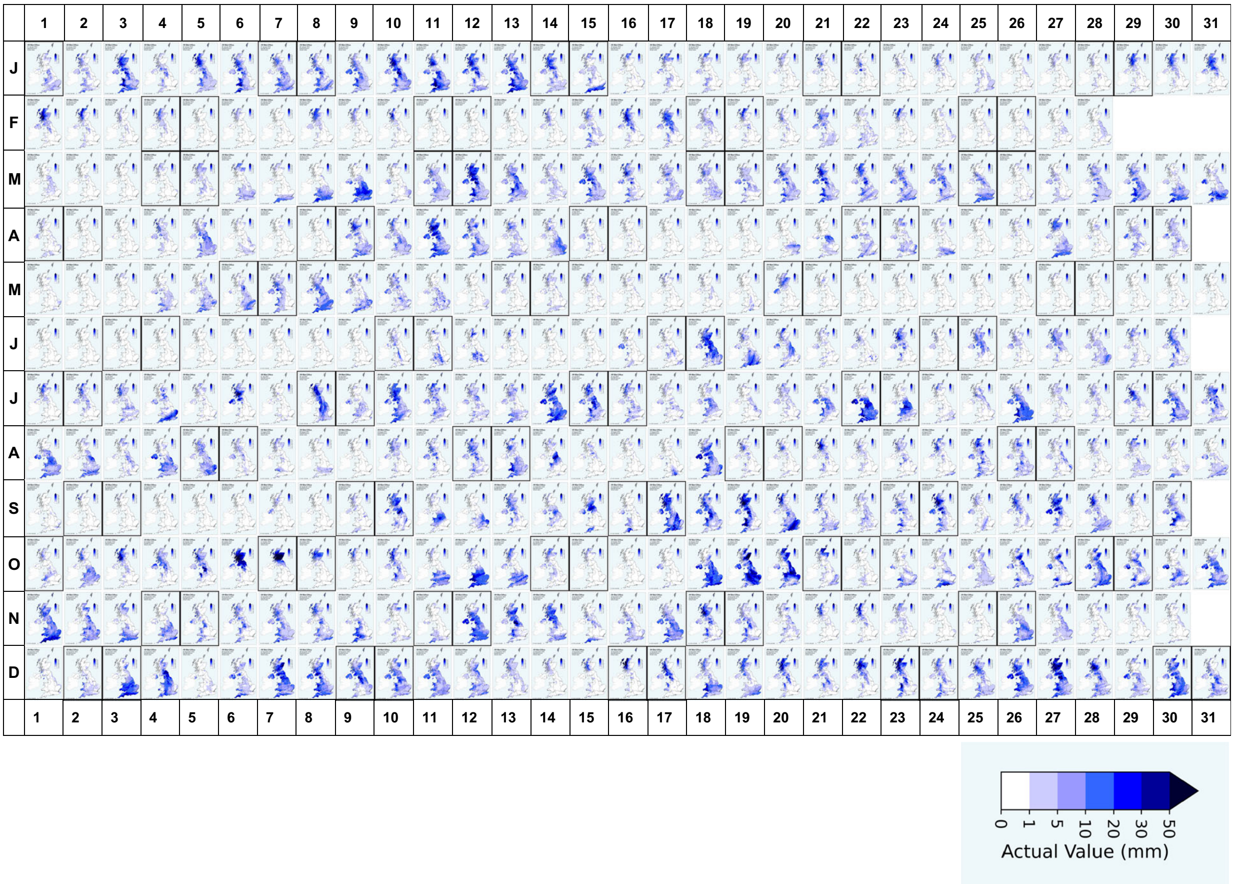


FIGURE 43 2023 daily actual rainfall by month (top to bottom) and day (left to right). Weekends are displayed with a black border. The darkest shades indicate areas over 50 mm.

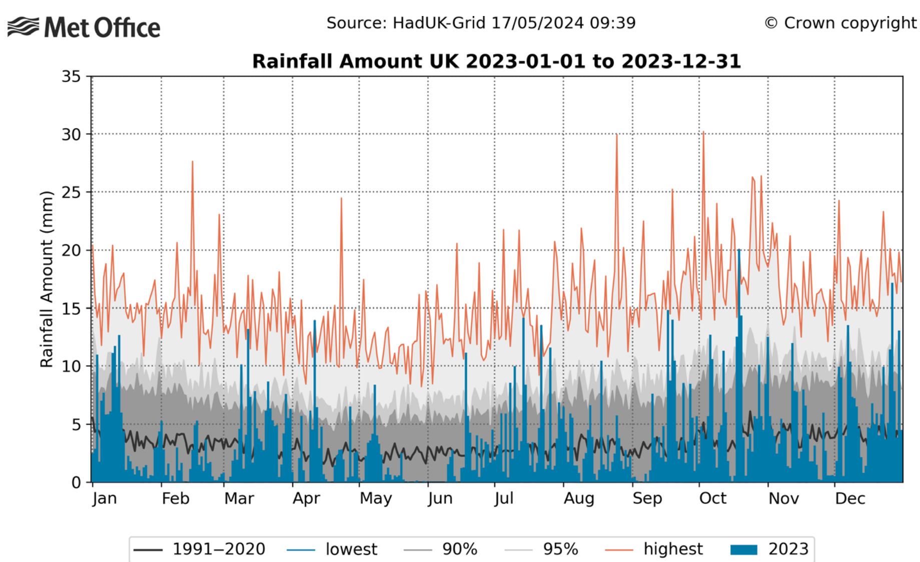


FIGURE 44 UK mean daily rainfall for each calendar day of the year 2023. The black line shows the 1991–2020 average for each calendar day; the red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1891–2023 inclusive.

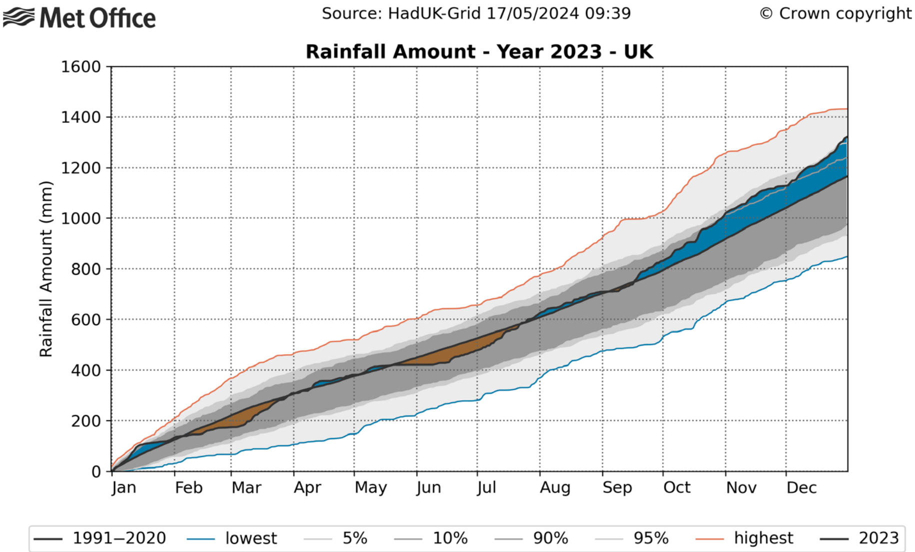


FIGURE 45 UK mean daily rainfall accumulation for the year so far, for each calendar day of the year 2023. The black line shows the 1991–2020 average for each calendar day; the red and blue lines the highest and lowest values and the grey shading the percentile values for each calendar day of the year based on the period 1891–2023 inclusive. The light brown/blue shaded areas show the accumulated rainfall deficit/surplus relative to the 1991–2020 average for the year so far from the start of January (assuming no rainfall deficit or surplus at the start of the year).

Irish Sea also affected parts of Wales, North West England and Cornwall; Manchester Airport was closed for 2 h and in Cornwall roads were closed including the A30 near Newquay and A39 near Truro.

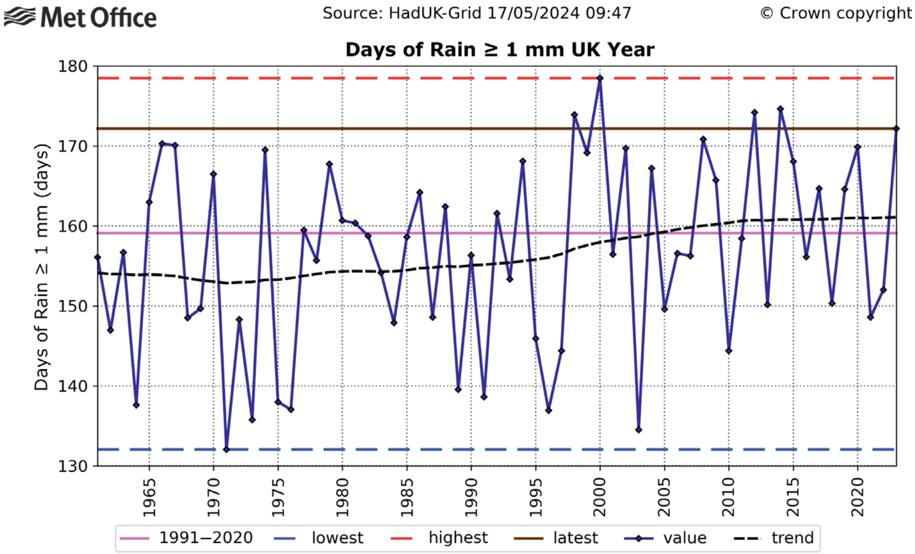
The most significant widespread snow occurred in early March. A northerly flow introduced an Arctic air mass, bringing widespread snow showers as far as southern England and associated impacts (8 cm at Huntsham, Devon and Odiham, Hampshire on 8th). This event culminated in heavy and disruptive snow across the south Pennines and Peak District caused by a low pressure system pushing milder Atlantic air back north into this cold air mass. Snow depths on 10th reached 32 cm at Buxton, 31 cm at Middleton (Derbyshire) and 24 cm at Leek, Thorncliffe (Staffordshire)—these stations being at around 300masl, while unofficial reports suggested snowfall accumulations of the order of 40 cm in some higher-lying Sheffield suburbs. The M62 was blocked for many hours due to snow clearance being hampered by drifting, and in Derbyshire a major incident was declared with mountain rescue teams assisting trapped motorists between Buxton and Ashbourne. Snow accumulations on power lines resulted in widespread power outages. Road closures and power outages also affected Wales and Northern Ireland. This was the UK's most significant March snowfall event since 18 to 19 March 2018 (around a fortnight after the much publicized 'Beast from the East' snow event of that year).

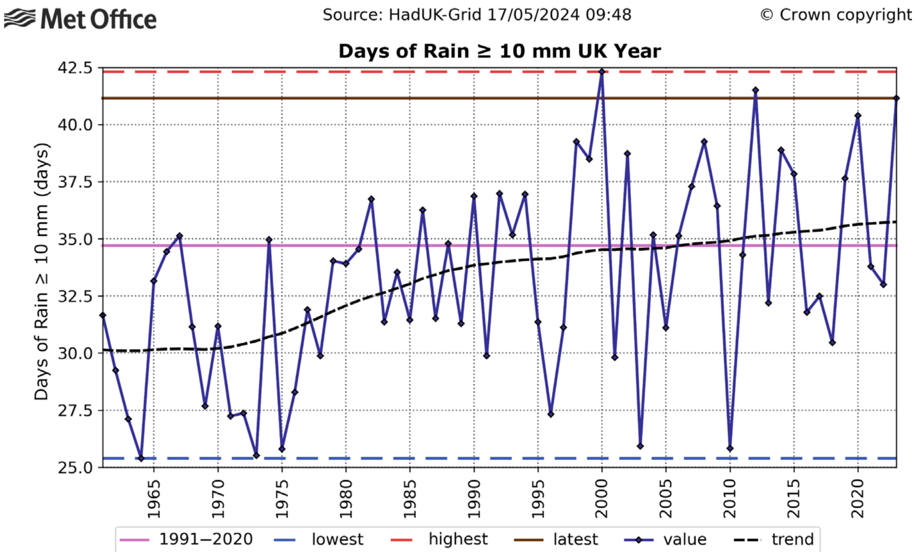
Heavy snow affected Cumbria and parts of Derbyshire in early December 2023 as snow showers moved east off the Irish Sea overnight 2nd to 3rd. A major incident was declared in Cumbria with a large number of roads closed including the M6 and rest centres opened for stranded travellers. Thousands of residents experienced loss of power, with unofficial depths locally of 10 to 20 cm or more across the southern Lake District (e.g., Ambleside). Holley and Silkstone (2024) describes the meteorology of this event. Further snow affected northern Scotland on 27 December from storm Gerrit, with a number of motorists trapped on the A9.

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 most notable spells of significant and widespread lying snow across lowland parts of the UK in recent years have been February to March 2018, January and March 2013 and January and December 2010, and overall the snow events of 2023 were very much less severe than these. 2010 was the snowiest year by far for the UK in the last two decades; comparable to several snowy years in the 1970s and 1980s.

Figure 53 shows the count of station-days where snow depth sensors recorded greater than or equal to 10 cm or 20 cm of lying snow. These series have not been adjusted for network size, consequently they are indicative but not homogeneous (with the 2023 network size less than half that of the 1960s to 1990s, see Appendix A13). Based on the metrics from Figure 53, while 2023 was a snowier year than five other years of the most recent decade (2014, 2016, 2019, 2020 and 2022), it was less snowy than the others—particularly 2013 and 2018. Despite our warming climate, impactful snow events are still to be expected but their number and severity have declined since the 1960s. 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

FIGURE 46 Annual days of rain (a) ≥1 mm and (b) ≥10 mm for the UK, 1961–2023. The tables show actual values for the UK and countries (days), with anomaly values for 2014–2023 and 2023 (days).





Raindays ≥ 1 mm	1961–1990	1991–2020	2014–2023	2023	2014–2023 anom wrt 1961–1990	2014–2023 anom wrt 1991–2020	2023 anom wrt 1961–1990	2023 anom wrt 1991–2020
UK	154	159	162	172	8	3	18	13
England	131	135	138	153	7	3	21	17
Wales	167	173	179	196	12	6	30	23
Scotland	184	191	194	194	10	3	9	2
Northern Ireland	177	182	184	200	7	2	23	18

Raindays ≥ 10 mm	1961–1990	1991–2020	2014–2023	2023	2014–2023 anom wrt 1961–1990	2014–2023 anom wrt 1991–2020	2023 anom wrt 1961–1990	2023 anom wrt 1991–2020
UK	31	35	36	41	4	1	10	6
England	21	24	25	32	3	1	11	8
Wales	44	48	50	59	5	2	15	11
Scotland	45	50	51	51	6	1	6	1
Northern Ireland	29	32	34	41	5	2	12	9

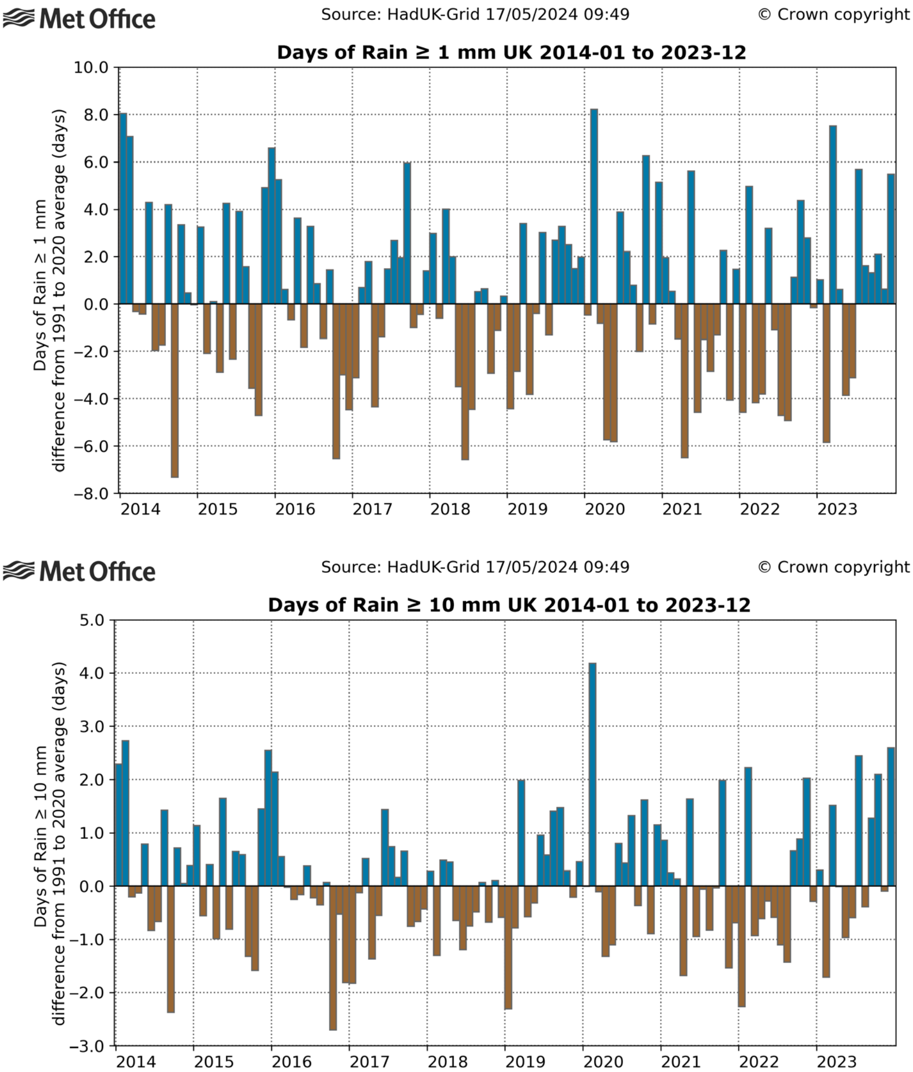


FIGURE 47 Days of rain (a) ≥1 mm (RR1) and (b) ≥10 mm (RR10) as monthly anomalies relative to 1991–2020 for the UK for 2014–2023.

(Wild et al., 2000) and there were also some very substantial snow events with very low temperatures through the 1970s and 1980s (see, e.g., Sholl, 2020, also Figure 66).

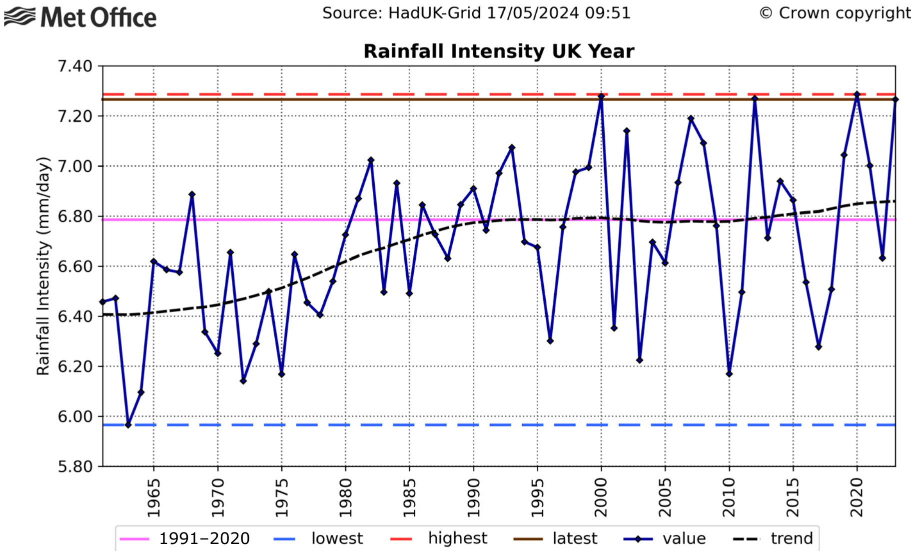
4 | SUNSHINE

The UK sunshine total for 2023 was 1435 h, 102% of the 1991–2020 average. The anomaly pattern was variable but in general slightly sunnier further north—particularly western Scotland. Overall, Scotland was sunniest relative to average (107%) and here it was the equal-ninth sunniest year in the series from 1910 (Figure 54). In terms of annual totals, Preston Cove House, Dorset was the sunniest location with 1959 h, 105% of average. Lerwick, Shetland was the dullest with 1133 h, 98%.

Figures 55–57 and Table 12 show seasonal and monthly sunshine anomalies for the UK for 2023 and the most recent decade 2014–2023. With high pressure, fine, settled weather and prolonged periods of sunshine, June was by a wide margin the sunniest month of the year with 245 h, 143% of the 1991–2020 average. It was the UK's sunniest June since 1975 and fifth sunniest in the series from 1910. It was also the UK's sunniest calendar month since May 2020 (the UK's sunniest month in the series with 267 h). Several stations recorded over 300 h of sunshine in June including 323.5 h at Preston Cove House, Dorset, although this falls well short of June 1925 when several stations in Devon and Cornwall recorded over 370 h. January was also notably sunny with 131%, of average, the fourth-sunniest January for the UK—although January 2022 was slightly sunnier. May was a sunny month across Wales and the west of England.

In addition to being mild and wet, December was extremely dull with only 28 h of sunshine, 64% of average. Sunshine totals were <1 h/day on average; this was the UK's equal-seventh dullest December in the series (although December 2021 was marginally duller). March and July were both notably dull. Sunshine totals in July

FIGURE 48 Annual rainfall intensity for the UK, 1961–2023. The table shows values for the UK and countries (mm/day).



	1961–1990	1991–2020	2014–2023	2023
UK	6.6	6.8	6.8	7.3
England	5.9	6.0	6.1	6.6
Wales	8.0	8.1	8.1	8.5
Scotland	7.4	7.8	7.8	8.1
Northern Ireland	5.9	6.1	6.3	6.7

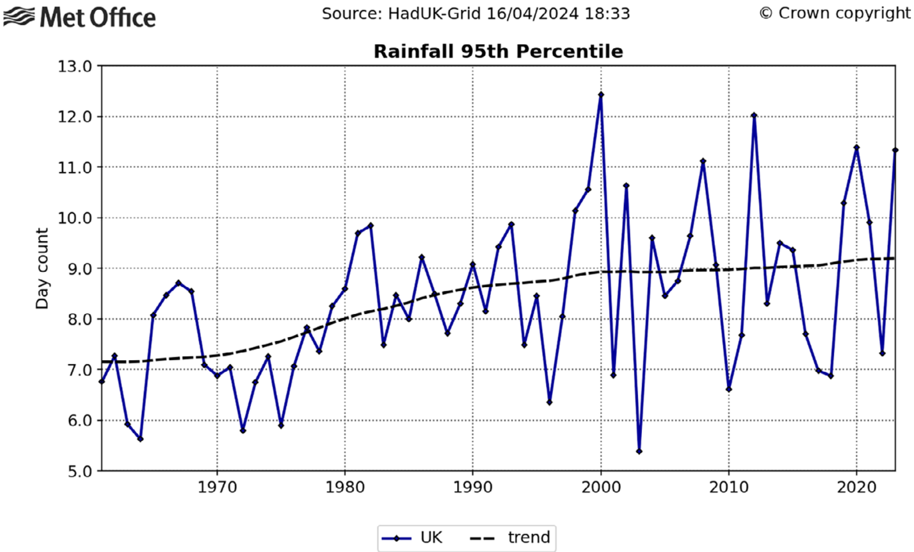
and August averaged <5 h/day compared with more than eight in June, while, despite the significantly shorter day lengths, the September sunshine total almost matched that of July. Overall, seasonal sunshine totals were unremarkable although winter 2023 (December 2022 to February 2023) was the tenth sunniest winter in the UK series.

While it is interesting to compare monthly sunshine anomalies for the most recent decade 2014–2013 (Figure 57) against mean sea level pressure anomalies (Figure 2), temperature anomalies (Figure 10) and rainfall anomalies (Figure 37), clearly, these comparisons are complex because of the characteristics of each individual month and the seasonal aspects of the UK's climate.

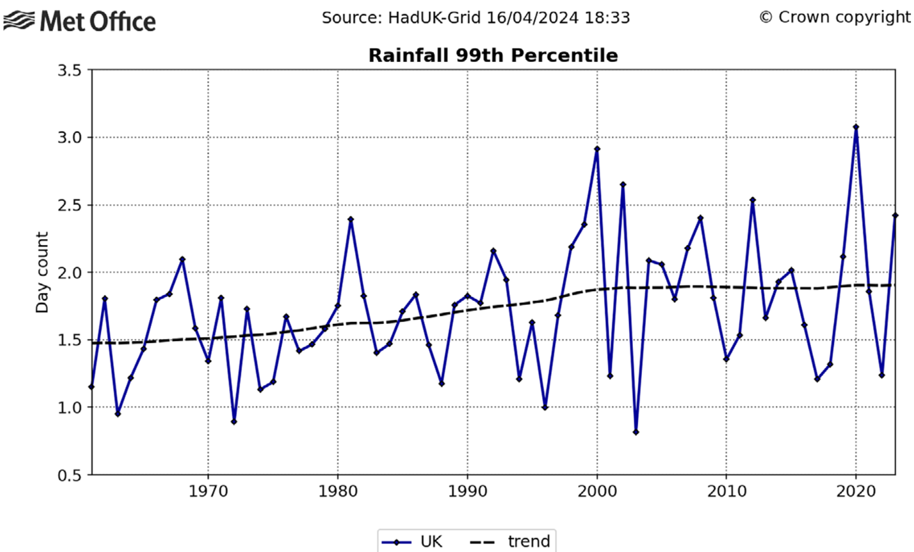
Figures 58 and 59 show annual and seasonal sunshine durations for the UK from 1910 to 2023 inclusive. The smoothed trend shows an increase in sunshine from the 1980s onward. The most recent decade 2014–2023 has been 4% sunnier than 1991–2020 and 9% sunnier than 1961–1990 with slightly larger increases across England compared with the other countries. Three years in the most recent decade 2014–2023 have been in the top-ten sunniest in the UK series; 2018, 2020 and 2022, and this is the sunniest 10-year period in the UK series.

The trend in annual sunshine is most apparent in the winter and spring series: UK sunshine totals have increased most in winter and spring compared with 1961–1990 (15% and 16%, respectively), and for England by 24% and 19%. Four winters in the most recent decade 2014–2023 have been in the top-ten sunniest in the UK series: 2015, 2018, 2019 and 2023. UK sunshine trends will be influenced by a combination of natural variability and circulation changes, as well as other regional and global drivers such as those contributing to global dimming and brightening trends including direct and indirect response to aerosols (Wild, 2009). 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 reduced aerosol emissions—although this article acknowledges that a similar upward trend is not also apparent in summer, which may be a result of competing mechanisms. The decadal statistics will reflect annual and decadal variability in the UK's climate in addition to the overall increasing sunshine trend.

The sunshine network is relatively sparse, with the 2023 network comprising around 112 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



	1961–1990	1991–2020	2014–2023	2023
UK	7.7	8.9	9.1	11.3
England	6.6	7.4	7.7	10.1
Wales	8.3	8.9	8.7	10.8
Scotland	9.2	11.2	11.0	12.6
Northern Ireland	8.9	10.4	11.4	16.5



	1961–1990	1991–2020	2014–2023	2023
UK	1.6	1.9	1.9	2.4
England	1.3	1.5	1.5	2.0
Wales	1.7	1.8	1.8	1.9
Scotland	1.9	2.5	2.4	3.0
Northern Ireland	1.8	2.2	2.3	3.8

FIGURE 49 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).

low elevation and topographic shading may be important. 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 ~5 min/day, on average). More details can be found in Appendix B2.

TABLE 9 Percentiles (mm) of UK mean daily rainfall for 1961–1990, 1991–2020, 2014–2023 and 2023.

	1961–1990	1991–2020	2014–2023	2023	2014–2023 % of 1961–1990	2014–2023 % of 1991–2020
50%	2.0	2.2	2.3	2.6	116	105
75%	4.4	4.7	4.8	5.5	110	102
90%	7.2	7.6	7.8	8.5	109	103
95%	9.1	9.7	9.9	11.4	109	102
99%	13.3	14.0	13.7	14.2	103	97
Max	19.3	18.6	18.9	20.1	98	101

Note: Also shown are percentage of average values for 2014–2023.

5 | WIND

5.1 | Extreme wind speed

The windiest days of 2023 are listed in Table 13, and named storms listed in Table 14. (In this report, storms are grouped by calendar year, not by winter season.) Storm-surge events of 2023 are described in Section 6.2. As with previous years, storms in 2023 were named as part of an initiative between the Met Office, Met Éireann and KNMI (the Irish and Dutch national weather services), forming the western European storm naming group. Other European national meteorological agencies also apply names to storms. Portugal, Spain, Luxembourg, France and Belgium form the south-western group; Norway, Sweden and Denmark the northern group.

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.

Unusually, there were no storms named by the western European storm naming group in year 2023 until Antoni on 5 August 2023. Altogether this group named nine storms in 2023: Antoni and Betty at the end of the 2022–2023 storm season, and Agnes to Gerrit in the 2023–2024 season. Storms named by other groups included Otto in February, Noa in April and Pia in December (Table 14), plus several others associated with storm surges listed in Table A5.

Otto was a fairly typical Atlantic winter storm for the UK, with the strongest winds across north-east Scotland, for example, 70 Kt (81 mph) at Lossiemouth, Moray and Tain Range, Ross and Cromarty. The storm deepened as it moved across the North Sea with the greatest impacts across Norway, Sweden and Denmark. Noa was the most significant April storm to affect England and Wales since 18 April 2013, gusts exceeded 50 Kt (58 mph) around exposed coastlines of the south and west, including the UK's highest gust of the year at a lowland station—83 Kt (96 mph) at Needles Old Battery, Isle of Wight (Table 15); huge waves affected the Cornwall coast. Nevertheless, significantly more powerful April storms have affected the UK in the past, including 1 April 1994, 11 April 1989 and 2 April 1973.

This was the second year in which two named storms have occurred in August, the other being 2020 (Ellen and Francis). Neither Antoni nor Betty were particularly severe for the UK but Betty caused widespread power cuts across the Republic of Ireland.

The period from late September to the end of the year was very unsettled, wet and stormy and included a run of significant named storms from Agnes (late September) to Gerrit (late December)—with Henk arriving in early 2024. This was the most active start to the named storm season since it was started in 2015. Agnes was an intense area of low pressure enhanced by energy from Tropical Storm Ophelia which affected the north-east coast of the US and caused serious flooding in New York. Fortunately, it had weakened by the time it reached the UK, although a gust of 73 Kt (84 mph) was recorded at Capel Curig, Conwy (see cover image). Babet was the most significant named storm for the UK in terms of weather impacts, largely as a result of heavy and persistent rain (see Section 9.4). Winds gusted at well over 50 Kt (58 mph) across northeast England and much of Scotland, for example, 67 Kt (77 mph) at Inverbervie, Kincardineshire; strong winds combined with driving rain resulted in atrocious weather conditions here for a sustained period. Leeds Bradford airport closed after an aircraft skidded off the runway during the storm, and 45 workers were airlifted off a North Sea drilling platform after it lost anchors during the storm. Winds gusted at over 100 Kt (115 mph) across Scotland's mountain summits.

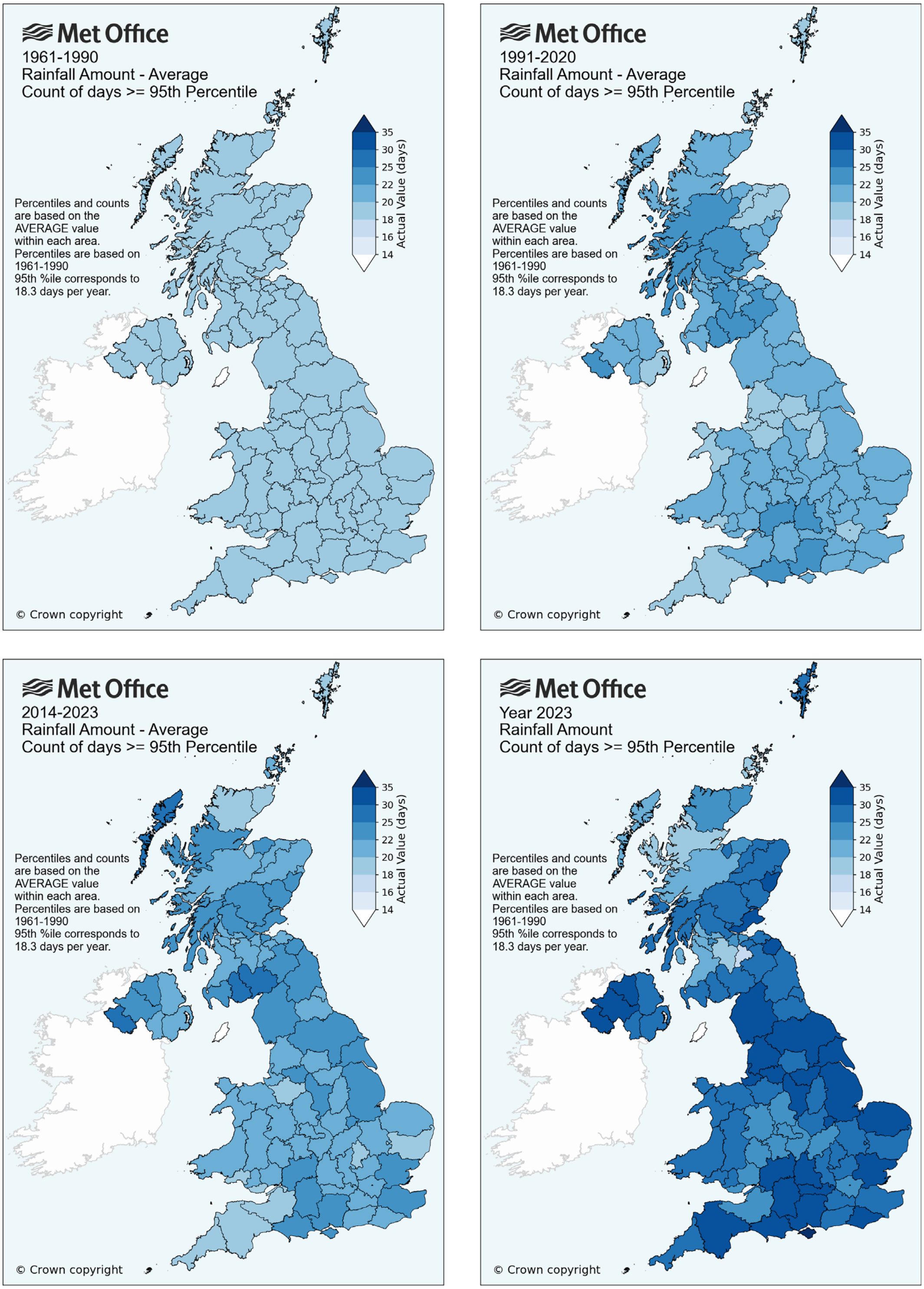


FIGURE 50 Average number of days per year for 1961–1990, 1991–2020 and 2014–2023 and actual number of days for 2023 in which the daily rainfall total for each county of the UK has exceeded the 95th percentile daily rainfall for that county based on the period 1961–1990. The 95th percentile corresponds to 1 in 20 days or 18.3 days per year, by definition—as shown on the map for 1961–1990. The legend scale extends to 35 days. Daily totals are based on the average value across each county.

Wind speeds from storm Ciarán were particularly severe across the Channel Islands and northern France (see Section 9.5 for details of this storm). The next three storms were all named by Met Éireann. The UK's strongest winds from Debi were around Irish Sea coasts with 60 Kt (69 mph) gusts in exposed locations. The worst

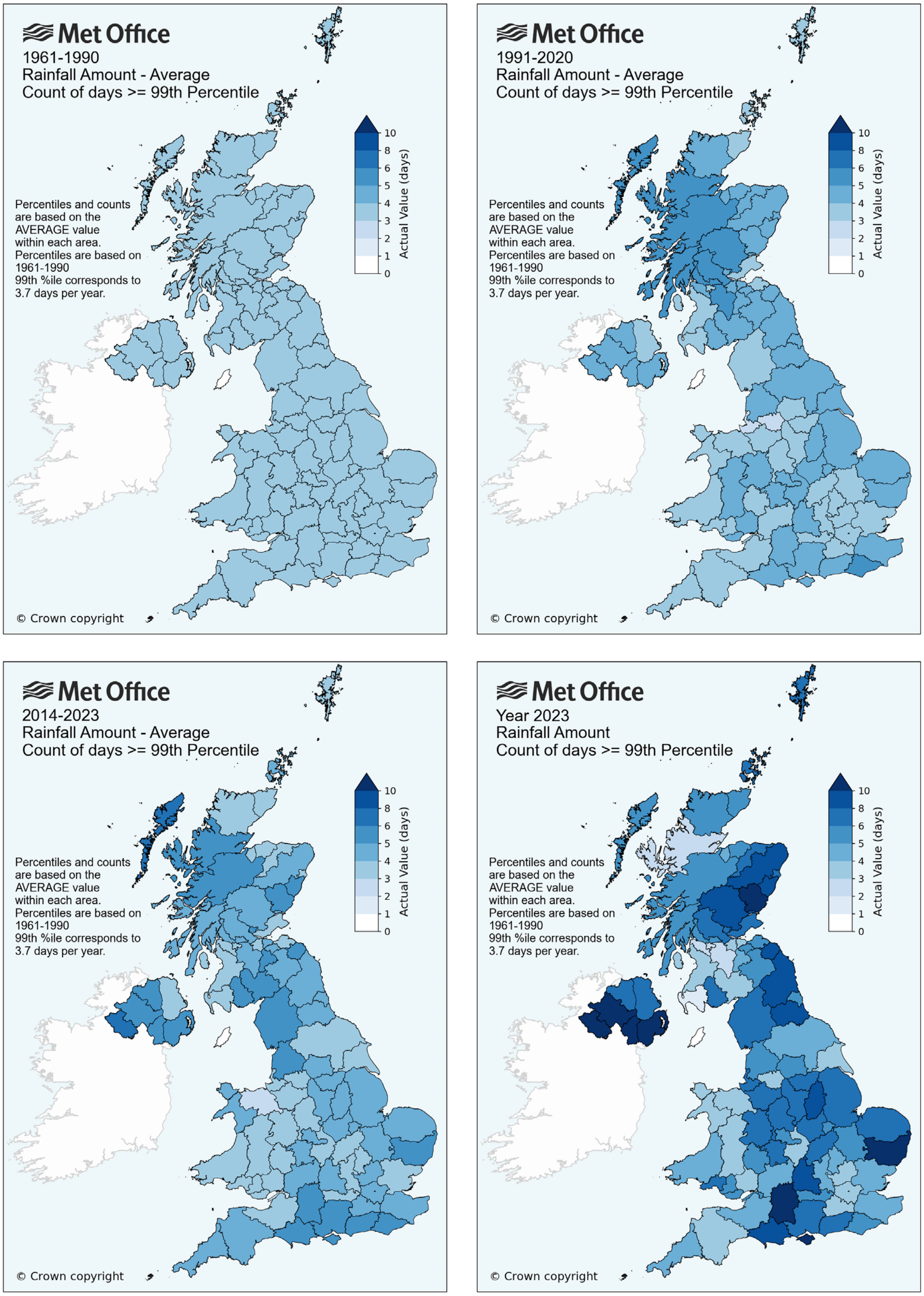


FIGURE 51 As Figure 50 for the 99th percentile. This corresponds to 1 in 100 days or 3.7 days per year. The legend scale extends to 10 days.

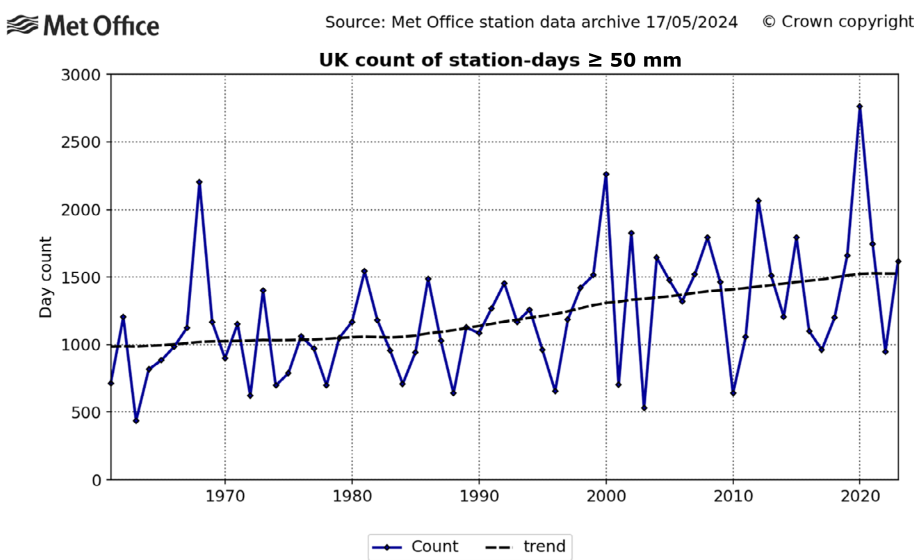
impacts from Debi, Elin and Fergus were all across the Republic of Ireland; Met Éireann issuing red warnings for both Debi and Fergus.

The storm with by far the most stations exceeding 50 Kt (58 mph), Pia, was not named by the western storm naming group, but named by the Danish Meteorological Institute (DMI) (Table 14). While gusts over 50 Kt were very widespread, gusts over 60 Kt (69 mph) were largely confined to northern Scotland, although Brizlee Wood, Northumberland recorded 70 Kt (81 mph). This storm

TABLE 10 Average count of the number of days per year in which the daily rainfall total for each county of the UK has exceeded its Xth percentile based on the period 1961–1990, as an average across all 97 counties—covering the periods 1961–1990, 1991–2020, 2014–2023 and actual counts for year 2023.

Percentile	1961–1990	1991–2020	2014–2023	2023	2014–2023 % of 1961–1990	2014–2023 % of 1991–2020
95	18.3	20.8	21.4	26.9	117	103
98	7.3	8.4	8.6	11.4	118	103
99	3.7	4.2	4.3	5.6	118	103
99.5	1.8	2.1	2.1	3.0	117	102
99.8	0.7	0.9	0.9	1.2	122	97

Note: Also shown are percentage of average values for 2014–2023.



	1961–1990	1991–2020	2014–2023	2023
UK	1023	1379	1499	1618

FIGURE 52 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 2023, adjusted for station network size and excluding stations above 500 metres 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 (1031, 1387). This is both because the adjustment for station network size has altered as a result of inclusion of year 2023, 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.

continued to intensify as it tracked across southern Scandinavia into the Baltic. Forty-six shipping containers were reported washed off a vessel of north-west Denmark.

The final storm of the year, Gerrit, arrived just after Christmas. Strong winds from this storm persisted through the 27th, 28th and 29th with the area of low pressure over northern Scotland slow to clear eastwards. The strongest winds of over 60 Kt (69 mph) were around the west coast of Wales, north-east coast of Scotland and the Northern Isles. The highest gusts included 77 Kt (89 mph) at Fair Isle, Shetland, 76 Kt (87 mph) at Mona, Isle of Anglesey, 75 Kt (86 mph) at Inverbervie, Kincardineshire, 74 Kt (85 mph) at Capel Curig, Conwy and 73 Kt (84 mph) at Lerwick, Shetland. Based on the number of stations recording 60 and 70 Kt gusts, this was the most powerful wind storm of the year to affect the UK overall. As usual, some of the main impacts related to travel disruption, for example, rail services being affected by speed restrictions and trees on the line. Thousands of properties in north-east Scotland and Shetland lost power, and in Stalybridge, Greater Manchester, a major incident was declared after around a hundred homes were damaged by a mini tornado.

As a measure of storminess Figure 60 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 Atlantic storms are large-scale systems having widespread effects which this metric is designed to capture. Localized convective gusts will not contribute, nor will storms where the strongest winds are confined to a relatively small region of the UK.

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 2023 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 the period of higher 40 Kt counts from the mid-1980s through the 1990s as shown in Figure 60 coincides with a similar period of positive phase of the winter NAO as shown in Figure 3. Since 2010, the winter NAO has mostly been positive, yet this is not reflected in the gust count. This earlier period also included some of 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 16th

TABLE 11 The snowiest days of year 2023.

Date	England (99)	Wales (20)	Scotland (54)	Northern Ireland (15)	Total (188)
01/01/2023			5		5
17/01/2023			13	1	14
18/01/2023		3	7	2	12
19/01/2023	2	3	7	4	16
20/01/2023		3	4	3	10
07/03/2023			9		9
08/03/2023	4	1	13		18
09/03/2023	6	6	11		23
10/03/2023	20	9	12	6	47
11/03/2023	8	6	7	3	24
12/03/2023	4	4	7		15
14/03/2023			5		5
02/12/2023	2		3		5
03/12/2023	7		6		13
04/12/2023	4		3		7

Note: The table lists dates where five or more stations across the UK recorded a snow depth at 09UTC ≥5 cm on that day. The table also gives a count of stations by country. The indicative number of snow observing sites in 2023 for each country (based on data availability) is also given in brackets. Colours refer to counts >10, 20, 30 stations.

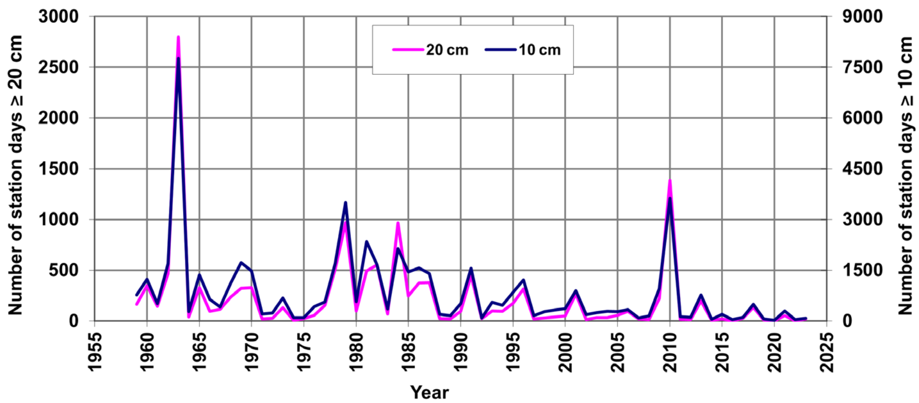
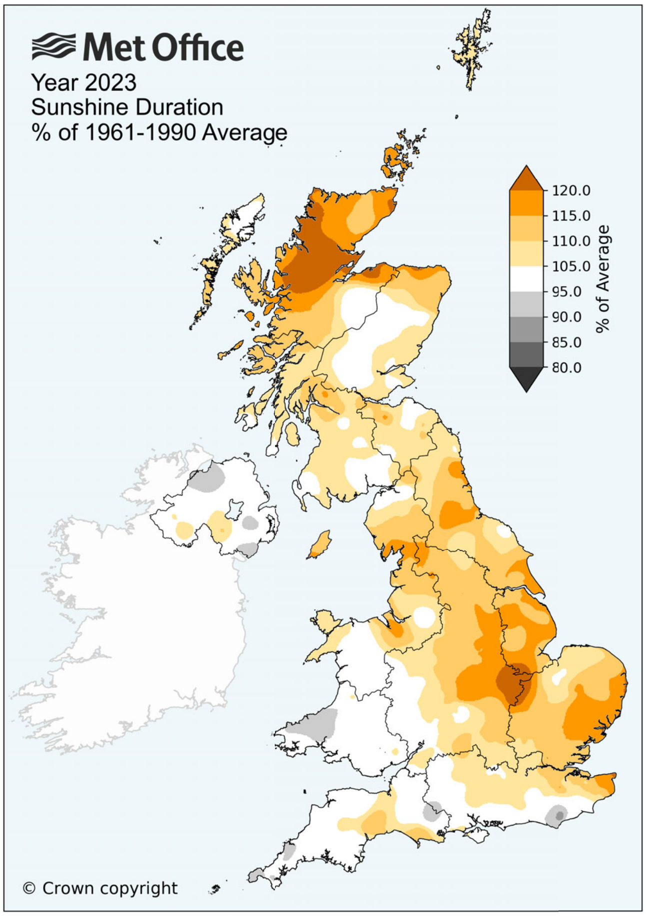
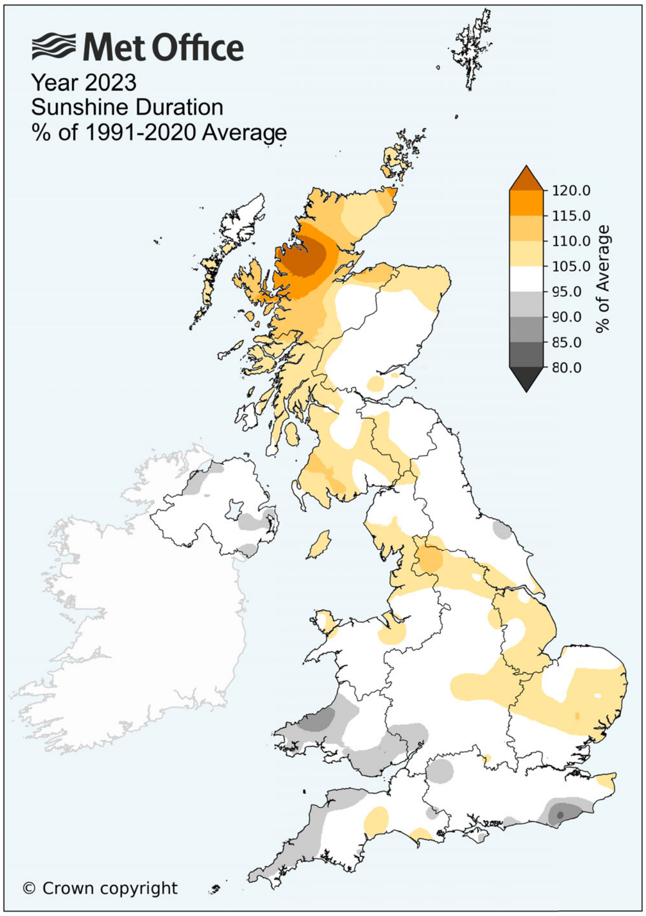


FIGURE 53 Count of number of station-days per year in the UK with recorded snow depths ≥20 cm (left hand axis) and 10 cm (right hand axis), excluding stations above 500 masl. This series has not been adjusted for network size. The 2023 values are 80 (10 cm) and 19 (20 cm).





2023	1961–1990	1991–2020
UK	108	102
England	109	101
Wales	101	97
Scotland	110	107
Northern Ireland	100	98

FIGURE 54 (a,b) Sunshine anomalies relative to 1961–1990 and 1991–2020 for year 2023. The table shows percentage of average values for the UK and countries.

October 1987. More recently, major winter storms have included 5th December 2013, 3 January 2012 and 8 December 2011 (for these three, the strongest winds being across Scotland). Storm Eunice on 18 February 2022 (for which two red warnings were issued, including London) was the most severe storm to affect England and Wales since February 2014, but even so, these storms of the 1980s and 1990s were much more severe. Any comparison of storms is complex as it depends on severity, spatial extent, and duration. Nevertheless, recent storms such as Ciarán on 1 to 2 November 2023 (which largely missed the UK to the south) and Ingunn on 1 February 2024 (which largely missed the UK to the north) are a clear reminder of the potential for exceptionally severe wind storms off the Atlantic to hit the UK. Ingunn (named by the Norwegian Meteorological Institute) was one of the most powerful wind storms in the north Atlantic in observational records, affecting Norway and Sweden.

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 60 is based comprises around 120 to 130 stations in the 1970s increasing to

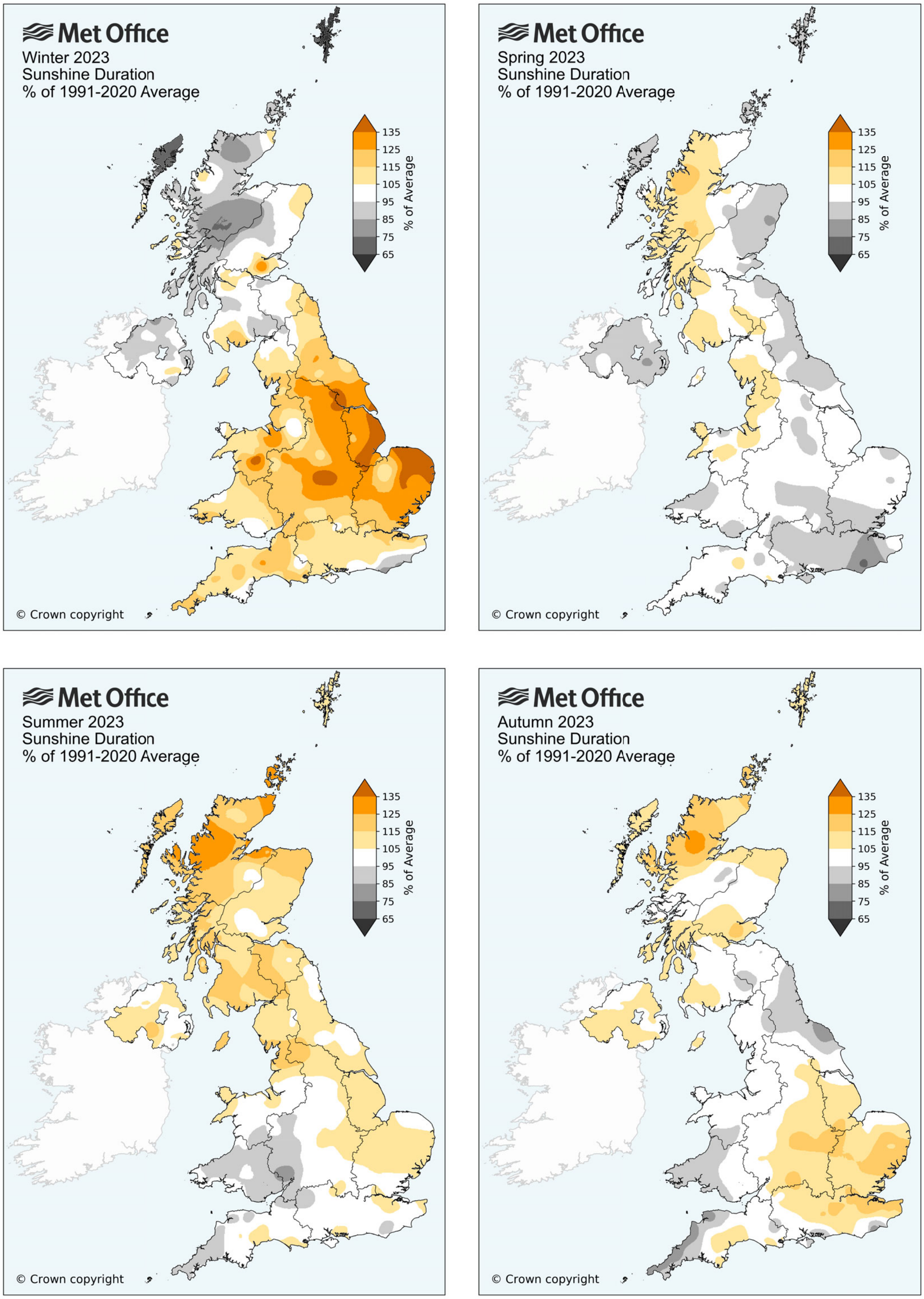


FIGURE 55 2023 seasonal sunshine anomalies relative to 1991–2020. Winter refers to the period December 2022 to February 2023.

180 stations in the 1990s before falling back to around 150 stations. Figure 60 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.

5.2 | Mean wind speed

Figure 61 shows UK annual mean wind speed from 1969 to 2023 based on the HadUK-Grid dataset. This series shows a downward trend through the 1980s and 1990s.

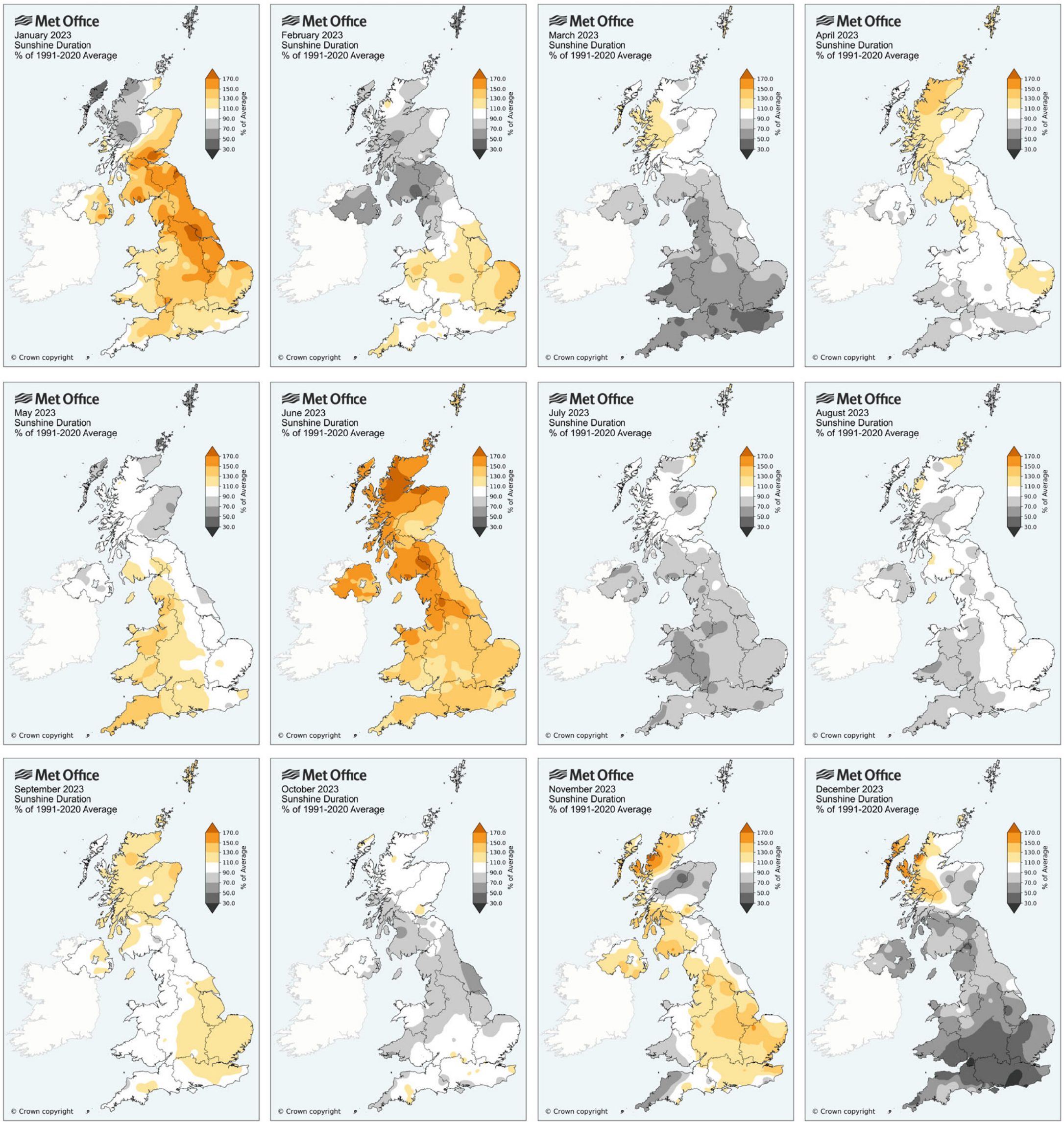


FIGURE 56 2023 monthly sunshine anomalies relative to 1991–2020. The legend scale ranges from 30% to 170%.

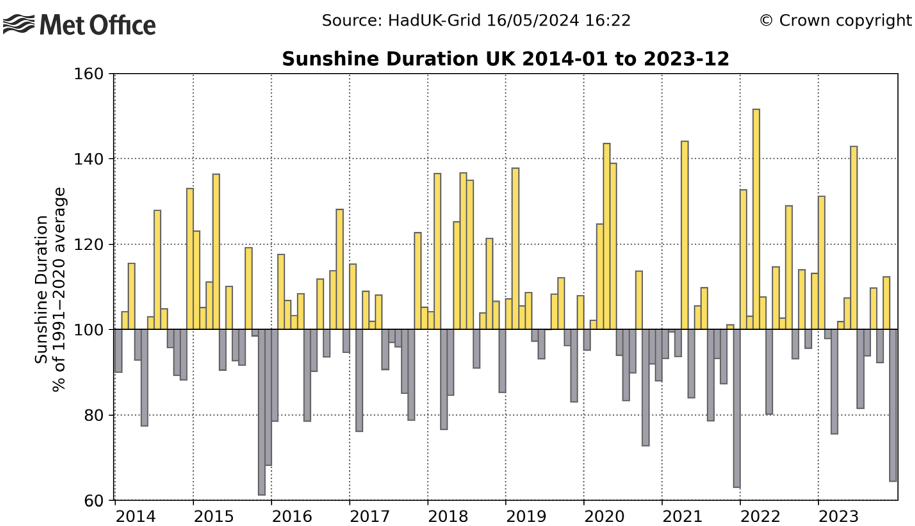


FIGURE 57 UK monthly sunshine anomalies relative to 1991–2020 for the most recent decade 2014–2023 (120 months).

TABLE 12 Monthly, seasonal and annual sunshine actual values (hours) and percentage of average values relative to 1991–2020 for the UK and countries for year 2023.

	UK		England		Wales		Scotland		Northern Ireland	
	Actual	**%**	**Actual**	**%**	**Actual**	**%**	**Actual**	**%**	**Actual**	**%**
January	62	131	76	138	56	119	42	121	49	116
February	70	98	86	110	74	108	49	77	40	60
March	82	76	77	66	66	61	96	99	84	83
April	158	102	160	98	143	90	162	114	138	93
May	206	107	225	113	244	128	170	93	173	94
June	245	143	258	138	242	136	227	155	226	150
July	141	82	155	79	125	71	129	92	104	76
August	152	94	169	94	128	80	133	99	122	90
September	140	110	154	109	129	100	122	115	123	109
October	85	92	94	92	82	90	70	94	81	95
November	65	112	75	116	52	94	51	108	64	118
December	28	64	29	56	24	57	27	90	26	68
Winter	181	112	220	120	178	113	123	95	140	95
Spring	447	98	462	96	453	99	428	102	395	91
Summer	538	106	583	103	495	96	489	116	452	107
Autumn	290	104	323	105	263	95	244	107	268	106
Annual	1435	102	1559	101	1366	97	1279	107	1230	98

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 below. The series lengths are 1910–2023 (114 years) except winter which is 1911–2023 (113 years).

The only months of the year notably windier than average were July and December (these being largely unsettled and westerly), while February to June and November were all notably less windy than average.

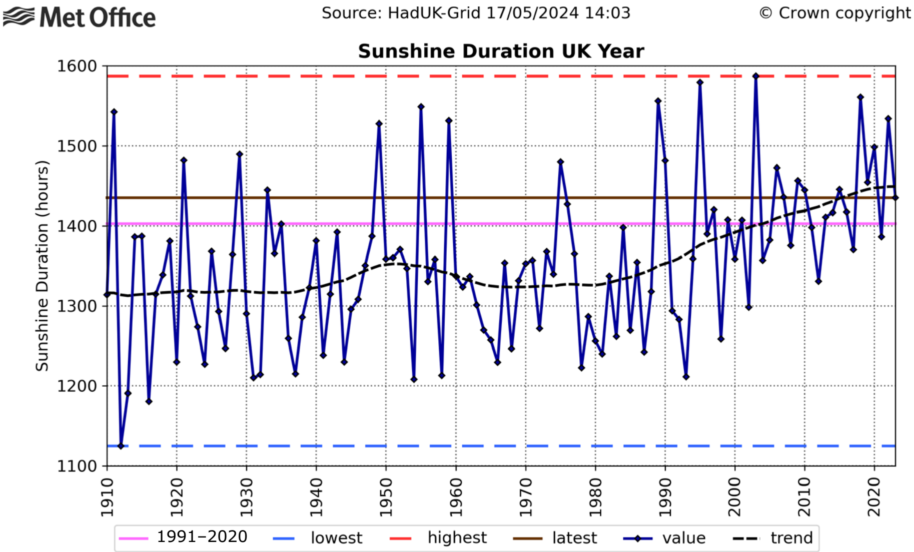
The 2021 BAMS state of the global climate report (Blunden and Boyer, 2022) shows that on a continental and global scale before around 2010 there was a widespread and general slowdown of near-surface winds termed 'global stilling'. More recently there are some indications of a reversal of this trend (Zeng et al., 2019). Blunden and 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. However, Dunn et al., 2022 show that this recent reversal of wind stilling may be lower than previous estimates (e.g., Zeng et al., 2019) due to errors in encoding of calm periods in near-surface wind speeds for many stations in Europe and Asia.

The UK mean wind speed series shown in Figure 61 broadly reflects the behaviours documented globally, although in the case of the UK the decline has slowed 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, 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

6.1 | Mean sea level

Since the beginning of the 20th century, sea levels in the UK have risen by about 1.5 ± 0.1 mm/year, but observational evidence suggests the rate is increasing (Kendon



	1961–1990	1991–2020	2014–2023	2023	2014–2023 % of 1961–1990	2014–2023 % of 1991–2020
UK	1328	1403	1452	1435	109	104
England	1430	1538	1600	1559	112	104
Wales	1352	1407	1444	1366	107	103
Scotland	1165	1200	1235	1279	106	103
Northern Ireland	1233	1255	1276	1230	103	102

FIGURE 58 Annual sunshine for the UK, 1910–2023. The table shows actual values for the UK and countries (hours) with percentage of average values for 2014–2023.

et al., 2021), which is consistent with estimate of global sea level rise (Fox-Kemper et al., 2021).

One of the UK's longest continuously-operating tide gauges is Newlyn, with observations beginning in May 1915. The State of the UK Climate reports usually includes a sea level index compiled from records from five long running tide gauges at Newlyn, Sheerness, North Shields, Aberdeen and Liverpool (e.g., Kendon et al., 2023). Unfortunately, we are unable to include that information this year, as only the gauge at Newlyn operated to a sufficient standard to produce data suitable for assessing long-term changes in sea level.

Nevertheless, the data that were available from the national UK tide gauge network suggests that 2023 was an exceptional year, with the highest annual mean on record at the long running record at Newlyn (Figure 62a) and with either the highest or second highest at all but one location returning an annual mean: Ilfracombe (Devon), Portsmouth (Hampshire), Newhaven (East Sussex), Lowestoft (Suffolk), Stornoway (Western Isles) and Port Erin (Isle of Man).

Figure 62b shows seasonal changes in sea level in Newlyn from 1915 to 2023. Sea levels were unprecedentedly high for an extended period between June and October, with four of these 5 months the highest on record. For 2023, the difference between the highest monthly mean (October) and the lowest (February) was ~37.5 cm, consistent with other sea level observations along the UK coastline. High sea levels are usually observed in autumn and winter (Bulgin et al., 2023), which could be explained by combined changes in atmospheric pressure, winds both in shallow water areas and in the deep ocean, and large-scale advected steric changes (density changes due to temperature and salinity variations). Monthly mean sea level pressure (mslp) for the UK tends to be lowest in autumn and early winter, associated with the jet stream shifting further south and introducing more active Atlantic low pressure systems at this time of year (a 1 hPa drop in pressure corresponding to 1 cm of sea level rise). UK monthly mslp anomalies can partially explain the high sea level in autumn 2023 (see Figure 2). However, the magnitude of seasonal changes varies across the country and from year to year.

There is evidence that the rate of UK sea-level rise is increasing, with the rate of sea level rise since the 1960s increasing to 2.4 ± 0.3 mm/year (Hogarth et al., 2020), from the long-term estimate of 1.5 ± 0.1 mm/year since the 1900s (Kendon et al., 2021). This change is also reflected in the record at Newlyn alone, where sea levels have risen at the rate of 2.4 ± 0.3 mm/year between 1960 and 2023 compared with 2.1 ± 0.2 mm/year over the entire length of the record (1916–2023).

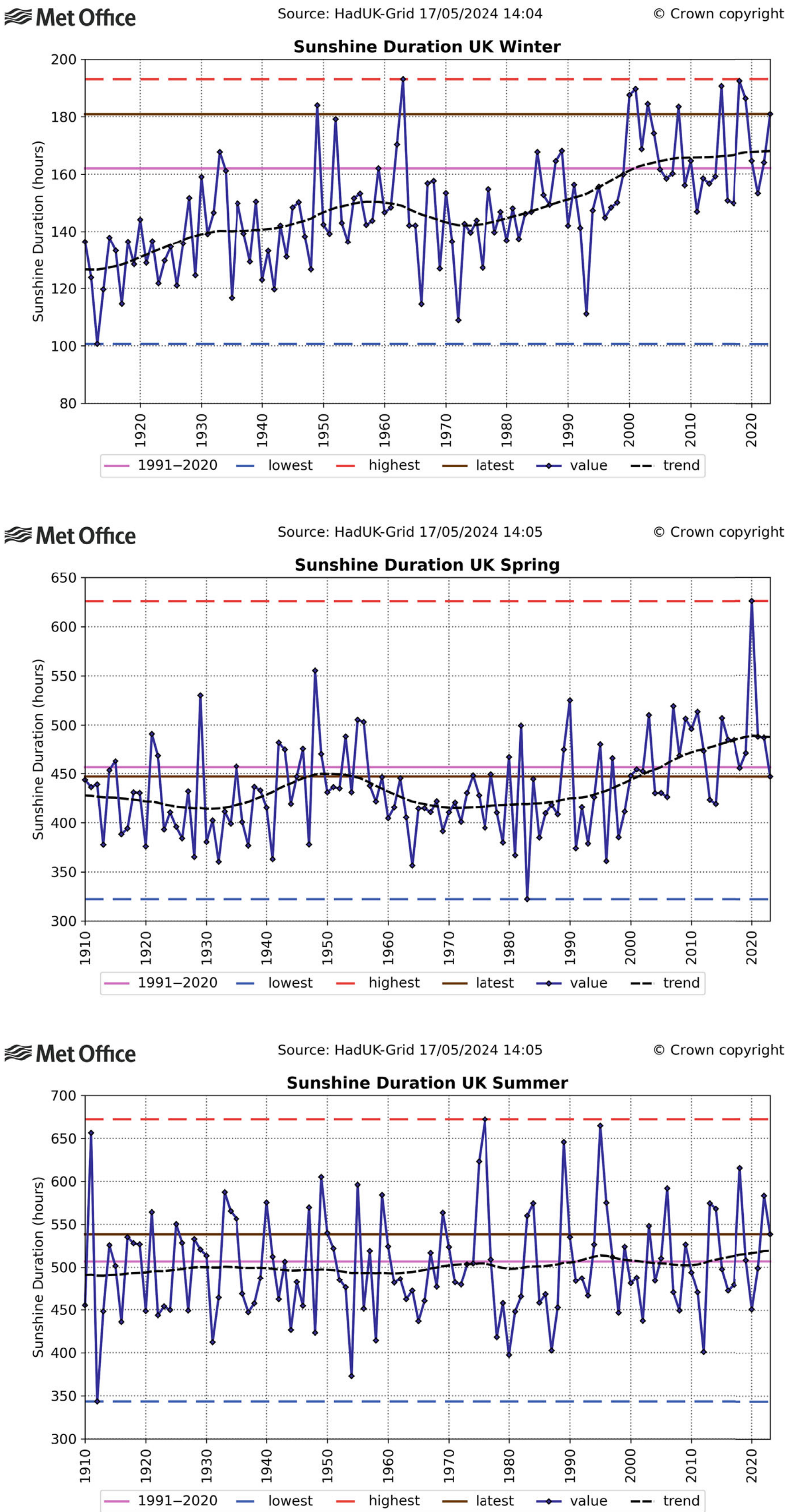
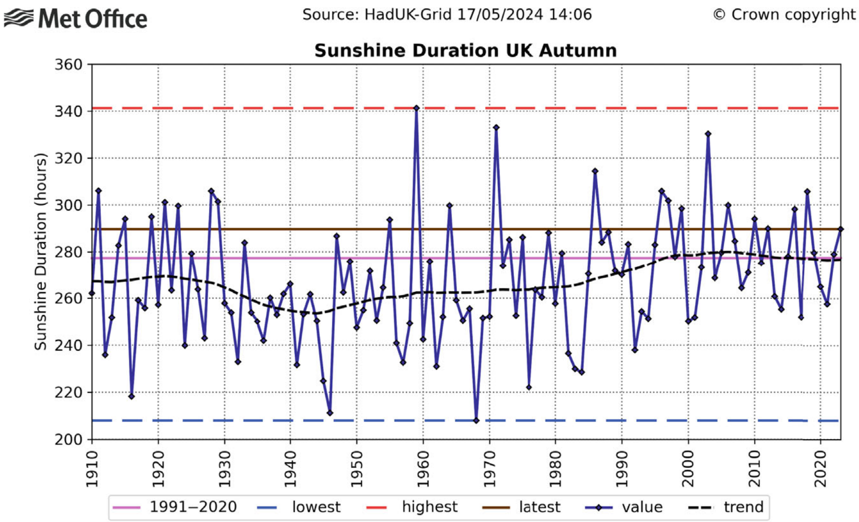


FIGURE 59 Seasonal sunshine for the UK for (a) winter, (b) spring, (c) summer, (d) autumn (overleaf) 1910–2023 (winter 1911–2023). Note the *y*-axis gridline spacing differs between the figures. The table shows actual values for the UK for each season (hours) with percentage of average values for 2014–2023.



	1961–1990	1991–2020	2014–2023	2023	2014–2023 % of 1961–1990	2014–2023 % of 1991–2020
Winter	147	162	169	181	115	104
Spring	419	457	487	447	116	107
Summer	498	507	521	538	105	103
Autumn	264	277	276	290	104	100

FIGURE 59 (Continued)

Figure 63 shows that these changes have become more pronounced in recent years, and during 1993–2023, sea level has risen at a rate of 4.6 ± 0.9 mm/year, giving a total sea-level rise since 1993 of about 14 cm, which is in good agreement with the 10.1 cm of global mean sea-level rise estimated from satellite altimetry (Johnson et al., 2023 updated).

6.2 | Extreme sea level

There were 16 extreme storm-surge events in 2023, of which 13 were associated with storms named either by the western European storm naming group (Met Office, Met Éireann and KNMI), DMI or Météo-France (see Table A5 for details). Storm surges for the UK are associated primarily with Atlantic low pressure weather systems, caused by wind stress at the sea surface and the horizontal gradient of atmospheric pressure, although the magnitude of any particular storm surge is influenced by many factors including the intensity and track of the weather system, bathymetry, and the shape of the UK coastline (Williams et al., 2016).

On 10 to 11 December storm Fergus led to skew surges (see Appendix A17 for an explanation of this term) up to 1 m in the Irish Sea, but occurred during neap tides and total water levels were not high. Storm Pia on 21 December resulted in the highest skew surges of the year observed in southeast England (Cromer, Norfolk 1.2 m, Lowestoft, Suffolk 1.5 m, Harwich, Essex 1.4 m, Sheerness, Kent 1.2 m and Dover 1 m) with >1 m modelled widespread across the North Sea. Despite Pia occurring during a neap tide, Harwich and Lowestoft recorded their maximum total sea level for the year (Figure 64c,e).

During storm Gerrit on 27 December there were widespread positive skew surges (0.5–1 m) in the west of the UK. Combined with a moderate spring tide this event led to the highest levels of the year at Millport, Ayrshire (near Glasgow). This event was also notable for negative surges (approaching −1 m) in the North Sea (Figure 64d,f). The contrast in skew surge patterns between storms Pia and Gerrit corresponds to the contrasting track of these two storms, with north-westerly winds from storm Pia and south-westerly winds from storm Gerrit (Figure 64a,b).

There were several named storms in August and September, not often observed at this time of year. Storms Antoni and Betty in August did not lead to significant storm surges. During storm Agnes on 27 September, there were high skew surges in north-west England (Workington, Cumbria 0.9 m), Scotland (Millport, Ayrshire 0.9 m, Portpatrick, Galloway 0.8 m) and Northern Ireland (Bangor, County Down 0.8 m). Agnes led to the highest totals of the year in Northern Ireland where the tidal range is small.

TABLE 13 The windiest days of year 2023.

Date	England (99)	Wales (11)	Scotland (33)	Northern Ireland (17)	Total (160)	Named storm
06/01/2023	3	1	6		10	
10/01/2023	3	4	5	2	14	
11/01/2023	8	8	3		19	
12/01/2023	19	9	1	3	32	
13/01/2023	8	4			12	
14/01/2023	8	2	5		15	
15/01/2023	7	3	1	1	12	
31/01/2023			11		11	
17/02/2023	9		21	1	31	Otto (DMI)
19/02/2023	1		10		11	
13/03/2023	16	10	1		27	
11/04/2023	15	10	1		26	Noa (Météo-France)
12/04/2023	19	9			28	Noa (Météo-France)
20/09/2023	4	7	3		14	
27/09/2023	5	9	1	2	17	Agnes
19/10/2023	2		13		15	Babet
20/10/2023	7		6	2	15	Babet
01/11/2023	5	3	2		10	Ciarán
02/11/2023	13	1			14	Ciarán
13/11/2023	13	9	1	2	25	Debi (Met Éireann)
23/11/2023	1	1	11		13	
09/12/2023	9	5		2	16	Elin (Met Éireann)
10/12/2023	4	9			13	Fergus (Met Éireann)
21/12/2023	29	4	25	5	63	Pia (DMI)
24/12/2023	9	3	15	1	28	
27/12/2023	16	11	16	2	45	Gerrit
28/12/2023	16	11	3		30	Gerrit
30/12/2023	8	4	2	3	17	
31/12/2023	6	3	3		12	

Note: The table lists dates where 10 or more stations across the UK recorded a maximum wind gust greater than or equal to 50 Kt (58 mph) on that day. The table also gives a count of stations by country. The indicative number of wind observing sites in 2023 for each country (based on data availability) is also given in brackets. Colours refer to counts >10, 20 and 30 stations.

Extreme sea levels in the UK are a combination of storm surge, waves, tide and mean sea level. If Agnes had been a few days later, the spring tide on 1 October would have led to very high total levels (e.g., 1 m higher at Heysham, Lancashire). Storm Ciarán also fell on moderate tides, so despite widespread skew surges of (0.5–1 m) the total water level was not high at most sites. In the Channel Islands, the modelled skew surge at Jersey was around 1 m, and Jersey was severely affected by wave damage, but unfortunately no tide gauge data was transmitted during that week. The highest level of 2023 was recorded at Bournemouth.

The moderate (0.5–1 m) skew surge on west and north coast of UK on 23 March was not associated with any named storm but coincided with the equinoctial spring tide, leading to this being the highest recorded level of the year at 18 sites in Scotland, Wales and the west coast of England.

The highest levels of 2023 observed on several east coast sites were not linked to any particular storms or meteorological conditions, but were due to September spring tides. In south and south-west England and south-west Wales the highest total sea-levels were also not associated with a named storm, but a spring tide combined with the sustained period of high mean sea-level throughout late October and early November (see Figure 62b). Additional figures with observations and operational surge modelling for all named storms of the year, and the three skew surges not associated with named storms, are available in Williams (2024). Highlighted storms and other high levels are listed in the Appendix A17 Tables A5 and A6.

TABLE 14 UK named storms of 2023.

Name	Date of impact on UK
Otto	17 February (named by Danish Meteorological Institute, DMI)*
Noa	11 to 12 April (named by Météo-France)*
Antoni	5 August
Betty	18 to 19 August
Agnes	27 to 28 September
Babet	18 to 21 October
Ciarán	1 to 2 November
Debi	13 November (named by Met Éireann)
Elin	9 December (named by Met Éireann)
Fergus	10 December (named by Met Éireann)
Pia	21 December (named by Danish Meteorological Institute, DMI)*
Gerrit	27 to 28 December

Note: Asterisks indicates notable storms named by other national meteorological services outside the Met Office storm naming group (Met Office, Met Éireann and KNMI) under different naming schemes. Named storms Antoni and Betty did not meet the count threshold used in Table 13.

7 | EXTREMES

7.1 | Annual extremes

Table 15 shows the UK weather extremes for year 2023. The highest temperature of the year, 33.5°C at Faversham, Kent on 10 September is described in the events Section 9.2. This was fairly modest compared with other years of the most recent decade, half of which have exceeded 35°C. The UK's highest annual maximum has occurred in September on only a handful of previous occasions in observational records, most recently in 2016. Although notably high for September, 33.5°C fell well short of the UK September record of 35.6°C set at Bawtry, South Yorkshire on 2 September 1906, with another higher value only 7 years previously: 34.4°C at Gravesend, Kent on 13 September 2016. The maximum for summer months were June (32.2°C), July (30.2°C) and August (28.4°C). Temperatures of 30°C in August are perhaps less common than might be expected, having failed to be reached in 2023, 2021, 2017 or 2014. The UK's highest daily minimum temperature also occurred in early September at two coastal stations (September was the warmest month of the year for UK near-coast SST with 15.7°C—see Figure 73).

The lowest minimum and grass minimum temperatures occurred in early March, in an Arctic airmass with clear skies, light winds and lying snow (as is typically the case for these annual extremes). The fact that the UK's highest and lowest temperatures of the year occurred outside the summer and winter months demonstrates the

TABLE 15 Annual extremes for the UK for year 2023.

Extreme	Observation	Date	Station
Highest daily maximum temperature (09–09 UTC)	33.5°C	10 September	Faversham, Kent, 46 masl
Lowest daily minimum temperature (09–09 UTC)	−16.0°C	9 March	Altnaharra, Sutherland, 81 masl
Lowest daily maximum temperature (09–09 UTC)	−4.0°C	2 December	Balmoral, Aberdeenshire, 283 masl
Highest daily minimum temperature (09–09 UTC)	20.5°C	7 September	Ventnor Park, Isle of Wight, 60masl
Lowest grass minimum temperature (09–09 UTC)	−19.4°C	8 March	Braemar, Aberdeenshire, 327 masl
Highest daily rainfall (09–09 UTC)	173.4 mm	19 October	Stonyford, Aberdeenshire, 195 masl
Greatest snow depth (09 UTC)	34 cm	18 January 19 January	Loch Glascarnoch, Ross and Cromarty, 269 masl
Highest daily sunshine	16.9 h	15 June	Loch of Hundland, Orkney, 28 masl
Highest gust speed	83 Kt 96 mph	12 April	Needles Old Battery, Isle of Wight, 80 masl
Highest gust speed (mountain)	107 Kt 123 mph	27 December	Cairngorm Summit, Inverness-shire 1237 masl

Note: Stations above 500 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. Channel Islands stations are excluded.

variable nature of the UK's climate. The greatest snow depth on 18 and 19 January was as a result of steady accumulation over the previous days from the 15th from persistent snow showers in a northerly airstream.

The highest daily rainfall occurred during storm Babet in which a red warning for rain was issued (see Section 9.4 for more details of this event). The highest rainfall total of the year would typically be associated with either orographic enhancement of frontal rainfall in a westerly Atlantic flow across western Scotland, the Cumbrian Fells or Snowdonia, particularly when an active front becomes stationary for a prolonged period (as, e.g., in 2021 and 2022), or, less commonly, a highly localized extreme convective rainfall event (as, e.g., in Norfolk in August 2020). Unusually, however, the 173.4 mm total at Stonyford was due to extreme orographic enhancement in an easterly

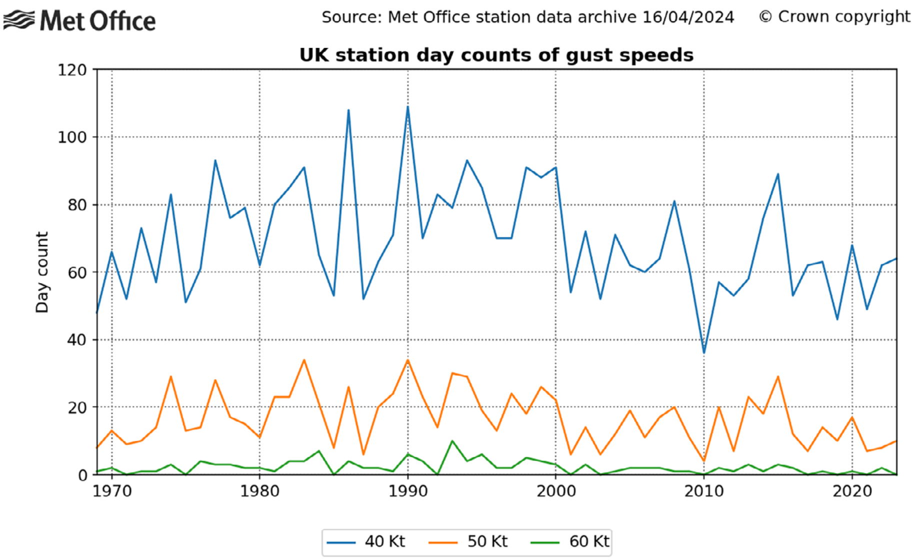
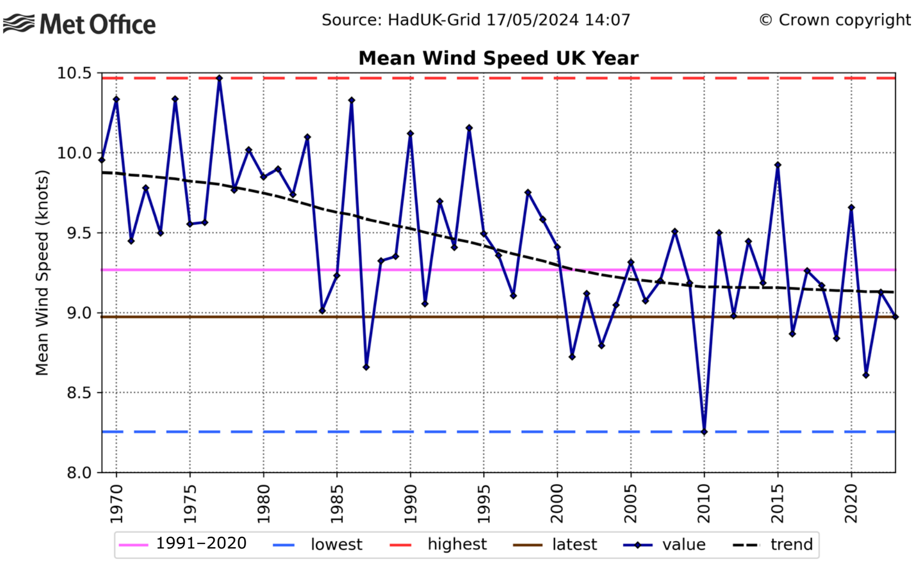


FIGURE 60 Count of the number of individual days each year during which max gust speeds ≥40, 50 and 60 Kt (46, 58, 69 mph; 74, 93, 111 kph) have been recorded by at least 20 or more UK stations, from 1969 to 2023. Stations above 500 masl are excluded. The counts for 2023 are 64 (40 Kt), 10 (50 Kt) and 0 (60 Kt). The 10 individual days in 2023 in which at least 20 stations recorded gusts ≥50 Kt are listed in Table 13, the majority of these being named storms.



	1991–2020	2014–2023	2023
UK	9.3	9.2	9.0
England	8.3	8.2	8.1
Wales	9.9	9.7	9.7
Scotland	10.7	10.7	10.3
Northern Ireland	8.5	8.6	8.4

FIGURE 61 Annual mean windspeed for the UK, 1969–2023. The table shows actual values for the UK and countries (Kt).

flow, affecting eastern Scotland (i.e., the reverse of the normal direction).

The highest gust speed was at Needles Old Battery, Isle of Wight, during storm Noa (named by Météo-France). This station is located at the western end of the Isle of Wight, at 80 masl at the top of a cliff and is fully exposed to westerly winds blowing up the English Channel. As a consequence it has recorded the UK's highest gust speed across all except mountain stations for a number of recent years. However, it is not very representative of southern England. The highest gust speed at a mountain station was at Cairngorm Summit during storm Gerrit (see Section 9.6).

Figures 65 and 66 show the UK's highest maximum and lowest minimum temperatures, by year, across all stations, from 1900. The UK's average highest maximum temperature for the most recent decade 2014–2023 was 35.6°C, 2.1°C higher than 1991–2020 and 4.3°C higher than 1961–1990—these changes being much greater than the equivalent increases for the UK annual mean temperature (0.42°C and 1.25°C) (Table 2, Figure 11). 35.6°C (the average highest maximum temperature for 2014–2023) was exceeded in 4 years of the 20th century (1911, 1932, 1976 and 1990), whereas in the 21st Century so far it has already been reached or exceeded in 7 years: 2003, 2006, 2015, 2018, 2019, 2020 and 2022.

The UK's average lowest minimum temperature for the most recent decade 2014–2023 was −14.6°C, 0.9°C higher than 1991–2020 and 4.4°C higher than 1961–1990. The period 1961–1990 included some particularly extreme cold spells with temperatures falling to −20°C or lower 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. The trends shown in these station series are likely to be affected by station data availability, particularly before the 1960s, since a lower station network density will be less able to capture extremes.

7.2 | Monthly temperature extremes

Castlederg, County Tyrone recorded a daily maximum temperature of 28.0°C on 8 September, a new Northern Ireland highest daily maximum temperature record for

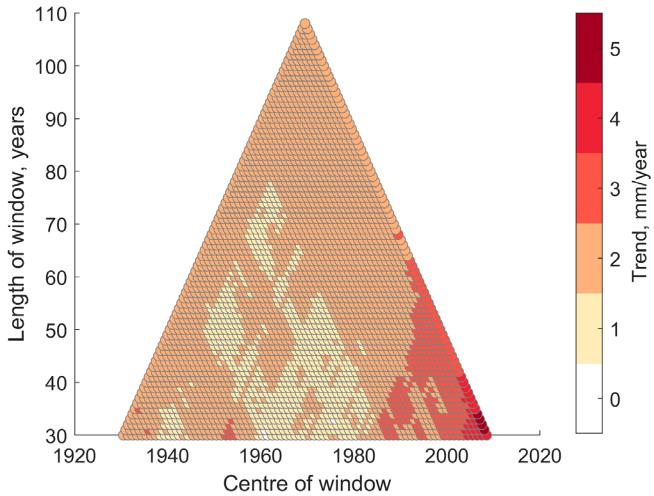


FIGURE 63 Trends at Newlyn fitted over all possible windows at least 30 years long between 1915 and 2023. Each point represents one window, with the value on the horizontal axis representing the centre of the window, the value on the vertical axis representing the length of the window, and the colour of the point encoding the value of the trend. So, for example, the point at (1960–1961) represents the trend over the period 1930–1990.

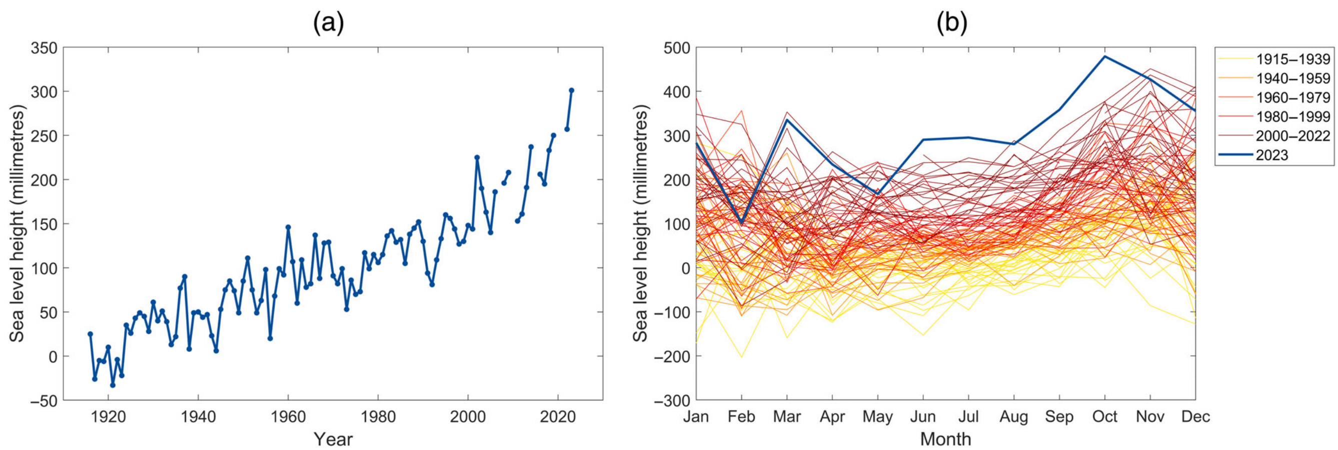


FIGURE 62 (a) Annual mean sea level at Newlyn, Cornwall, 1916–2023 with 2007, 2010, 2015, 2020 and 2021 missing due to insufficient data. (b) Monthly means at Newlyn, 1915–2023. Each individual year plotted as a single line coloured by year. Heights are millimetres above Ordnance Datum Newlyn (ODN), based on mean sea level at Newlyn 1915–1921.

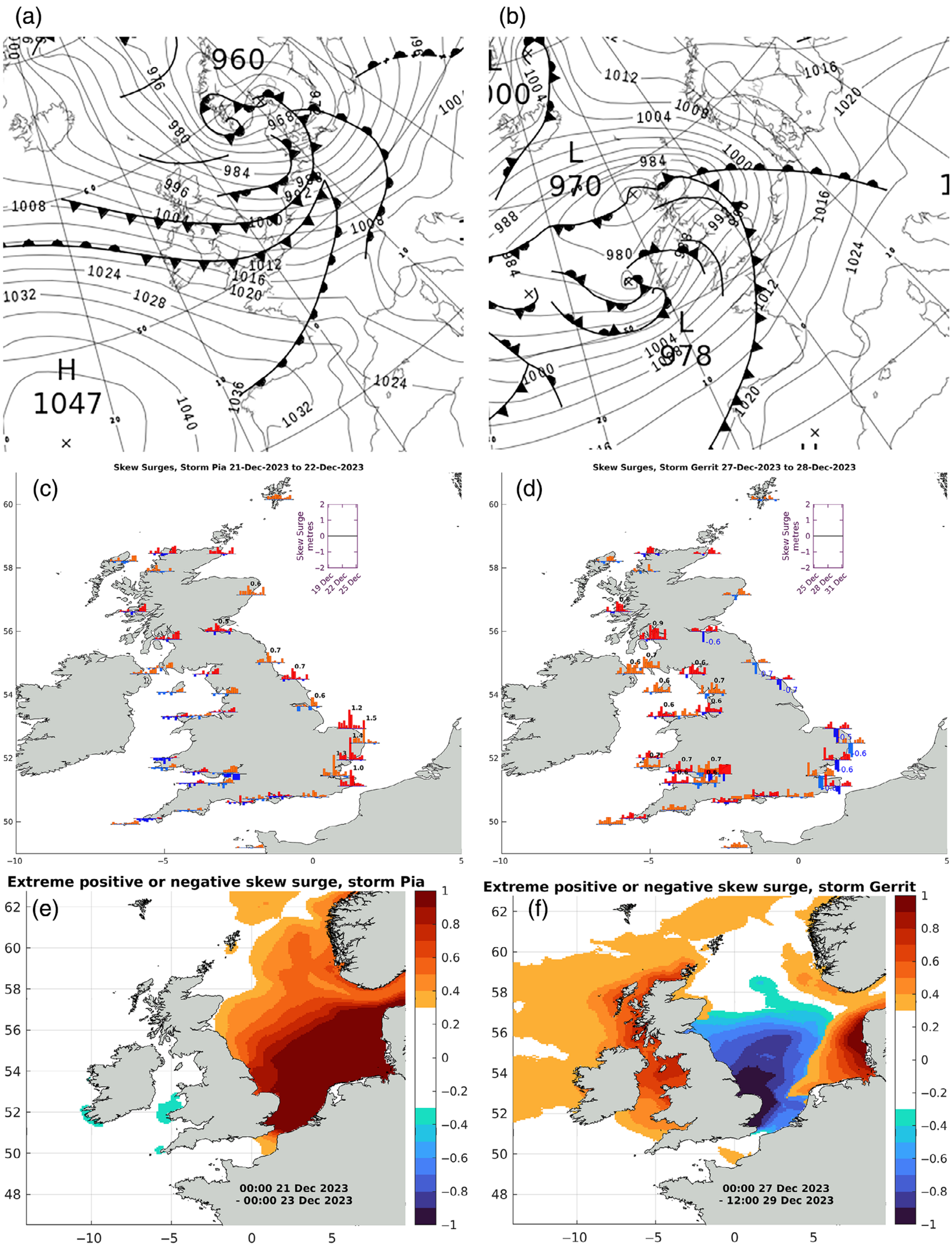


FIGURE 64 (a,b) Analysis chart at 1200 UTC 21 December 2023 (storm Pia) and 1800 UTC 27 December 2023 (storm Gerrit). (c,d) Skew surge from tide gauge observations. (e,f) Skew surge from storm surge model of storms Pia and Gerrit. Pia caused high skew surges on the east coast, in the North Sea. Gerrit was high on the west coast and lower levels than the predicted tide on the east. The model used here is the NEMO surge and tide operational model (Furner et al., 2016), and it shows patterns of extreme skew surges in open water that correspond well with observed extremes.

September, exceeding 27.6°C at Armagh on 1 September 1906.

Prestatyn, Denbighshire recorded a daily minimum temperature of 20.0°C on 25 June, a new Wales highest daily minimum temperature record for June, exceeding 19.9°C at Swansea, Victoria Park on 30 June 1976.

Portglenone, County Antrim recorded a daily minimum temperature of 17.5°C on 14 June, equalling the Northern Ireland highest daily minimum temperature record for June, at Annaghmore, County Armagh on 18 June 2005.

All official UK station records are available on the Met Office website at https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-extremes. For more details of the verification process for these records, see Appendix A7.

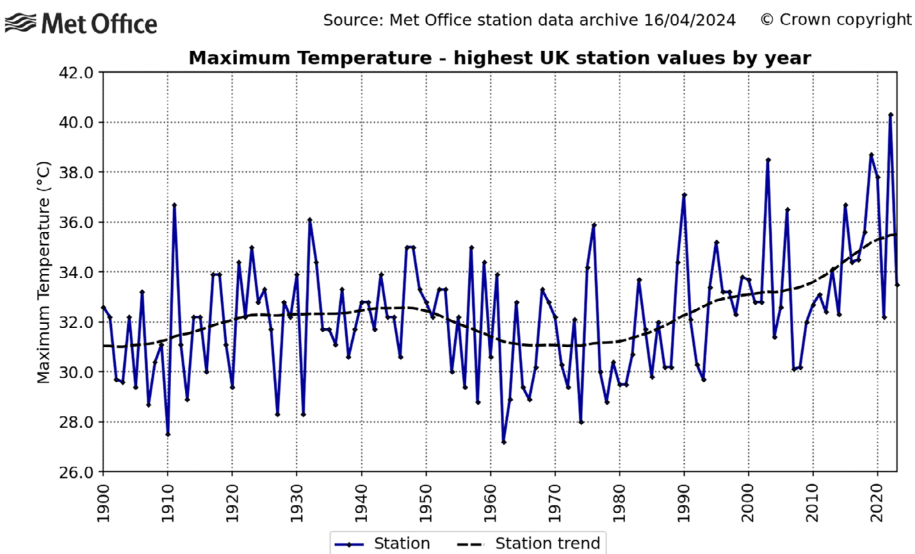
8 | CLIMATE CHANGE CONTEXT

8.1 | Temperature

An attribution study was carried out to quantify the influence of human-caused climate change on the likelihood of reaching a UK annual average temperature at or above that recorded in 2023 (Ciavarella and McCarthy, 2024). The method used an established Met Office system for rapid attribution of extreme events (Christidis, 2021). The analysis used observed values of the UK annual temperature and near surface temperature data for the UK from 14 climate model simulations from the sixth phase of the global coupled model intercomparison project (CMIP6, Eyring et al. 2016). One set of model simulations used only natural climate forcings ('NAT') for the period 1850–2020, while another set used all natural and human-caused forcings ('ALL') for the historical period and the SSP2-4.5 emissions scenario, often described as a 'medium' emissions scenario, out to 2100. These simulations provide estimates of the likelihood of the UK annual temperature exceeding the observed 2023 value for the following scenarios: A natural climate without human-caused greenhouse gases; the current climate taken as a 20-year period centred on 2023; an end-of-century climate under a medium emissions scenario taken as the period 2081–2100.

The estimated return period for a UK annual average temperature exceeding 9.97°C in the NAT simulations was once every 460 years (with a range of 82–587). For the ALL simulations in the present day, this fell to once every 3 years (with a range of 2.86–3.17). For the ALL simulations in the future, it fell further, meaning an annual mean temperature like 2023 being exceeded more frequently than every other year. Human-caused climate change is therefore estimated to have increased the likelihood of a year as warm as 2023 by a factor of more than 150.

Figure 67 plots annual T_{mean} for the UK from 1884 to 2023 alongside UK climate projections (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 RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (Murphy et al., 2018, Harris et al., 2022). RCPs

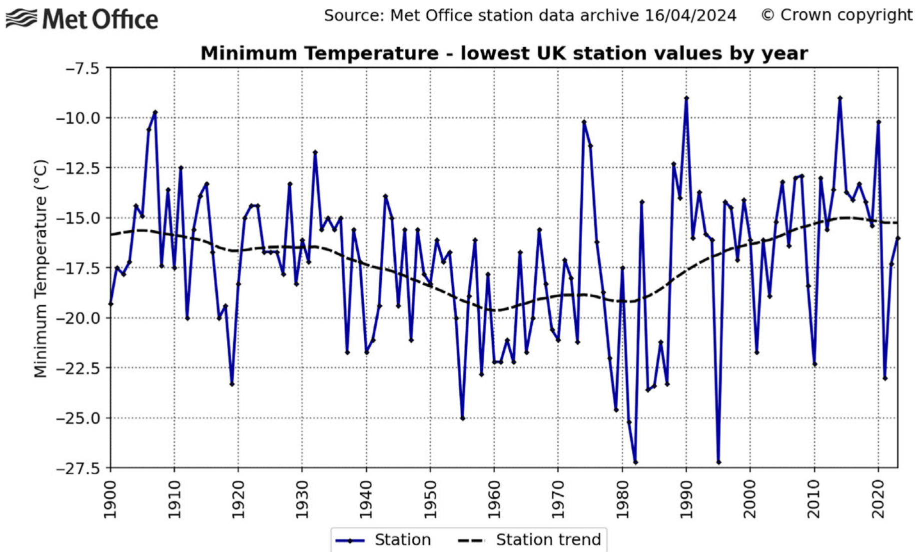


	1961–1990	1991–2020	2014–2023	2023
T_{max}	31.3	33.5	35.6	33.5

FIGURE 65 UK highest maximum temperature station observations for each year 1900 to 2023. The table shows actual values (°C). The figure shows the evolution of 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). Not all values have been manually checked, and values may change as further data are digitized.

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 shows 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 (50th percentile), ranging from +0.4°C to +4.2°C (5th to 95th percentiles). Under the RCP 4.5 scenario a year such as 2023 (anomaly +0.83°C, the UK's second warmest year



	1961–1990	1991–2020	2014–2023	2023
T_{min}	−19.0	−15.5	−14.6	−16.0

FIGURE 66 UK lowest minimum temperature station observations for each year 1900 to 2023. The table shows actual values (°C). The figure shows the national record in 1982 and 1995 (−27.2°)—which also occurred in 1895. Not all values have been manually checked, and values may change as further data are digitized.

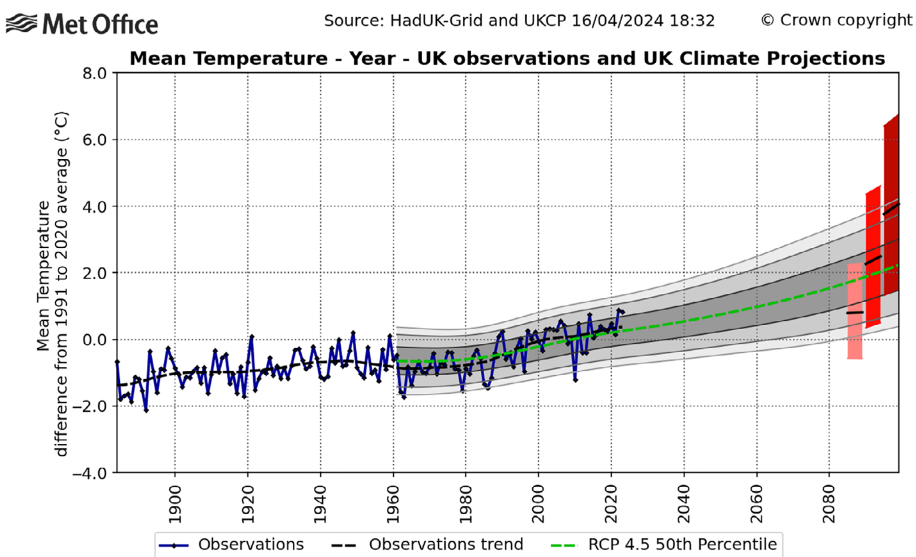


FIGURE 67 Annual mean temperature for the UK, 1884–2023 and UK Climate Projections plume plot 1961–2100 as anomalies relative to 1991–2020 showing Representative Concentration Pathway (RCP) 4.5. The grey shading shows the 5–95 percentile, 10–90 percentile, and 25–75 percentile ranges. Other scenarios 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.

on record) would be considered an average year by the 2050s and 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 16). For comparison, the future UK climate projections 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 around 4°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 the UK's 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, more than 3°C warmer than 2023. This difference of 3°C is comparable to that between the UK's warmest and coldest years on record, 1892 and 2022 (Figure 11).

The attribution study results are, unsurprisingly, similar to an equivalent study reported in last year's report on the record-breaking annual mean temperature of 2022 (Kendon et al., 2023). The study indicates that, despite being the warmest and second warmest years on record, 2022 and 2023 are not necessarily extreme in the context of the UK's current climate and therefore emphasizes that observations alone do not provide the full context for year 2023. An important implication of the study is that there is the potential for a far higher UK annual average temperature, not just in the future but also in the present-day climate. Taken together, the attribution study and climate projections show that

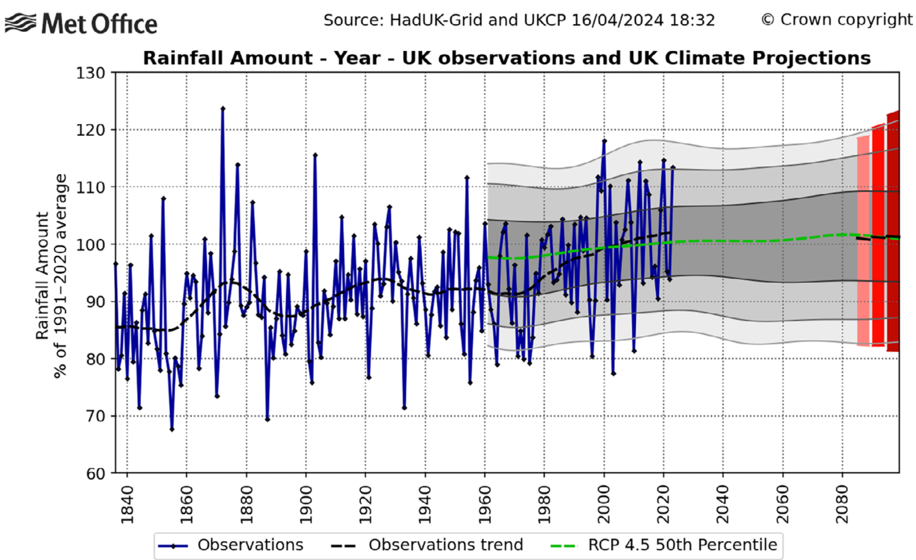


FIGURE 68 Annual rainfall for the UK, 1836–2023 and UK Climate Projections plume plot 1961–2100 as anomalies relative to 1991–2020 showing Representative Concentration Pathway (RCP) 4.5. The grey shading shows the 5–95 percentile, 10–90 percentile and 25–75 percentile ranges. Other scenarios RCP 2.6 (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.

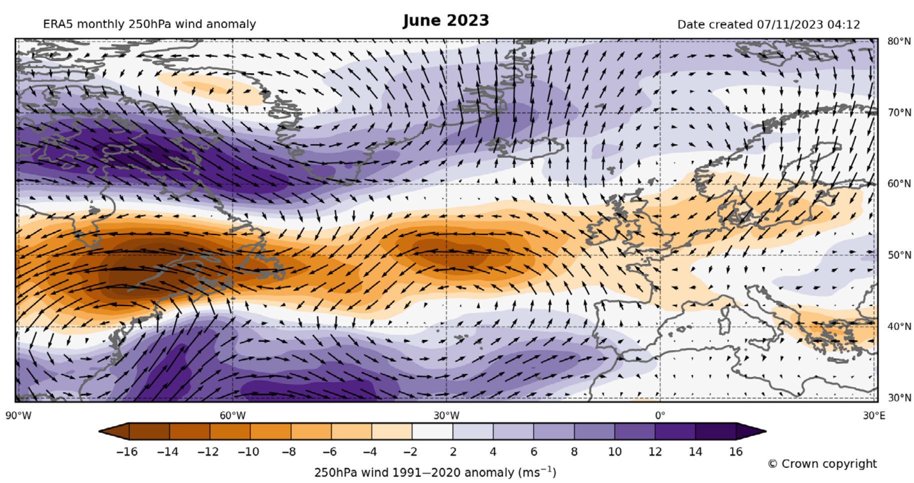


FIGURE 69 June 2023 wind anomalies (ms^{-1}) at 250 hPa relative to the 1991–2020 average using the ERA5 reanalysis (Hersbach et al., 2020). 250 hPa is a level of equal pressure equivalent to a height of ∼10,500 km at the level of the jet stream.

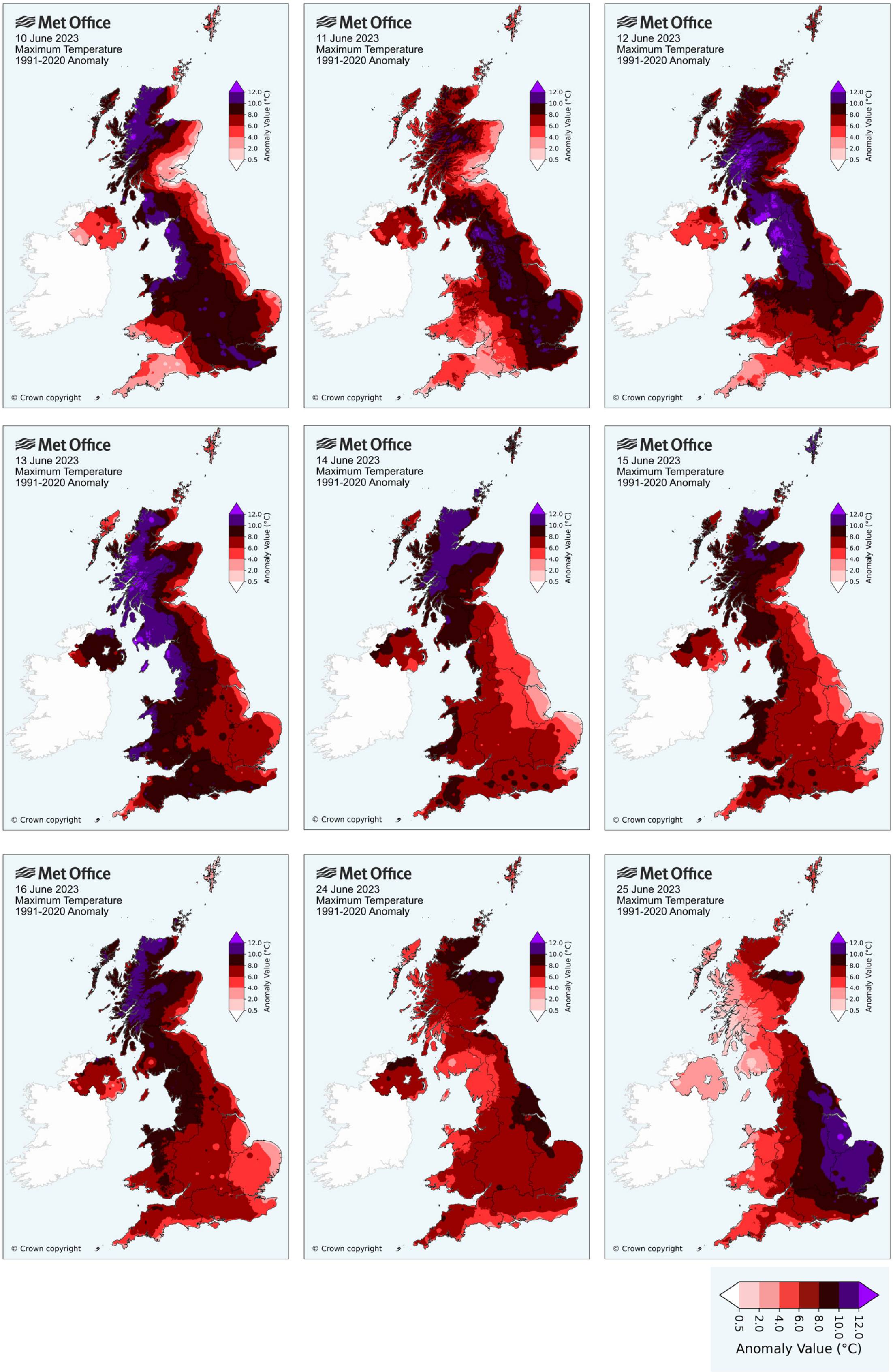


FIGURE 70 The hottest days of June 2023: daily maximum temperature anomalies (°C) relative to the 1991–2020 June average for the week of 10 to 16 June, plus 24 and 25 June.

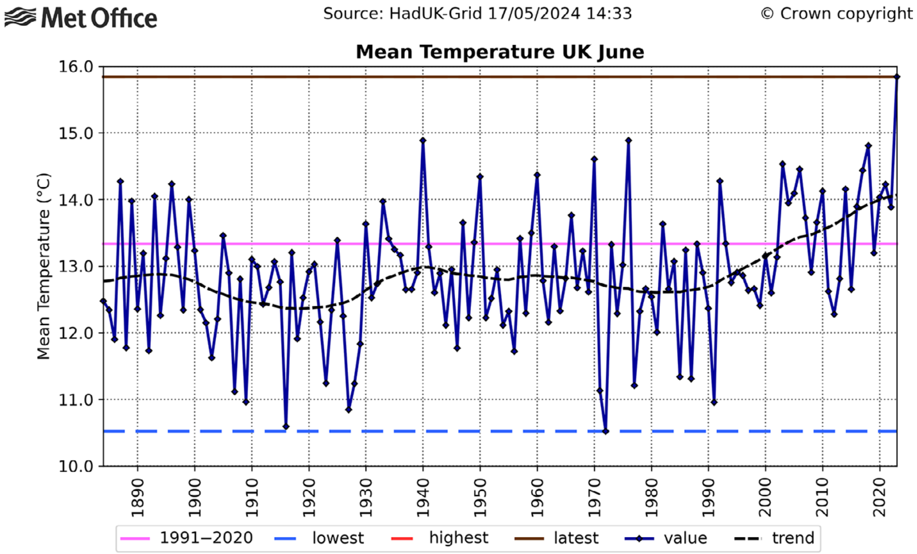


FIGURE 71 June mean temperature for the UK (°C), 1884–2023.

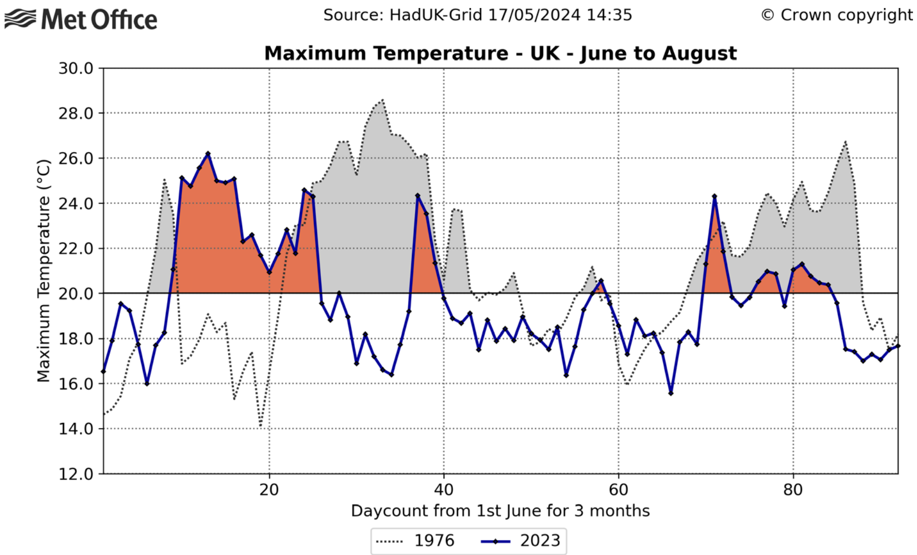


FIGURE 72 UK mean maximum temperature for summer 2023 and summer 1976 compared. The shading shows periods with an average maximum temperature above 20°C in 2023 (red) and 1976 (grey). For UK mean maximum temperature, the hottest day of June 2023 was the 13th with an average daily maximum temperature of 26.2°C.

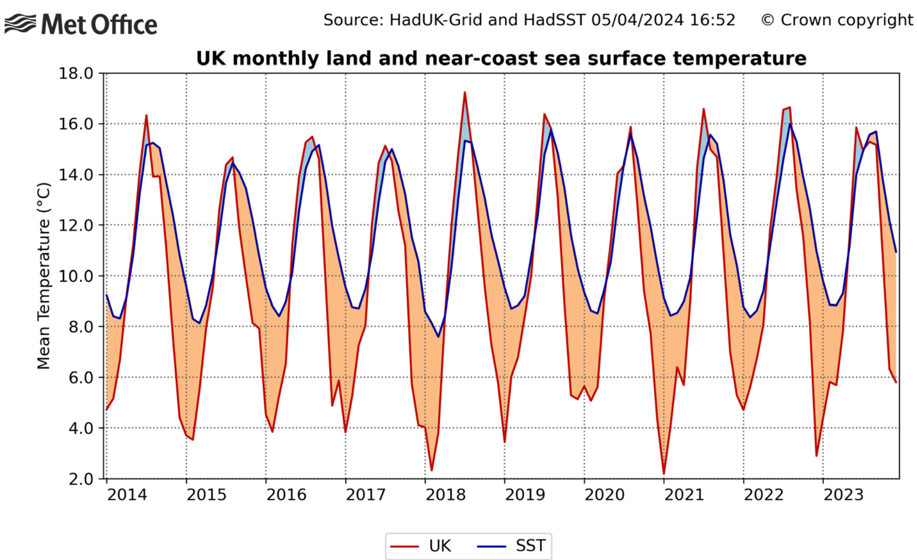


FIGURE 73 UK monthly mean temperature over land and monthly mean sea surface temperature (SST) across near-coastal waters around the UK (°C) for the most recent decade 2014–2023 as actual values. The difference between the two series is shaded pale red where UK near-coast SST is higher than UK air temperature over land, and pale blue where it is lower.

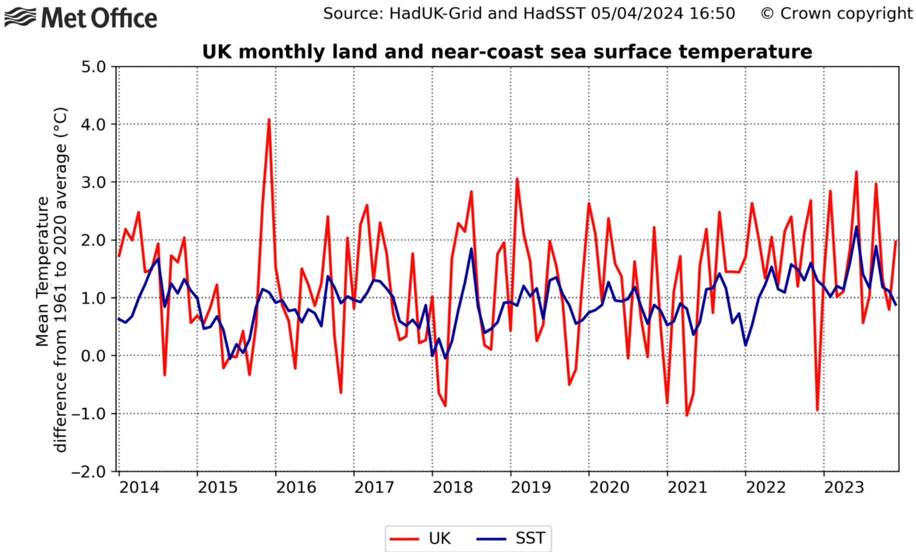


FIGURE 74 UK monthly mean temperature over land and monthly mean sea surface temperature (SST) across near-coastal waters around the UK for the most recent decade 2014–2023 as anomalies relative to the 1961–1990 monthly average (°C).

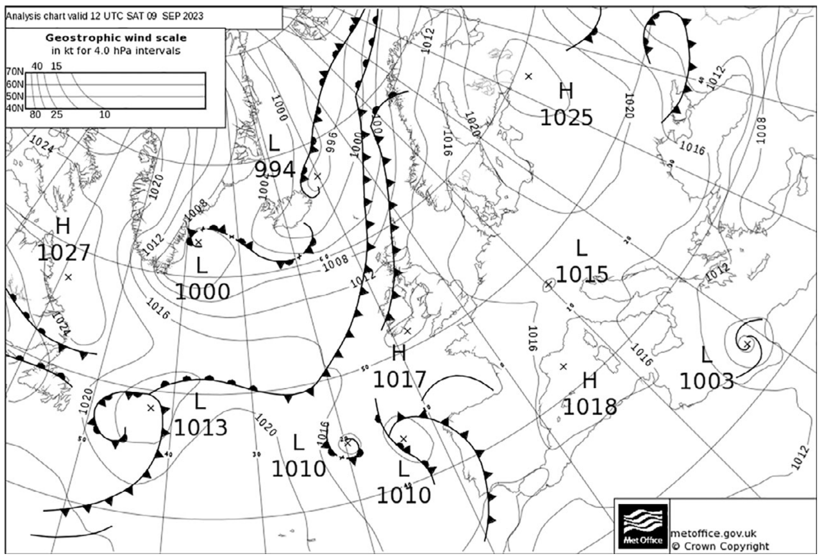


FIGURE 75 Analysis chart at 1200 UTC 9 September 2023.

years like 2022 or 2023 should not be regarded as unusual and will be increasingly likely in coming decades. By 2100, under an intermediate scenario, many if not most years will be as warm and some potentially much warmer.

8.2 | Rainfall

Figure 68 similarly plots annual rainfall for the UK from 1836 to 2023 alongside UK climate projections (UKCP) from 1961 to 2100. As for Figure 67, 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 with 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 emission scenarios. The other major difference when compared with temperature is the range of 5th to 95th percentiles by 2100 is still within that of the observations,

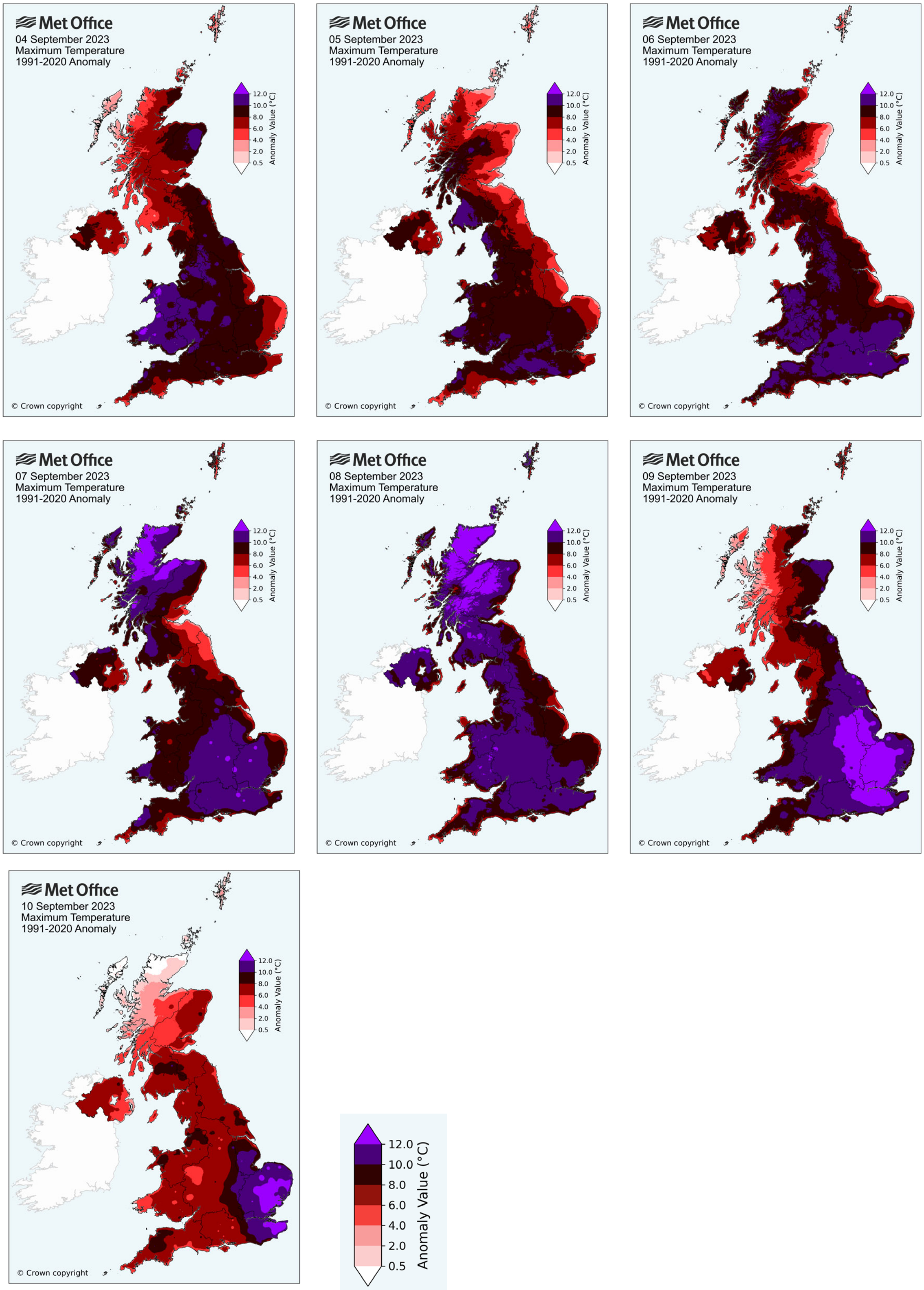


FIGURE 76 The hottest days of September 2023: daily maximum temperature anomalies (°C) relative to the 1991–2020 September average for the week of 4–10 September.

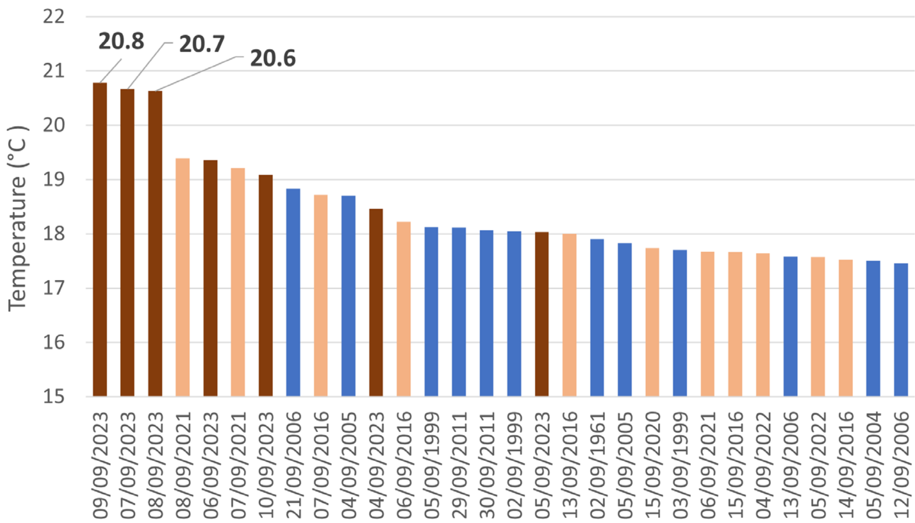


FIGURE 77 UK daily mean temperature (°C) for the 30 hottest days of September from 1960 to 2023, with bars shaded dark brown occurring in 2023, bars shaded pale orange other years in the most recent decade 2014–2023 and bars shaded blue earlier years.

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 with 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

This section describes notable weather events which occurred during 2023. 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 2023 is also included in the Section 5 of this report.

9.1 | Record warm June

June was a fine, warm and settled month across the UK. Pressure was higher than normal, with Atlantic weather fronts mostly blocked and an anomalous south-easterly flow at high level (Figure 69). Figure 70 shows daily maximum temperature anomalies for the week of 10th to 16th, and the 24th and 25th June 2023 relative to the June 1991–2020 average. The highest anomalies during the week of the 10th, exceeding 12°C, were mostly in the west and north, with cooler conditions further east due to easterly winds off the North Sea—for example, 29.9°C at Crosby, Merseyside compared with 17.7°C at Donna Nook, Lincolnshire on the 13th. The 24th and 25th were also very warm (Figure 70). The heat and humidity led to outbreaks of thunderstorms at times.

The UK recorded its warmest June in the series from 1884 by a margin of over 0.9°C (Figure 71) and it was the warmest June across all four nations. The likelihood of a UK June mean temperature exceeding 14.9°C, the previous UK June temperature record (set in Junes of 1940 and 1976) has at least doubled (comparing 1991–2020 to 1925–1955, the 30-year period centred on 1940) with a ~3% chance of being exceeded in the current climate (Lowe and Wallace, 2023).

Figure 72 compares UK average daily maximum temperatures for summer 2023 and summer 1976. The main heatwave of June 2023 occurred much earlier in the month, whereas in 1976 it started much later but then extended to the second half of July—with a further heatwave in August. The highest June temperature in 2023 (32.2°C) was relatively modest compared with June 1976 (35.6°C).

In the CET series from 1659, the Junes of 1846, 1676, 1826 and 1822 were all warmer than 2023 (but, similar to the UK series, neither 1976 nor 1940) (1976, 1846 and 1822 were all warmer in the Oxford Radcliffe series from 1814)—emphasizing the importance of multi-century series for long term context.

A significant contributing factor for this event was a major North Atlantic marine heatwave, which brought record-breaking temperatures in the North Atlantic and around the UK. A severe marine heatwave was declared in mid-June, which further amplified temperatures over the UK land. This may have contributed a 0.6°C increase in the UK mean temperature for June (Berthou et al., 2023). Figures 73 and 74 show monthly UK air temperature over land and near-coast SST averaged over the most recent decade 2014–2023 as actuals and anomalies relative to the 1961–1990 monthly average. See Appendix A11 for details of the UK near-coast SST series. UK near-coast SST is warmer on average than UK land (1991–2020 average 11.4°C compared with 9.1°C), with a lag in the annual temperature cycle compared with UK land and the maximum difference in early winter of around +5°C. The variability of UK near-coast SST monthly anomalies is less than half that of UK land. In the most recent decade there were 13 months with the UK mean temperature below the 1961–1990 monthly average, compared with only 3 months for near-coast SST.

The June 2023 near-coast SST monthly anomaly (+2.2°C) was the highest of any month in the most recent decade, coinciding with the highest June UK land anomaly. While there are some other months in the most recent decade where peaks in anomalies coincide (e.g., July 2018 and September 2023), others do not and overall these monthly anomaly series are only weakly correlated (R^2 0.24).

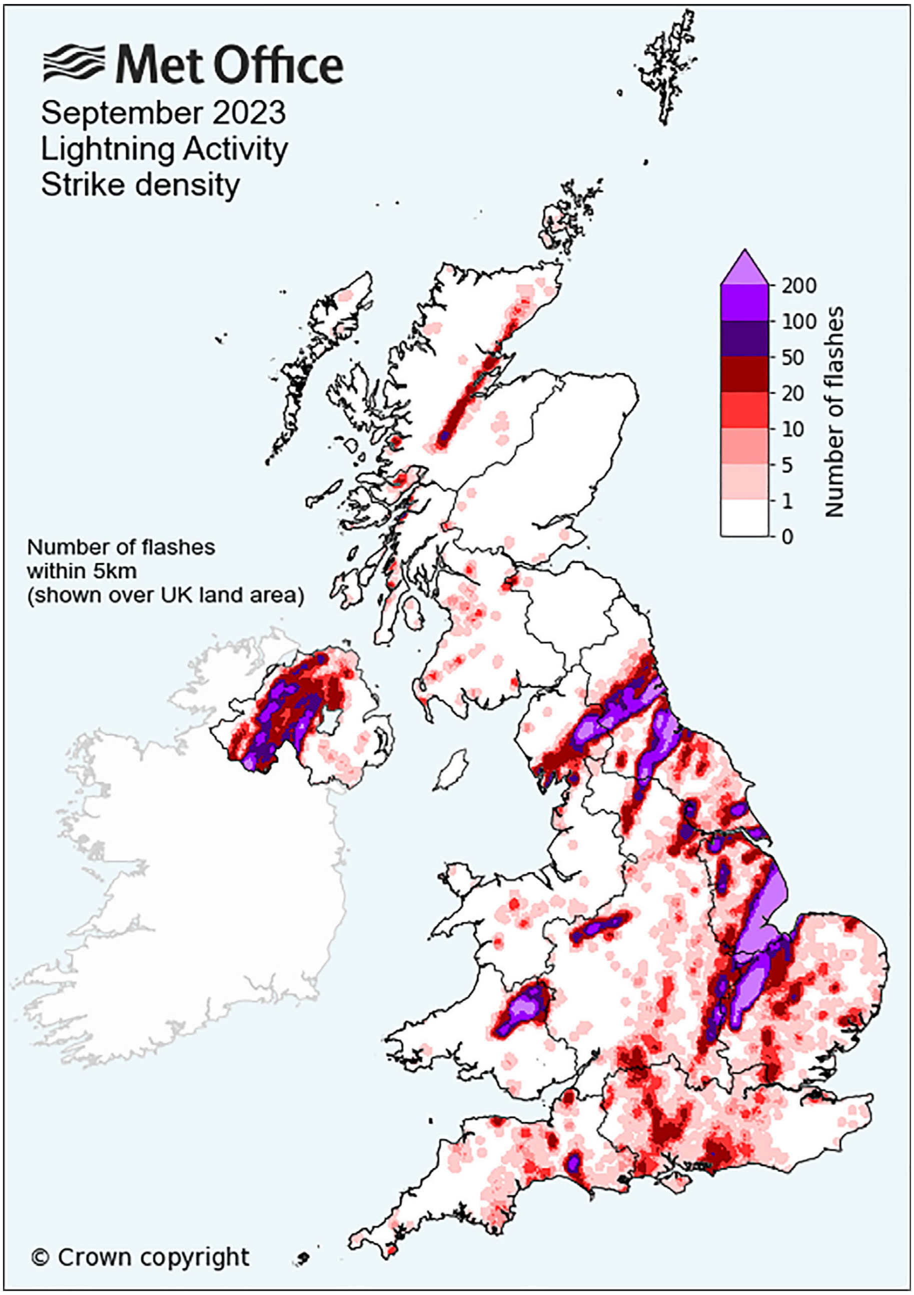


FIGURE 78 Number of lightning flashes recorded across the UK (within a distance of 5 km) during September 2023. Data are from the Met Office operational long range lightning location system LEELA (Lightning Electromagnetic Emission Location by Arrival time difference) consisting of 10 sensors located across Europe.

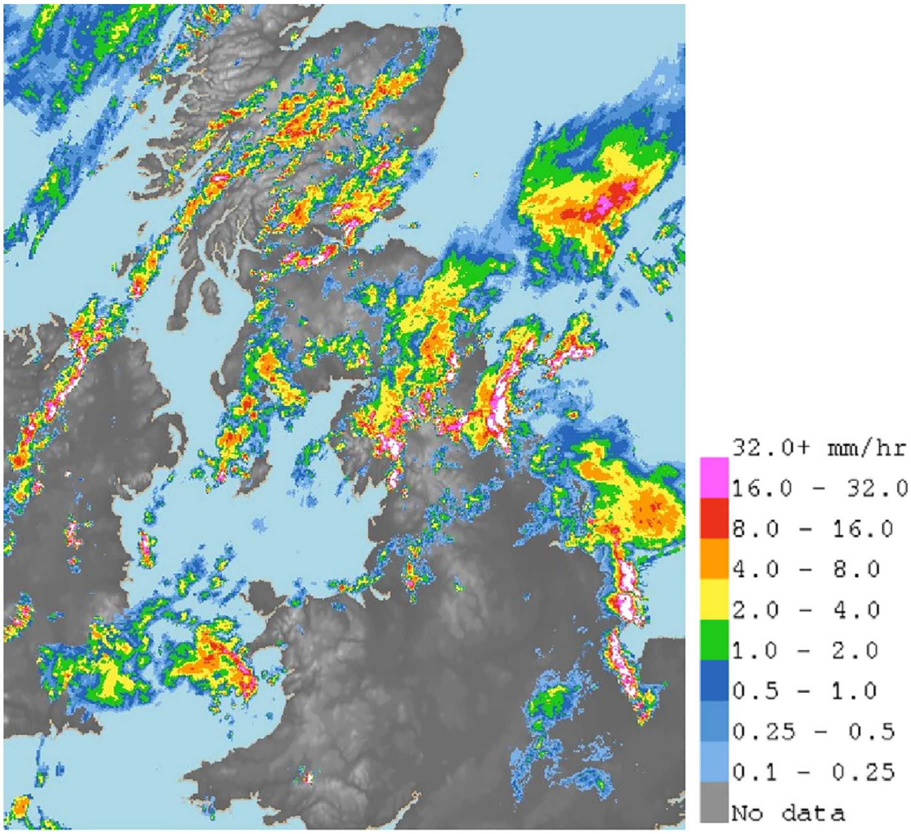


FIGURE 79 UK rain-radar image at 1700 UTC 10 September 2023. Areas in white indicate rainfall rates exceeding 32 mm/h. These locations align with the areas of most dense recorded lightning flashes as shown in Figure 78.

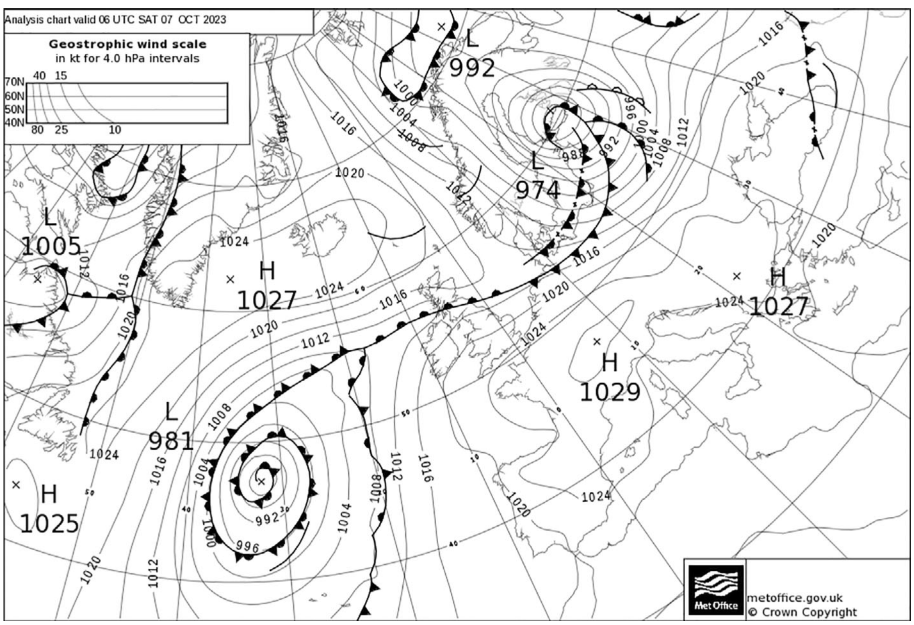


FIGURE 80 Analysis chart at 0600 UTC 7 October 2023.

9.2 | September heatwave

In early September, the jet stream shifted to the north allowing high pressure to build across the UK with a light southerly flow bringing a hot Tropical Continental Airmass (Figure 75). This pattern is fairly typical of heatwave conditions for the UK, and resulted in hot, dry, sunny weather. Former tropical cyclone Franklin amplified this build-up of high pressure as it moved north-east into the North Atlantic early in the month.

Temperatures exceeded 30°C somewhere in England each day of the week of Monday 4 to Sunday 10 September, and in west Wales on the 4th. Figure 76

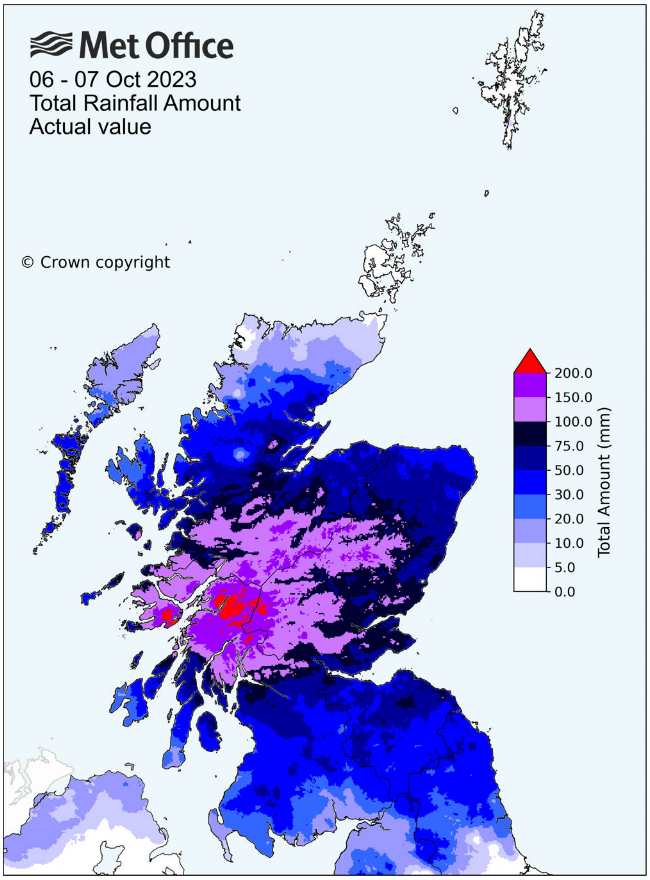


FIGURE 81 Daily rainfall totals (mm) across Scotland 6–7 October 2023.

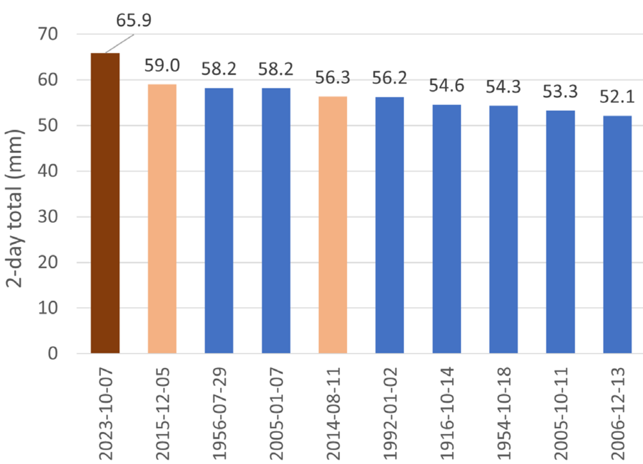


FIGURE 82 Scotland's 10 wettest independent 2-day periods on record, from 1891 to 2023. The date is the end day. Bars shaded pale orange are other years in the most recent decade 2014–2023 and bars shaded blue are earlier years.

shows daily maximum temperature anomalies relative to the 1991–2020 September average for this spell. On 7th and 8th, maximum temperatures across northern Scotland reached 27°C–29°C, around 12°C above the September 1991–2020 average in this area, while a new September Northern Ireland temperature record of 28.0°C was set on 8th (Section 7.2). On 9th and 10th, maximum temperatures across south-east England reached 31°C–32°C, more than 12°C above the September average in this area including the UK's highest temperature of the year, 33.5°C on 10th—unusually late in the year (Section 7.1).

This heatwave would not have been particularly unusual had it occurred during the high summer months (July or August), but the 7-day run of 30°C in 2023 was, for September, the longest such run in the UK's observational records, exceeding the 5 days of 1929 and 1911. A number of stations with 100+ year records recorded their hottest September day, including Armagh (County Armagh), Lerwick (Shetland), Wisley (Surrey), Balmoral (Aberdeenshire), Wick Airport (Caithness), Woburn (Bedfordshire), Cranwell (Lincolnshire) and Leuchars (Fife). Stornoway Airport, Western Isles and Durham recorded their highest September temperatures since 1 September 1906, and Sheffield and Oxford since 8 September 1911.

The UK's daily mean temperature exceeded 20°C for three consecutive days from 7 to 9 September, making these the UK's three warmest September days on record by a wide margin, based on a daily series from 1960; half the UK's top-ten warmest September days in this series occurred during this spell (Figure 77). This statistic must be interpreted cautiously however because it is highly probable that one or more September days before 1960 may have been warmer for the UK overall. In particular, on 1 September 1906 the temperature exceeded 32°C as far as northern Scotland with 32.2°C at Gordon Castle, Moray and 32°C–33°C widely across England. The warmest September days in the CET daily maximum temperature series from 1878 were 1 and 2 September 1906, each more than 2°C warmer than any day in September 2023, while September 1911 was also warmer for CET T_{max}. Examples like this demonstrate the importance of further data digitization to help extend the daily HadUK-Grid dataset further back before 1960 to capture more historical extremes and provide longer-term context.

UK recorded its equal-warmest September on record in the series from 1884, shared with 2006. England and Wales each recorded their warmest September on record, and it was also warmest in the September CET series from 1659. An attribution analysis by Wallace and Pirret (2023) found that a September this warm would be exceptionally unlikely in a natural climate, but with a 3% chance of reaching or exceeding it in the current climate.

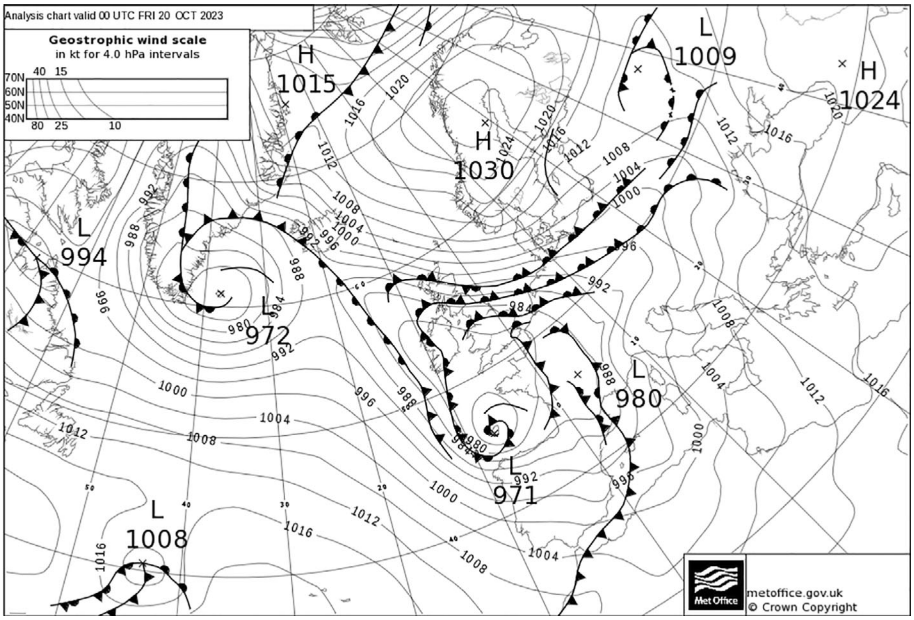


FIGURE 83 Analysis chart at 0000 UTC 20 October 2023.

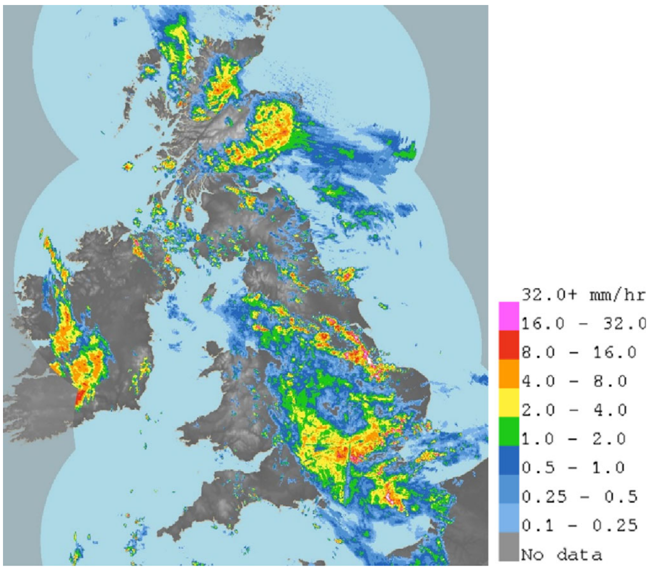


FIGURE 84 UK rain-radar image at 0000 UTC 20 October 2023.

While the right combination of factors is still needed, climate change is making such late-season warmth more likely.

The heat and humidity from this heatwave made uncomfortable conditions for the elderly and vulnerable and difficult conditions for sleeping at night. Despite the often cool and rather unsettled weather in July and August, 2023 overall saw the third highest heat-associated mortality for the UK based on a series of monitoring reports from 2016 (HSA, 2024). Of the five heat episodes identified in the HSA report in 2023, the period from 3 to 13 September was the longest and had the highest total heat-associated mortality.

As so often happens in the UK, the heat and humidity led to some intense thunderstorms with lightning and torrential downpours. Figure 78 shows the north-easterly track of these thunderstorms. Figure 79 shows some of the more intense storms across northern and eastern England on 10 September. Several rain-gauges across Cumbria, County Durham, Tyne & Wear and Northumberland recorded hourly rainfall totals of between 20 and 30 mm/h including, for example, 29.4 mm at Harpington Hill Farm and 26.4 mm at Darlington, both County Durham. Flash flooding and lightning strikes from these storms caused significant impacts.

9.3 | Scotland's wettest 2-day period

Much of Scotland experienced widespread and prolonged rainfall from 6 to 7 October 2023 from an 'atmospheric river'—a narrow stream of moisture laden air capable of causing very high rainfall totals. Figure 80 shows the frontal system associated with this rain, marking the boundary between warm air to the south and much colder air to the north. On 7 October, daily maximum temperatures reached 25.7°C at Faversham, Kent, but only 7.7°C at Aviemore, Inverness-shire.

The wettest area was across a swathe of the southern and central Highlands, with 100–150 mm falling widely over this 2-day period (Figure 81). High rainfall totals also extended further east to Perth and Kinross, Stirling and Falkirk, Angus and Fife with over 75 mm falling at some

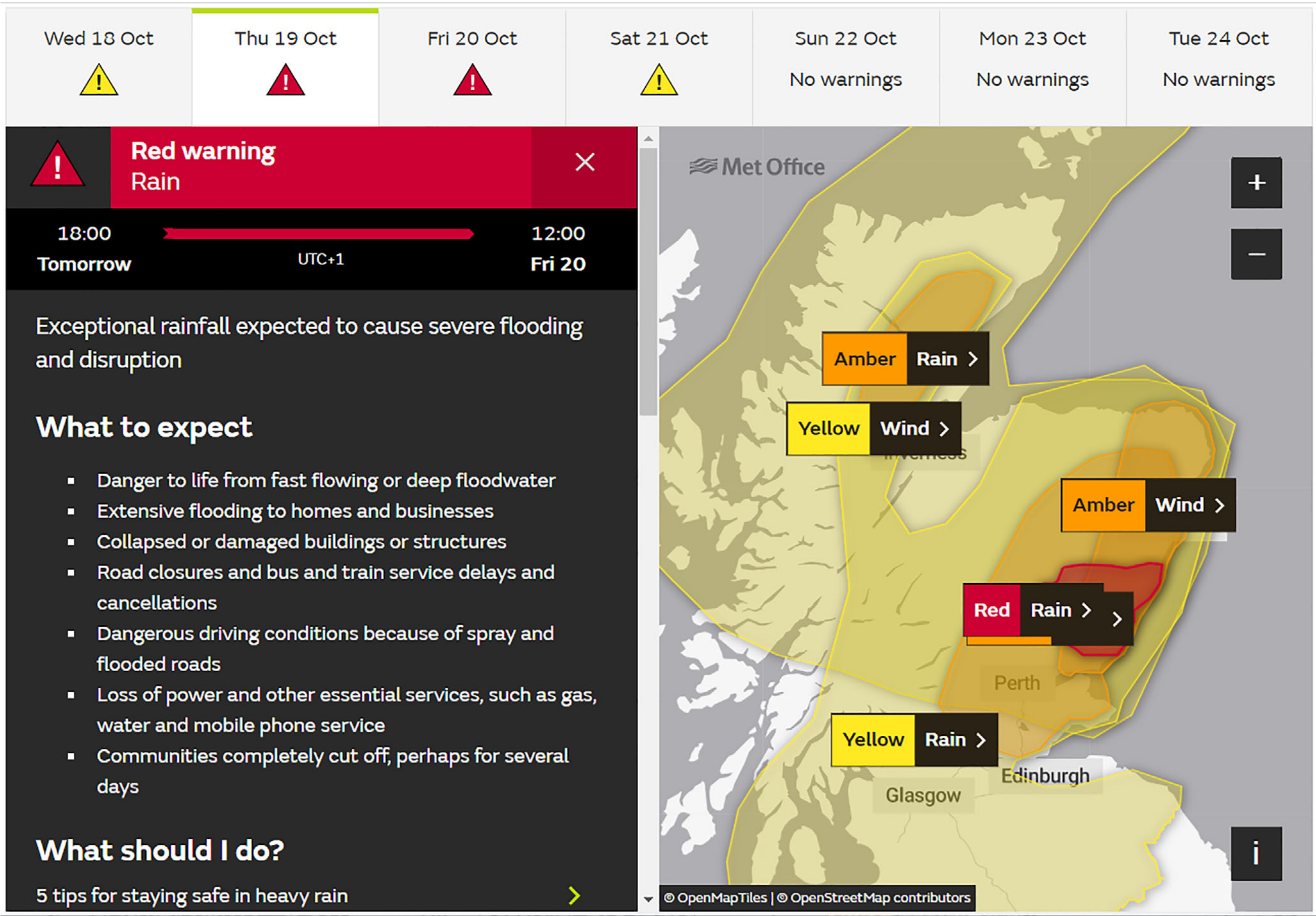


FIGURE 85 Met Office red warning for rain issued for parts of eastern Scotland for 1800 BST Thursday 19 October to 1200 BST Friday 20 October 2023. The map also shows amber and yellow warning areas for both rain and wind.

locations near the East Coast. In the wettest locations rainfall totals reached 150–200 mm or more, with the highest total 217 mm, 121% of the 1991–2020 October average at Allt na Lairige, Argyll (328 masl), near the head of Loch Fyne.

The two-day rainfall total averaged across the whole of Scotland for 6 and 7 October 2023 was 65.9 mm, making this the wettest two-day period on record for Scotland in a series from 1891, ahead of 4–5 December 2015 (storm Desmond) and 28 to 29 July 1956 (Figure 82) (data before 1961 are based on a smaller number of stations due to more limited data availability, see Appendix A2). The Scotland rainfall totals for these two consecutive days 6th and 7th were 32.6 and 31.5 mm, respectively—each independently within Scotland's top-30 wettest days in this series and the wettest days in this series since 3 October 2020. Six of Scotland's 10 wettest 2-day periods on record have occurred in the 21st century, including three in the most recent decade.

Inevitably for such extreme rainfall, there were significant impacts across Scotland. In Argyll, the A83 was closed due to a landslip with 10 people airlifted from their vehicles, while several other major trunk roads were also closed. Rail services across Scotland were severely affected, and at Inverary, bales of silage were washed away by the River Aray. Scottish farmers reported the loss of several million pounds worth of unharvested vegetables damaged by floodwaters. Over 50 flood warnings were issued across Scotland, including severe flood warnings for parts of Aviemore and Perth.

9.4 | Storm Babet

Storm Babet brought exceptional rainfall to parts of eastern Scotland, while heavy, persistent and widespread rain also affected much of England, Wales and Northern Ireland. Babet tracked south to north as it approached the UK, an unusual direction, allowing the system to pick up additional moisture as it crossed the Bay of Biscay. The rain-bearing fronts remained stationary across eastern Scotland for a prolonged period, being unable to clear north-east due to an area of high pressure over

Scandinavia (Figures 83 and 84). The Met Office issued two red warnings for persistent heavy rain across eastern Scotland for 19th–20th, and 21st October, with several other amber warnings for rain and wind covering Scotland, Northern Ireland, Wales and parts of northern England (Figure 85). The last time the Met Office issued a red warning for rain was from storm Dennis in mid-February 2020, covering parts of South Wales.

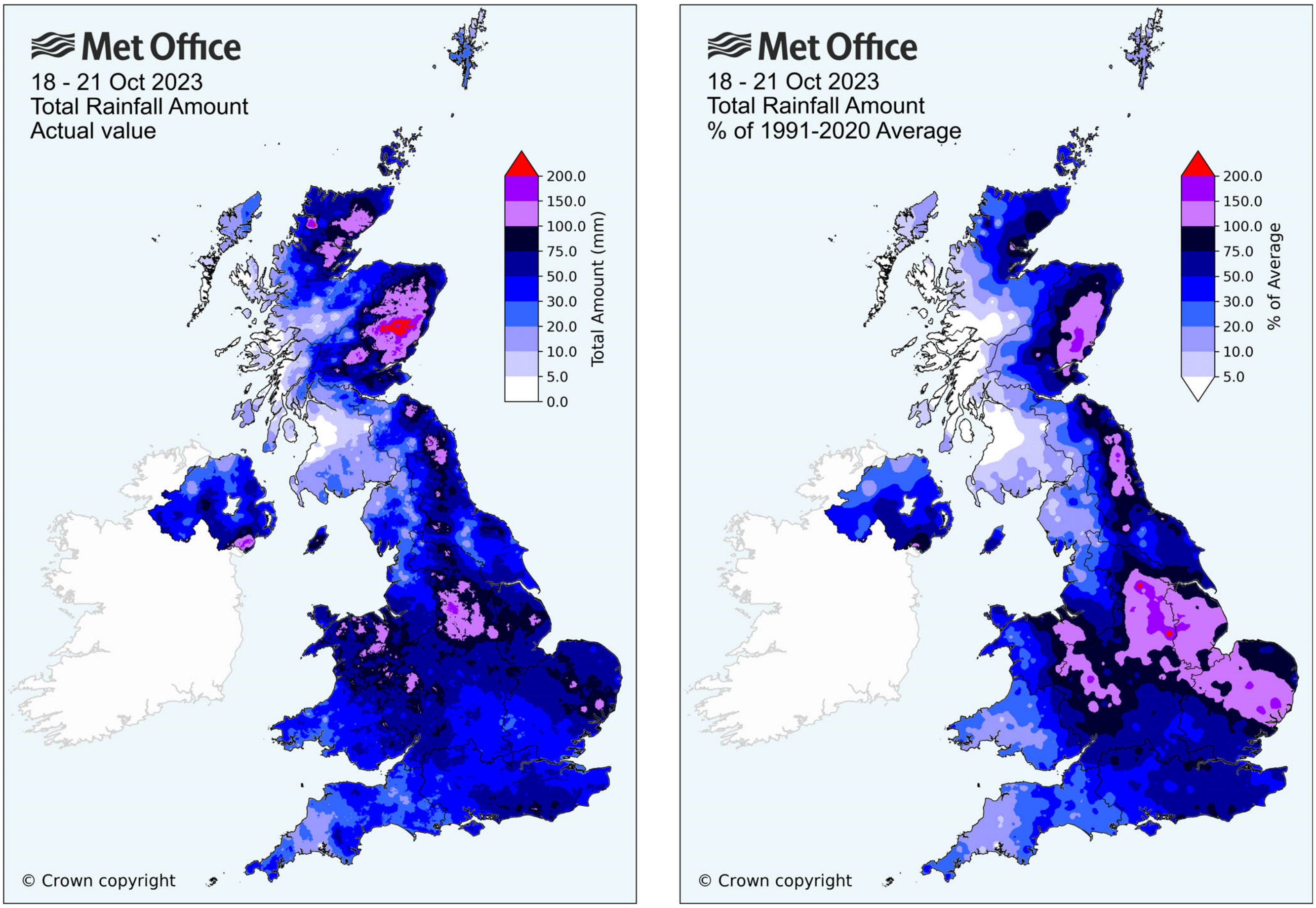


FIGURE 86 Cumulative UK rainfall 18–21 October 2023 as actual value (mm, a) and percentage of October 1991–2020 monthly average (b).

TABLE 16 Highest station rainfall totals for 18–21 October 2023 across Eastern Scotland (mm), and percentage of October 1991–2020 monthly average rainfall.

Station	County	Elevation (masl)	Total (mm)	October average (mm)	% of average
Stonyford	Aberdeenshire	195	232.8	144.2	161.5
Waterside, Glen Esk	Angus	185	203.8	131.7	154.8
Durris	Kincardineshire	107	188.3	124.9	150.7
Fettercairn, Glensaugh No 2	Kincardineshire	171	186.1	133.1	139.9
Charr	Kincardineshire	251	184.8	143.5	128.8
Invermark Bridge	Angus	255	178.4	142.2	125.5
Forfar S Wks	Angus	61	164.4	90.9	180.9
Mongour	Kincardineshire	315	158.8	139.6	113.7
Spittal of Glenmuick No 2	Aberdeenshire	407	147.2	148.0	99.5
Balconnel	Angus	149	145.5	102.7	141.7

Figure 86 shows the accumulated daily rainfall for the 4-day period 18–21 October 2023 from storm Babet as actual totals in mm (left) and percentage of the October whole-month average (right). Large swathes of the UK received over 50 mm of rain, with 75–100 mm widely across eastern Scotland, the Pennines, North Wales, the Mourne Mountains of Northern Ireland and parts of the West Midlands, East Anglia and south-east England, and over 100 mm in the wetter locations (some places having over 150 mm). The gridding process aims to take topographical influences into account, and this shows a significant area of eastern Scotland receiving over 200 mm (shaded in red). Much of the Midlands, East Anglia, south Pennines, Northumberland and eastern Scotland received rainfall exceeding the whole-month average, with significantly more than this in some areas.

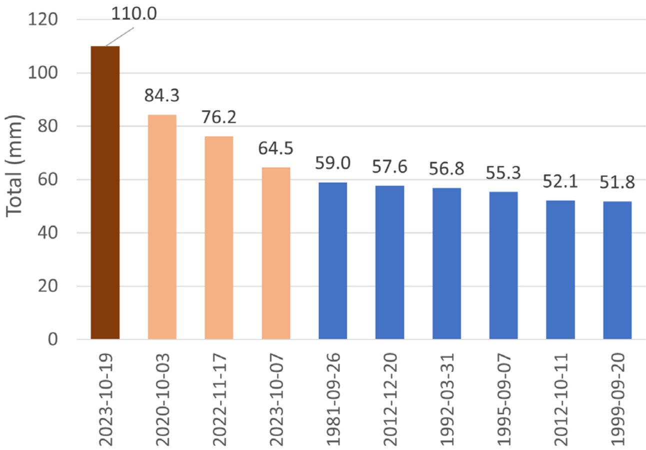


FIGURE 87 The 10 wettest days for the county series of Angus from 1961 to 2023. Bars shaded pale orange are other years in the most recent decade 2014–2023 and bars shaded blue are earlier. Dates before 1961 are excluded from this analysis due to the large reduction in number of stations used in the HadUK-Grid dataset which will affect daily rainfall statistics for county-sized areas before this date (see Appendix A2).

Table 16 lists the highest station totals from 18 to 21 October (0900 UTC 18th to 0900 UTC 22nd) from this event. The wettest locations in eastern Scotland recorded totals for the 3 day period of 150–200 mm, with two rain-gauges exceeding 200 mm. The wettest day of this period was 19th October, with some exceptional daily totals including 173.4 mm at Stonyford (the highest daily total of 2023), 168.4 mm at Waterside, Glen Esk and 151.6 mm at Invermark Bridge (all in Angus) and 131.8 mm at Charr, Kincardineshire. Rainfall totals were many times higher inland than they were a few tens of km away on the coast due to extreme orographic enhancement in the unusual south-easterly flow.

19 October 2023 was, by a wide margin, the wettest day for the county of Angus (coinciding with the red warning area) in the series from 1961, while 7 October

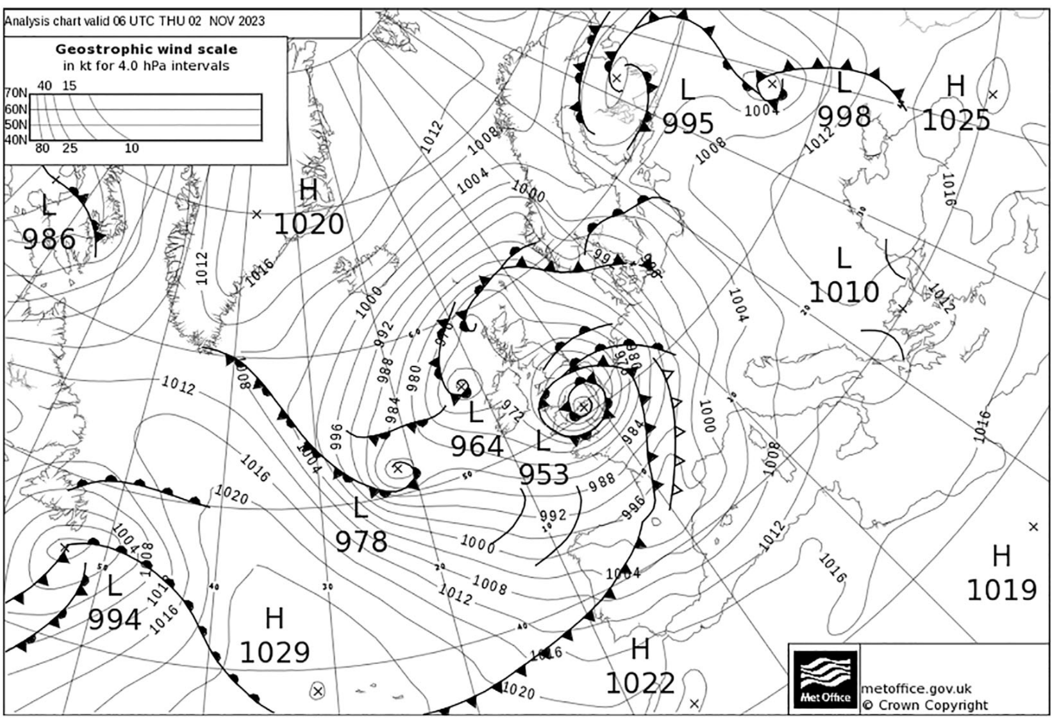


FIGURE 88 Analysis chart at 0600 UTC 2 November 2023.

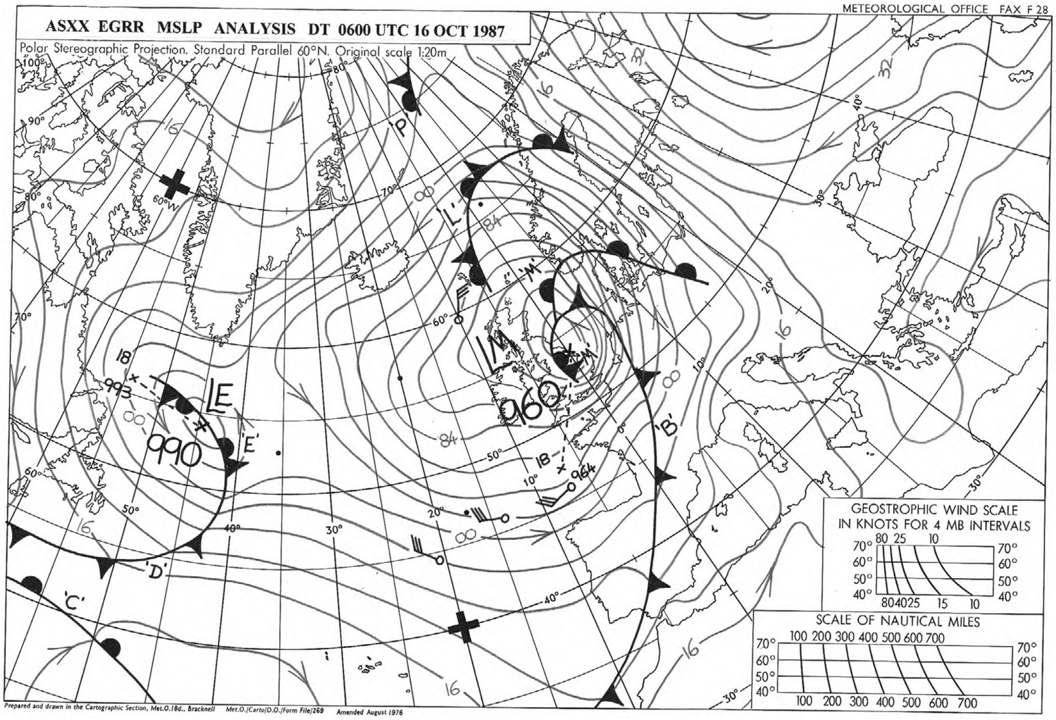


FIGURE 89 Analysis chart at 0600 UTC 16 October 1987.

(less than a fortnight previously) was the fourth wettest day. Four of the 10 wettest days on record for this county have occurred in the last 5 years (Figure 87). These statistics in the observations are illustrative of the expected increases in rainfall extremes as the UK's climate continues to warm. (Data before 1961 are not shown due to the limited number of stations at county-level.)

For England and Wales overall, the 3-day period 18 to 20 October 2023 was the third-wettest independent (non-overlapping) 3-day period on record in a daily series from 1891, with 53.0 mm of rain falling and the only wetter periods on record being 28–30 October 2000 (60.0 mm) and 23–25 September 2012 (54.8 mm). Nine of the 10 wettest independent 3-day periods on record for England and Wales in this series have been associated with large-scale autumn or winter low pressure systems, with six of these 10 in October (the event in late August 1986 was associated with ex-hurricane Charley). Many stations recorded their wettest October day during this event, for example, 61.4 mm at Sheffield on 20th (139-year record), 46.8 mm at Waddington, Lincolnshire on 19th (76 years), 48.2 mm at Wattisham, Suffolk on 19th (63 years).

A prolonged widespread heavy rain event such as this will inevitably result in significant flood impacts. Multiple severe flood warnings were issued by the Environment Agency (EA) and the Scottish Environment Protection Agency (SEPA). At least seven people were reported to have died as a result of the storm (although some of these were from wind impacts rather than flooding). In Scotland, hundreds of homes and businesses were inundated with the town of Brechin severely affected after defences were overtopped by the river South Esk. The main A90 trunk road was closed between Forfar and Brechin after storm Babet damaged a bridge, and schools across Angus were closed. Scottish farmers were reported to have lost crops, and some sheep were also washed away by floodwater.

Over 1000 homes in England were also affected by flooding across Yorkshire, the East Midlands and the Humber area. In Chesterfield (Derbyshire), around 400 homes were flooded while 500 homes were evacuated in Retford, Nottinghamshire and widespread flooding affected other locations such as Stafford and Wrexham. Derby's Museum of Making was flooded, and a major incident declared in Suffolk. Rail services on the East Coast were severely affected due to flooded lines.

9.5 | Storm Ciarán

Across most of the UK, wind speeds from Storm Ciarán on 1–2 November 2023 were fairly typical for a major Atlantic storm. However, further south, exceptionally severe and damaging winds on the southern flank of this storm affected northern France and the

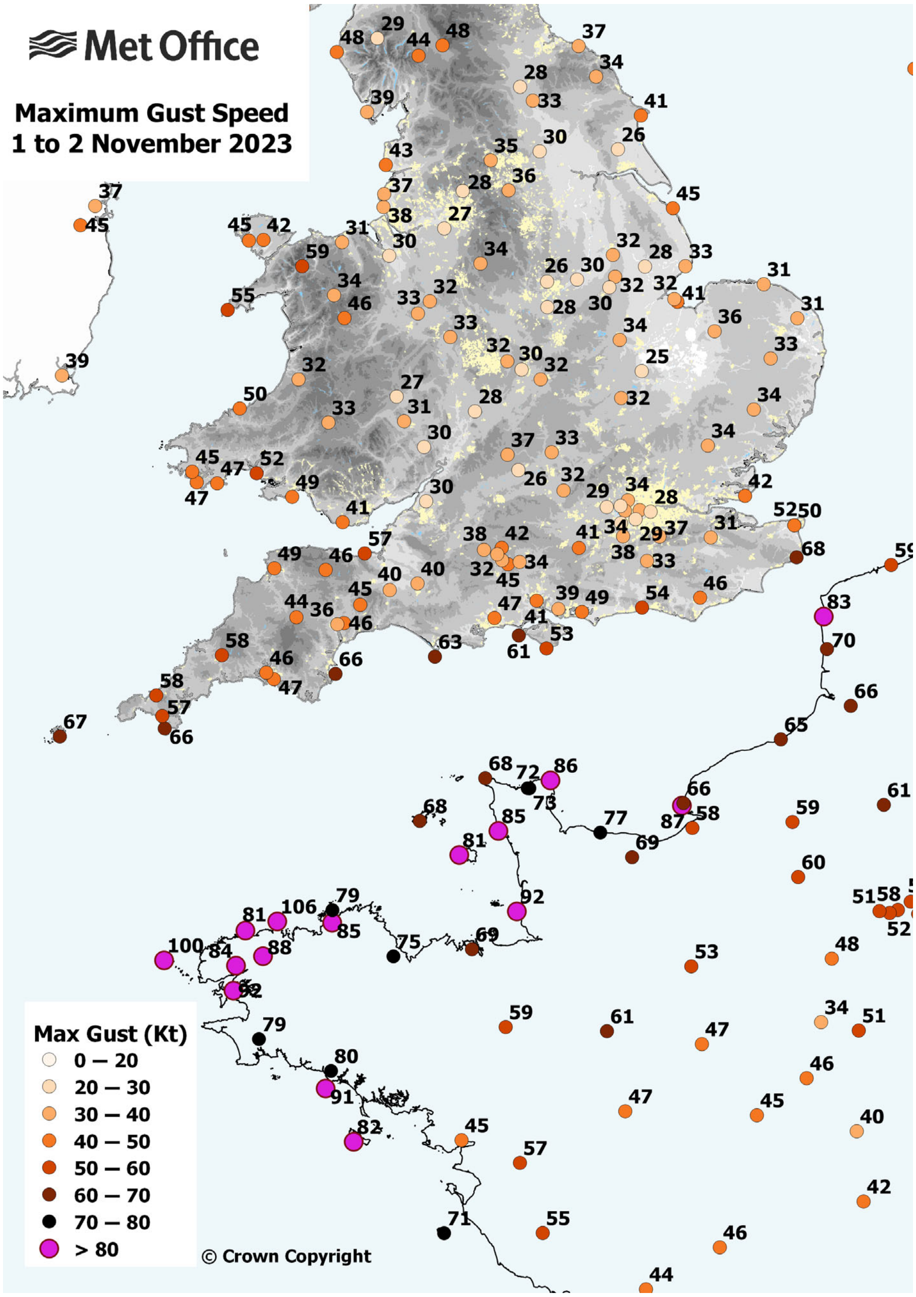


FIGURE 90 Maximum gust speeds (Kt) across the southern half of the UK and northern France 1–2 November 2023. The grey shades over the UK show underlying topography.

Channel Islands. In this area, maximum gust speeds were comparable in severity with those experienced in the south-east of England during the 'Great Storm' of 16 October 1987.

Figures 88 and 89 compare the analysis charts for storm Ciarán and 16 October 1987 illustrating the similarity between these two events. Similar to the 'Great Storm', Ciarán underwent 'explosive cyclogenesis'—rapidly deepening and gaining strength as it approached the UK from the south-west. The central pressure dropped by 28 hPa in 24 hours, falling below 955 hPa at several stations on the south coast. St Catherine's Point (Isle of Wight) and Culdrose (Cornwall) each recorded 953.6 hPa, England's lowest November pressure on record, lower than the previous record in 1916. Wales also recorded its lowest November pressure.

In the Channel Islands, Jersey Airport recorded a gust of 81 Kt (93 mph), the highest gust since the 'Great Storm' of 16 October 1987. Wind gusts on the Atlantic and Channel coasts of Brittany and Normandy exceeded 80 Kt (92 mph), in places over 90 Kt (104 mph). Two stations in Brittany reached 100 Kt (115 mph) including 106 Kt (122 mph) at Ile de Batz (Figure 90). Winds of this severity are indicative of an exceptionally severe storm, comparable to those experienced in the south-east of

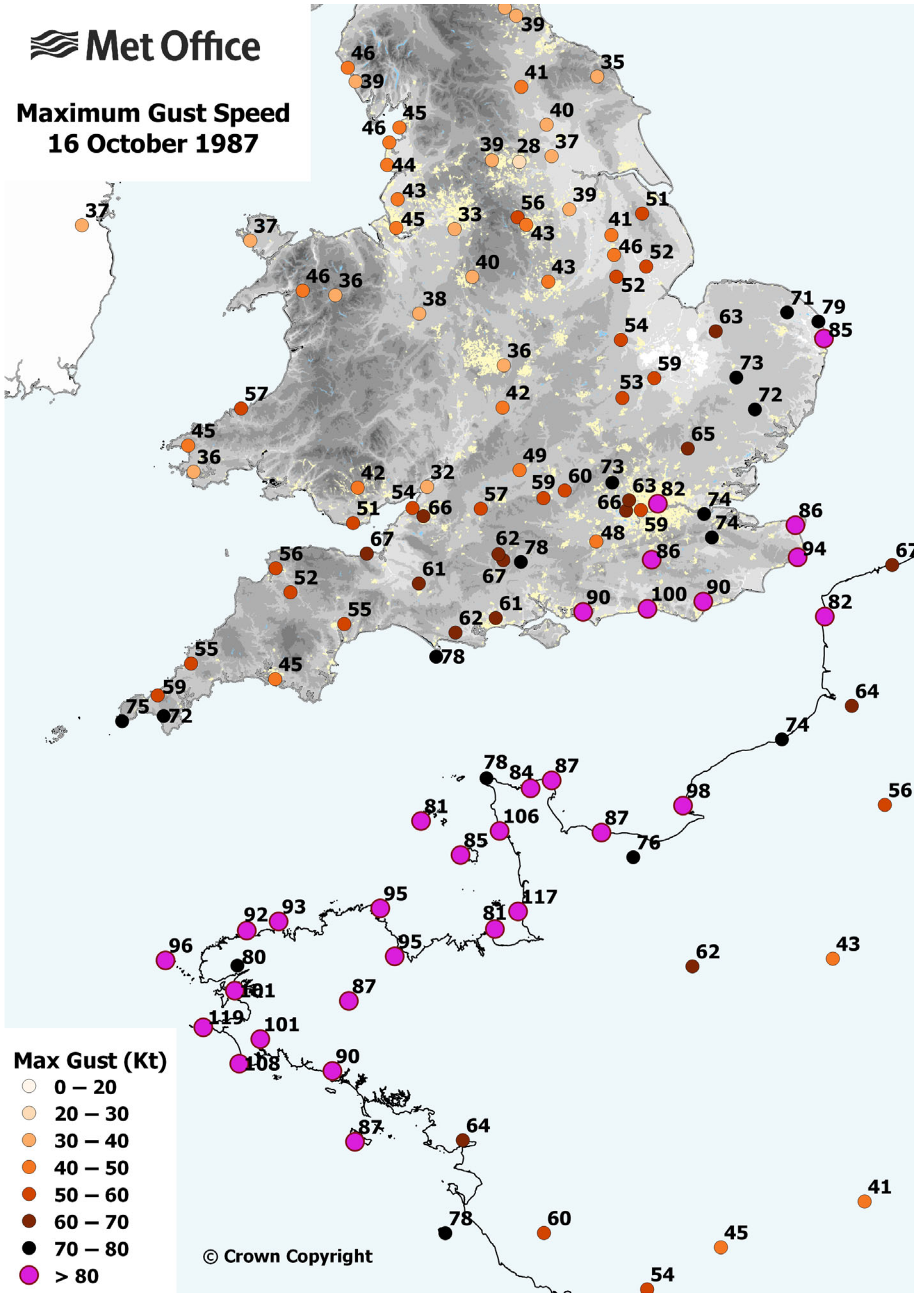


FIGURE 91 Maximum gust speeds (Kt) across the southern half of the UK and northern France 16 October 1987. The grey shades over the UK show underlying topography. Values across northern France have been taken from Figure 10 of Burt and Mansfield (1988) due to problems with how historical maximum gust speed data for overseas stations are stored for this period in the Met Office MIDAS database.

England from the 'Great Storm' of 16 October 1987—where a gust of 100 Kt (115 mph) was recorded at Shorehamby-Sea, West Sussex (Figure 91). However, overall the 'Great Storm' of 1987 was much more severe; gusts for example, reaching 119 Kt (137 mph) at Pointe du Raz, Brittany.

The Channel Islands and northern France experienced the worst weather impacts, with numerous fallen trees and significant damage to buildings, with a tornado and large hail affecting eastern parts of Jersey at the height of the storm (Knightley et al., 2024). Jersey's Met Service issued a red weather warning and a major incident was declared. In northern France, a reported 1.2 million people were without electricity, and across western Europe more widely, heavy rain and flooding linked to storm Ciarán reportedly led to at least 13 deaths.

If Ciarán had tracked 150 km further north, impacts across the UK would have been much worse: this early in the autumn many trees were still in leaf with saturated ground also increasing the risk of uprooting. However, since October 1987, major advances in the ability to forecast severe storms have taken place, with greatly improved communications of warnings (including the storm naming scheme) allowing mitigating actions to be taken well in advance.

Even so, the storm brought significant impacts to the UK. The port of Dover was temporarily closed, the Great Western Main line closed and many commuters advised to work from home. Hundreds of schools were shut and almost 150,000 homes left without power. Large waves battered the South Coast, several vehicles were swept into the sea and a major incident was declared in Hampshire and the Isle of Wight. At West Bay in Dorset, a section of cliff collapsed into the sea, and in Surrey a power outage at three water treatment plants left thousands without a water supply.

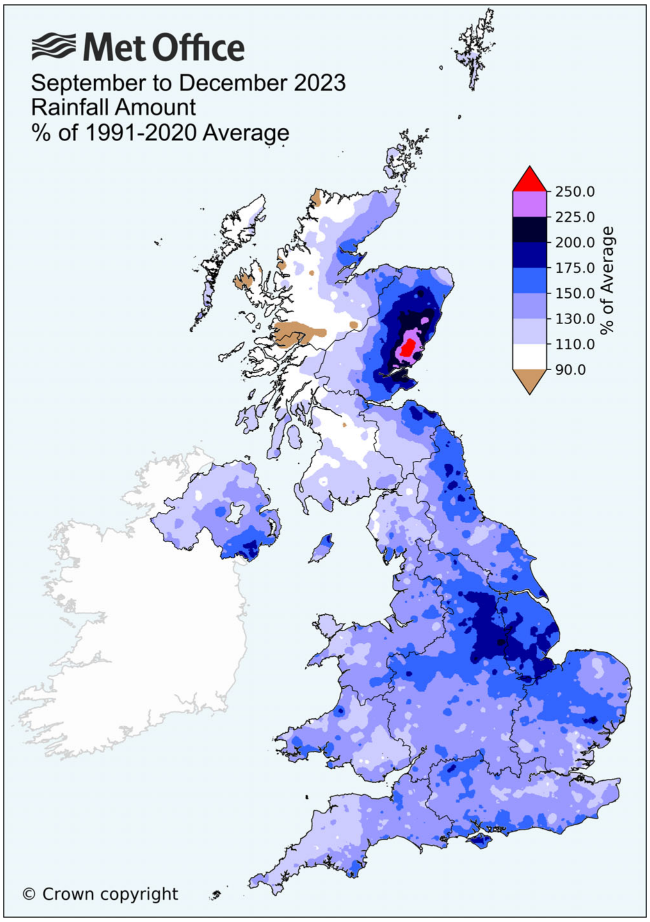


FIGURE 92 UK rainfall for September to December 2023 as a percentage of the September to December 1991–2020 average.

9.6 | Named storms September to December

The sequence of named storms from September to December resulted in an exceptionally wet end to the year. Many parts of eastern England, eastern Scotland and the south-east of Northern Ireland recorded over 150% of the 1991–2020 average rainfall in this four-month period, with the wettest areas in eastern Scotland exceeding 200% (Figure 92). Figure 93 shows UK average daily rainfall through this period, illustrating the contributions from named storms Agnes to Gerrit and the almost continuously unsettled nature of the weather with only a brief respite during the colder spell from late November to early December. Figures 94 (a and b) show rainfall accumulations through this period in the wettest areas—the counties of Angus and Nottinghamshire—with the major step after mid-October from storm Babet. Each of these counties recorded their wettest September to December in the monthly series from 1836, for Angus by a margin of 130 mm (more than the December long term average). The UK recorded its wettest September to December since 2000 (Figure 95). Autumn 2000 brought the most serious and extensive flood event across

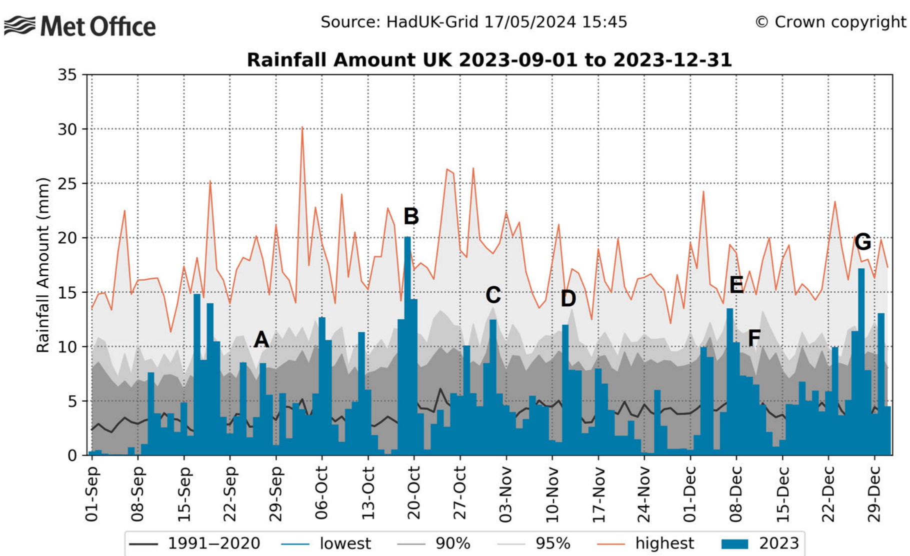
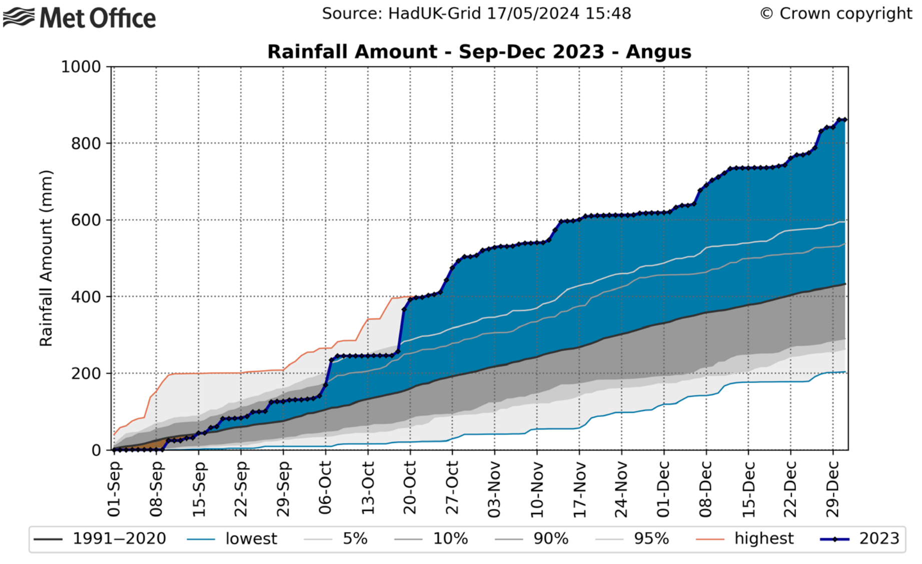


FIGURE 93 UK daily rainfall September to December 2023 (mm, blue bars). The black line shows the 1991–2020 average for each calendar day based on 1991–2020, the grey shaded areas percentiles and red line highest daily value based on the daily series 1891–2023. Named storms are labelled: Agnes (27–28 September), Babet (18–21 September), Ciaran (1–2 November), Debi (13 November), Elin (9 December), Fergus (10 December) and Gerrit (27–28 December).



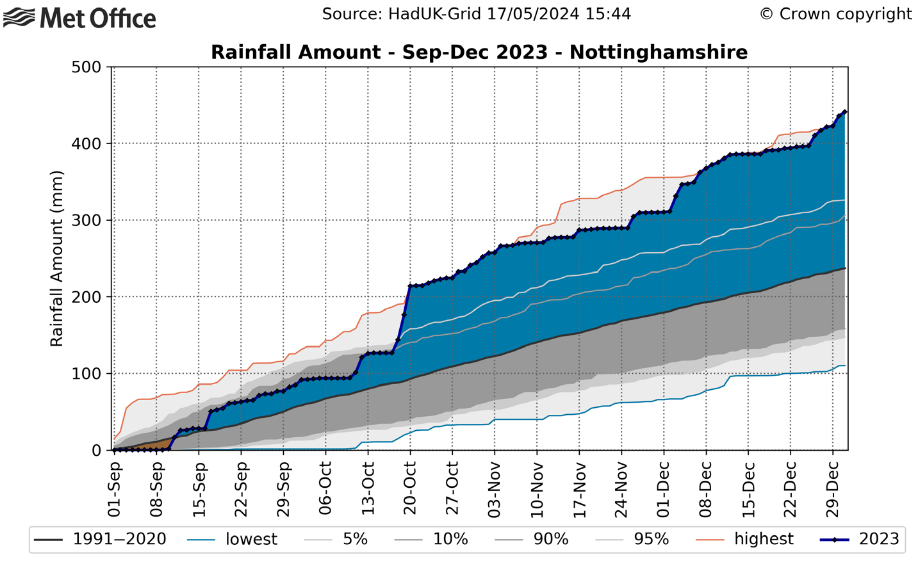


FIGURE 94 Daily rainfall accumulations from September to December 2023 for the counties of Angus and Nottinghamshire (mm, blue shaded area). The black line shows the 1991–2020 average daily accumulation, the grey shaded areas percentiles and red and blue lines the highest and lowest daily accumulations based on the period 1961–2023.

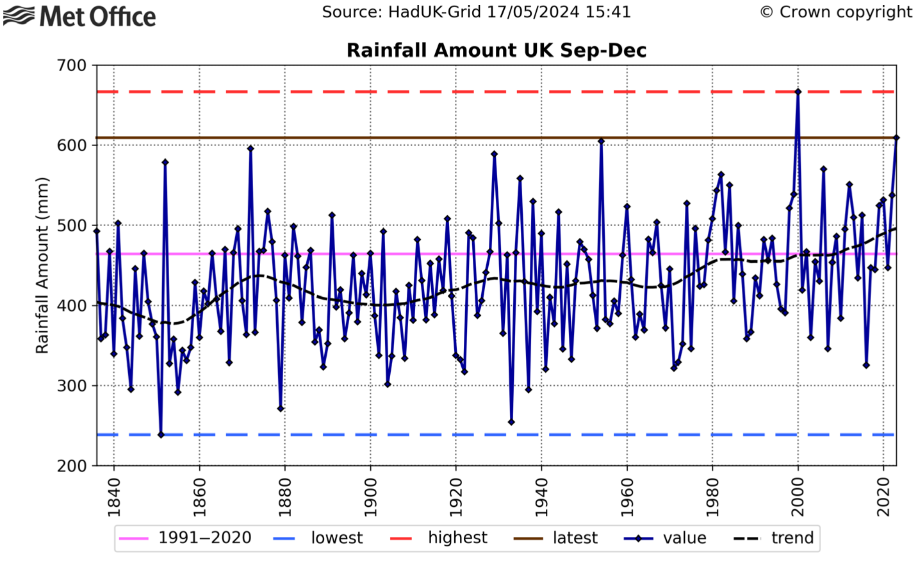


FIGURE 95 UK rainfall 1836–2024 (mm) for the 4-month period September to December.

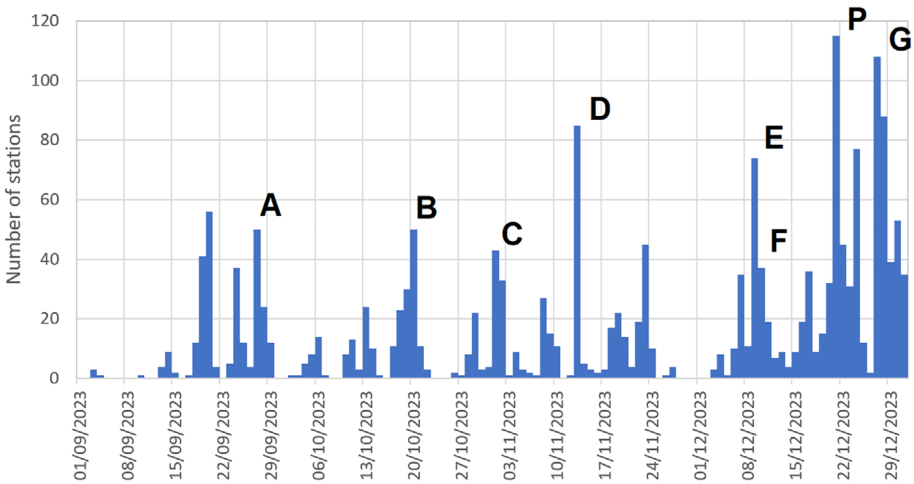


FIGURE 96 Count of the number of stations across the UK by date recording a wind gust ≥40 Kt (46 mph) from September to December 2023. Named storms are labelled: Agnes (27–28 September), Babet (18–21 September), Ciaran (1–2 November), Debi (13 November), Elin (9 December), Fergus (10 December), Pia* (21 December) and Gerrit (27–28 December). *Named by the Danish Meteorological Institute, DMI.

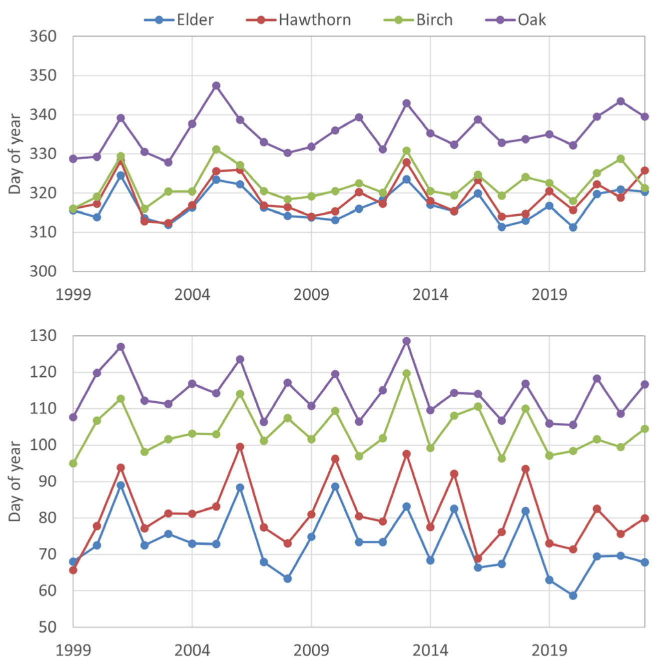


FIGURE 97 Mean day of year of first leaf and bare tree for four common shrub or tree species: Elder, Hawthorn, Silver Birch and Oak, derived from UK observations contributed to Nature's Calendar from 1999 to 2023.

England and Wales since the snowmelt-generated floods of March 1947 (Marsh and Dale, 2002).

By the arrival of storm Gerrit on 27 December, concerns about flooding increased with temporary flood barriers installed along parts of the River Severn at Ironbridge, Shropshire and Bewdley, Worcestershire. In Yorkshire, sections of the M62 and A1M were closed due to flooding and there were huge crowds of stranded passengers at London King's Cross Station after the East

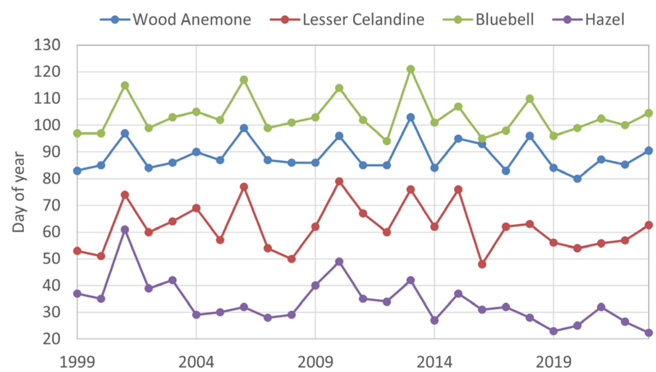


FIGURE 98 Mean day of year of first flowering for four flower species: Hazel, Lesser Celandine, Wood Anemone and Bluebell, derived from UK observations contributed to Nature's Calendar from 1999 to 2023.

Coast Main Line was closed north of Newcastle (with impacts made worse by the number of travellers just after Christmas).

Figure 96 shows a count of the number of stations across the UK each day from September to December 2023 recording a wind gust of 40 Kt (46 mph) or higher, with the peaks generally coinciding with named storms through this period.

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. In the UK, phenology data are collected by a citizen science

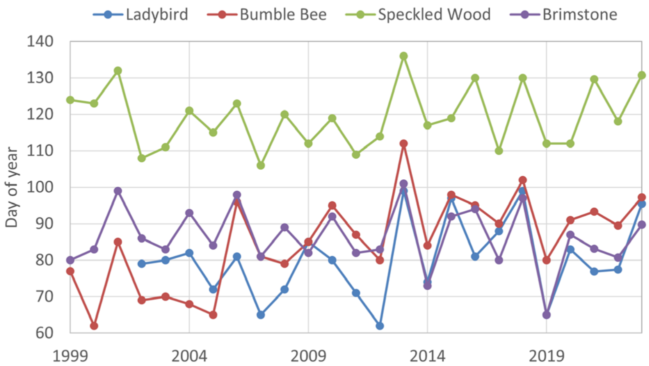


FIGURE 99 Mean day of year of first appearance of four invertebrate species: 7-spot Ladybird, Brimstone butterfly, Red-tailed Bumblebee and Speckled Wood butterfly, derived from UK observations contributed to Nature's Calendar from 1999 to 2023.

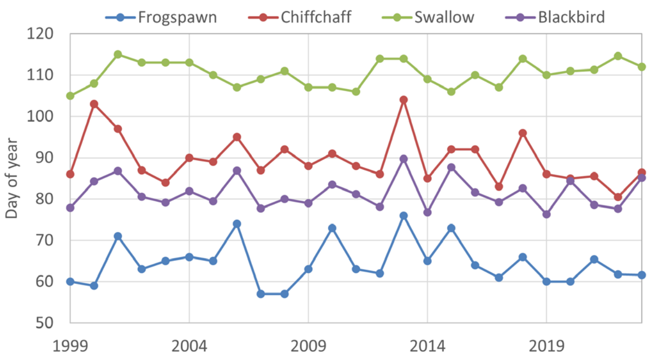


FIGURE 100 Mean day of year of first nest building of Blackbird, first observation of Chiffchaff and Swallow and first appearance of Common Frog spawn, derived from UK observations contributed to Nature's Calendar from 1999 to 2023.

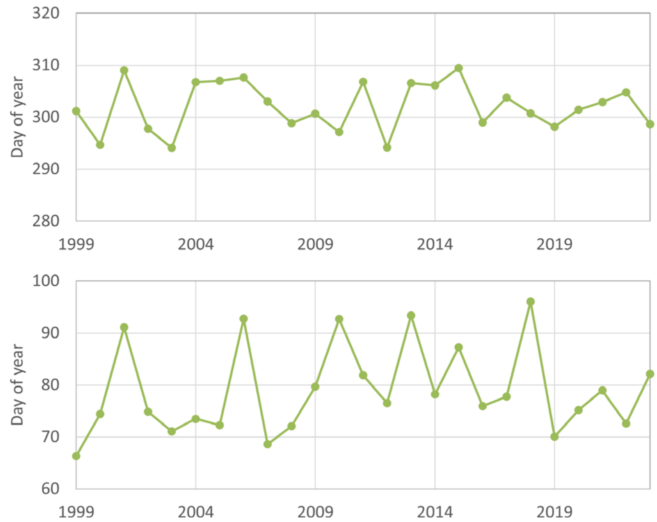


FIGURE 101 Mean day of year of first and last lawn cut, derived from UK observations contributed to Nature's Calendar from 1999 to 2023.

project called Nature's Calendar which relies 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 (Figure 97), four flower species (Figure 98), four invertebrate species (Figure 99), and four vertebrate species (Figure 100). We also show first and last lawn cutting dates which integrate both grass responses to temperature and human behaviour (Figure 101). For the 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 early February to Bluebell in April. With the exception of Speckled Wood butterfly the other listed invertebrates overwinter as adults. The vertebrates are a diverse group: evidence of breeding (frogspawn) in the cold-blooded Common Frog, nest building in the Blackbird, first appearance of the short distance migrant/resident Chiffchaff, and first appearance of the long distance migrant Swallow. Table 17 provides a summary of these data.

Spring 2023 was a near average or late year for most events, although the early Hazel flowering, the earliest in this series, and, to a lesser extent Elder first leafing, were likely encouraged by early season warmth in late January and February (Figure 20, Table 1). In fact, Hazel flowering has shown a significant advance over the 1999–2023 period. Other species were more influenced by the colder first half of March. High September temperatures and a generally mild autumn led to three of four woody species having later-than-average autumn dates (Figure 20, Table 1). Overall, the leaf-on season (the difference between first leaf and bare dates) was 4 days longer than the baseline largely due to a later autumn, although the lawn cutting season was 7 days shorter than the baseline. The timing of lawn cutting is quite complex; both low temperatures and dry soils inhibit vegetative growth, while wet grass discourages cutting. Spring responses to temperature varied from 1 to 7 days earlier for every 1°C increase in mean temperature of the 1–3 months before 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.

TABLE 17 Mean dates of example events for woody plant species, flowers, invertebrates and vertebrates, and lawn first and last cut derived from UK observations contributed to Nature's Calendar from 1999 to 2023.

Group	Event	Species	Mean first date 1999–2022	2023 mean first relative to 1999–2022	Mean response to a 1°C increase in <month(s) right>	Month (s)	R^2 (%)
Woody plants	First Leaf	Elder	14-Mar	−5.6	−6.9	JFM	69
		Hawthorn	22-Mar	−1.6	−7.7	JFM	68
		Silver Birch	13-Apr	+0.6	−5.8	FMA	80
		Oak	24-Apr	+2.6	−5.9	FMA	77
Woody plants	Bare	Elder	11-Nov	+3.6	2.1	O	45
		Hawthorn	13-Nov	+7.2	2.6	O	45
		Silver Birch	17-Nov	−1.0	2.4	O	46
		Oak	30-Nov	+4.2	3.1	O	58
Flowers	First Flower	Hazel	3-Feb	−12.0	−5.0	DJF	36
		Lesser Celandine	2-Mar	+0.7	−6.6	JFM	52
		Wood Anemone	29-Mar	+1.9	−5.1	JFM	72
		Bluebell	13-Apr	+1.3	−5.2	FMA	49
Invertebrates	First seen	7-spot Ladybird	20-Mar	+16.0	−4.3	M	28
		Brimstone butterfly	27-Mar	+3.6	−5.3	M	66
		Red-tailed Bumblebee	25-Mar	+12.5	−5.4	M	31
		Speckled Wood butterfly	28-Apr	+12.0	−7.2	MA	69
Vertebrates	First seen nest building	Blackbird	22-Mar	+3.8	−2.2	M	56
	First Seen	Frogspawn	5-Mar	−3.0	−4.5	JFM	71
		Chiffchaff	30-Mar	−3.2	−3.5	M	59
		Swallow	20-Apr	+1.8	(−0.8)	(A)	11
Grass	First in spring	Lawn cutting	19-Mar	+3.2	−7.0	JFM	65
	Last in autumn		28-Oct	−3.5	2.9	O	58

Note: Columns show the mean dates for the baseline period (1999–2022), the anomaly in days for 2023 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 $p < 0.05$. The final column shows the proportion of the variance in the mean first date explained by the temperature variables (R^2).

AUTHOR CONTRIBUTIONS

Section 6: Jevrejeva S., Matthews A., Williams J. **Section 10:** Garforth J., Sparks T. All other sections: other authors.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Centre for Environmental Data Analysis at https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb

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APPENDIX A: DATASETS

These appendices provide information about the underlying datasets used in this report. Much of the content is repeated from previous reports, with only minor updates, but they are included here in full for reference.

A1 | NAO index

The Winter North Atlantic Oscillation (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 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 1885–2023 and 1850–2023, respectively. If the WNAO and temperature/rainfall series are detrended using the trend lines shown in the figures, the R^2 values increase to 0.62 and 0.28). This means that well over half of the annual variability for UK winter mean temperature and over a quarter for rainfall may be associated with the WNAO (Figure 3). Importantly, however, it also means 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—located to the east of the Shetland Islands and in north-west Greenland, respectively. These reflect the smaller spatial scale and a more northerly track of summer Atlantic low pressure systems (Folland et al., 2009). Due to their location 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 2023 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 0.48 for summer rainfall based on years 1884–2023 and 1850–2023, respectively. If the SNAO and temperature/rainfall series are detrended using the trend lines shown in the figures, then these R^2 values change to 0.35 and 0.47). 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. 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.

A2 | 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 1.3.0.0 of the dataset. The previous version 1.2.0.0 was used in the State of the UK Climate 2022 report (Kendon et al., 2023). The main change from v1.2.0.0 to v1.3.0.0 has been the inclusion of the latest year, 2023 although see also discussion of Figure A1. Evaluating and improving the HadUK-Grid dataset and associated underlying station data remain active and ongoing task.

The underlying source of UK station data used to produce the gridded dataset is the Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Database. This has been supplemented by further recently digitized historic data from multiple sources including Met Office Monthly and Daily Weather Reports and monthly rainfall totals from both British Rainfall and the 'Rainfall Rescue' project, comprising digitized 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. (2023). This version of HadUK-Grid has been built using the second version of this rainfall rescue collection (v2.0.0, Hawkins, 2023), also used for HadUK-Grid v1.2.0.0.

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 mostly 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 station values directly. This approach has the advantage of ensuring that they 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 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

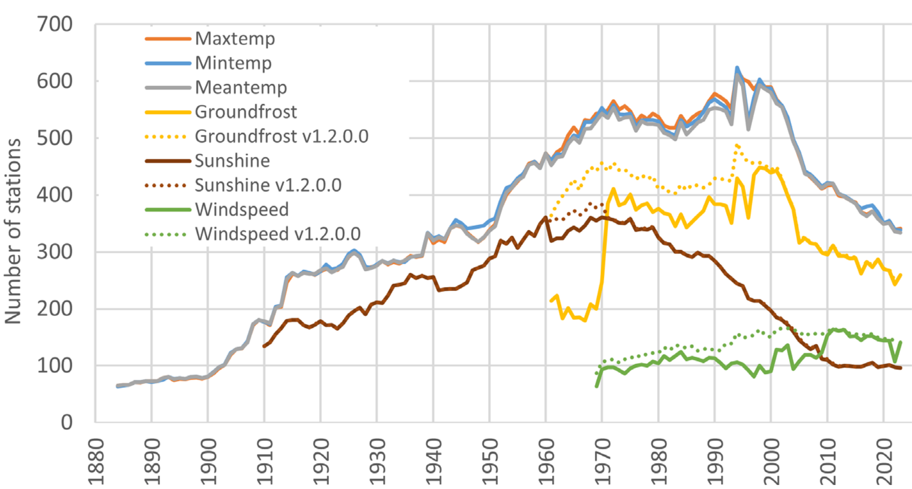

FIGURE A1 Numbers of stations used for gridding in this report (solid lines)—monthly T_{max}, T_{min}, T_{mean} (1884–2023), monthly days of ground frost (1961–2023), monthly sunshine (1910–2023) and monthly windspeed (1969–2023). Number of stations used for the previous version of HadUK-Grid (v1.2.0.0) for groundfrost, sunshine and windspeed (dotted).

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 temperature is below 0°C	1961	Monthly
Heating degree days	Day-by-day sum of number of degrees by which the mean temperature is <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.

that they are not exactly consistent (indeed observations from monthly rain-gauges, or digitized monthly rainfall data from Rainfall Rescue, can only be used for 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 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 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 over 300 from the 1950s to 1980s, followed by a steady decline to around 100 stations in 2010, thereafter being stable. The number of monthly windspeed stations rises from 100 to 120 in the 1970s and 1980s to over 150 stations in the 2010s, followed by a slight fall.

The number of stations used for groundfrost, sunshine and windspeed have reduced at different points in the historical series when comparing v1.3.0.0 to the previous version v1.2.0.0 (shown dotted in Figure A1). These reductions in station numbers have been caused by changes made in the data processing steps in the latest version upstream of the gridding process.

- For groundfrost this reduction has been caused by an automated quality control process flagging the historical data which have been removed as suspect (mostly affecting data from 1961 to 1970).
- For sunshine the small reduction in the 1960s has been caused by the removal of digitized monthly sunshine data through this period where we wish to reverify the data source.
- For windspeed the reduction from 1969 to 2010 has been caused by changes to rules applied relating to data completeness when compiling daily mean windspeeds, which in turn have followed through to monthly statistics.

We anticipate that the vast majority of observations removed will be likely to be satisfactory for gridding and will be reintroduced in future versions of this dataset, but we have removed them from this version as a precaution. The impact on the large-scale metrics in this report (i.e., area averages by country or UK for these variables) is expected to be minimal.

As would be expected the number of stations for daily temperature over the period 1960–2023 matches that for monthly temperature (Figure A2).

Figure A3 shows the number of stations for monthly and daily rainfall. The inclusion of digitized monthly rainfall data sources prior to 1961, in particular Rainfall Rescue data, has effectively eliminated the step change in station numbers before 1960, with the number of stations in the dataset in 2023 equivalent to that in the 1880s. The total number of stations in the network does not in itself provide the full picture however. As an

TABLE A2 Approximate total number of observations used for each variable in v1.3.0.0.

Climate variable	Number of years	Number of grids	Average number of stations values per grid	Total number of station values
Monthly T_{max}	140	1680	355	600,000
Monthly rainfall	188	2256	3453	7,800,000
Monthly groundfrost	63	756	329	250,000
Monthly sunshine	114	1368	235	320,000
Monthly windspeed	55	660	116	77,000
Daily T_{max}	64	23376	512	12,000,000
Daily rainfall	133	48577	1918	93,000,000

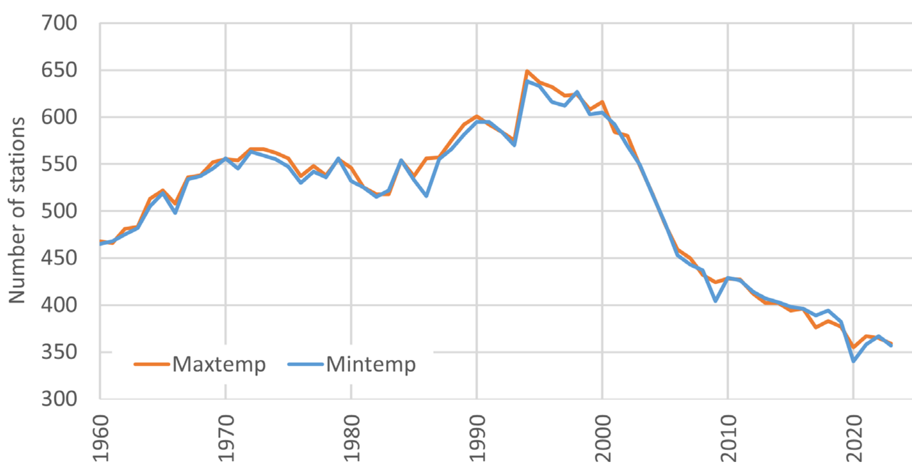

FIGURE A2 Numbers of stations used for daily temperature 1960–2023. The numbers are very similar to those for monthly T_{max} and monthly T_{min} as shown in Figure A1.

example, Figure A4 compares the monthly rainfall station coverage in September 1885 (a) and September 2023 (b). While there are fewer stations in 2023, they are generally better spatially distributed, with 1885 having significant clustering in some areas such as 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. Even so, the addition of these recently digitized data still represent a major improvement.

The step change in station numbers is still present for daily rainfall in v1.3.0.0. Since the majority of the

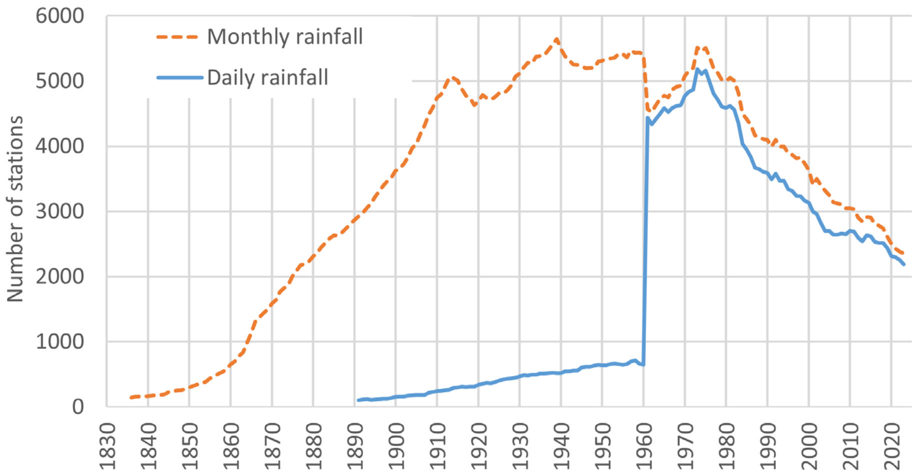

FIGURE A3 Numbers of stations used for monthly rainfall (1836–2023) and daily rainfall (1891–2023).

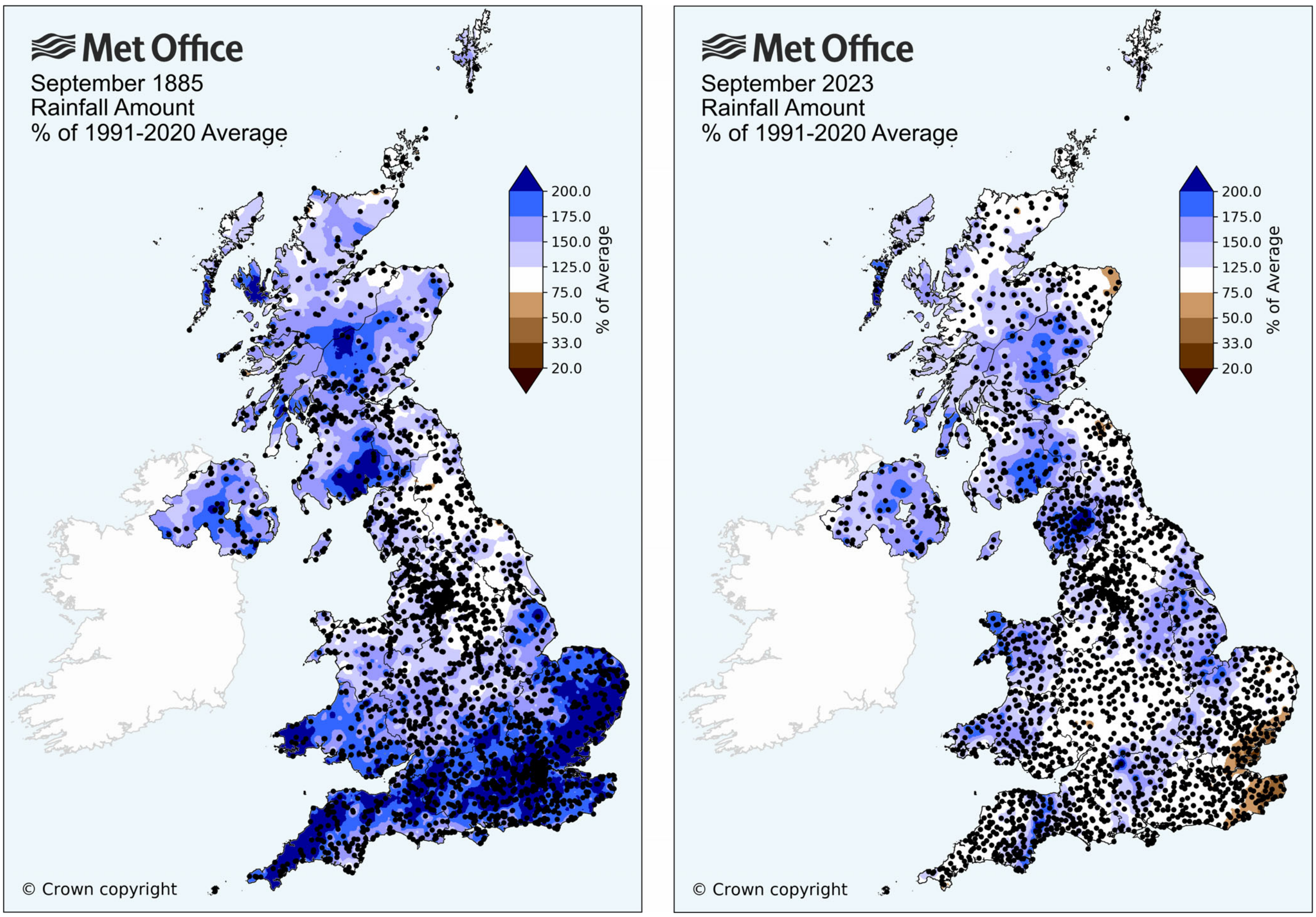

FIGURE A4 (a,b) The station network used in HadUK-Grid v1.3.0.0 comparing monthly rainfall for September 1885 (2620 stations) and September 2023 (2282 stations).

monthly rainfall observations will be from stations returning daily values, this emphasizes the potential of future digitization work to increase the amount of daily rainfall data, although the total volume of data required to bring the number of daily stations up to equal the number of monthly stations would be very much greater. For example, an average of 3000 stations each day for 100 years would be equivalent to over 100 million observations, approximately doubling the number of observations in the HadUK-Grid dataset, possibly requiring a new approach to digitization (e.g., the use of AI). Investigating the efficacy of different digitization approaches is an ongoing active area of research both in the Met Office and elsewhere.

A3 | The observing network in 2023

Figure A5 shows the state of the UK's observing network in 2023 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 its high spatial variation, the network is

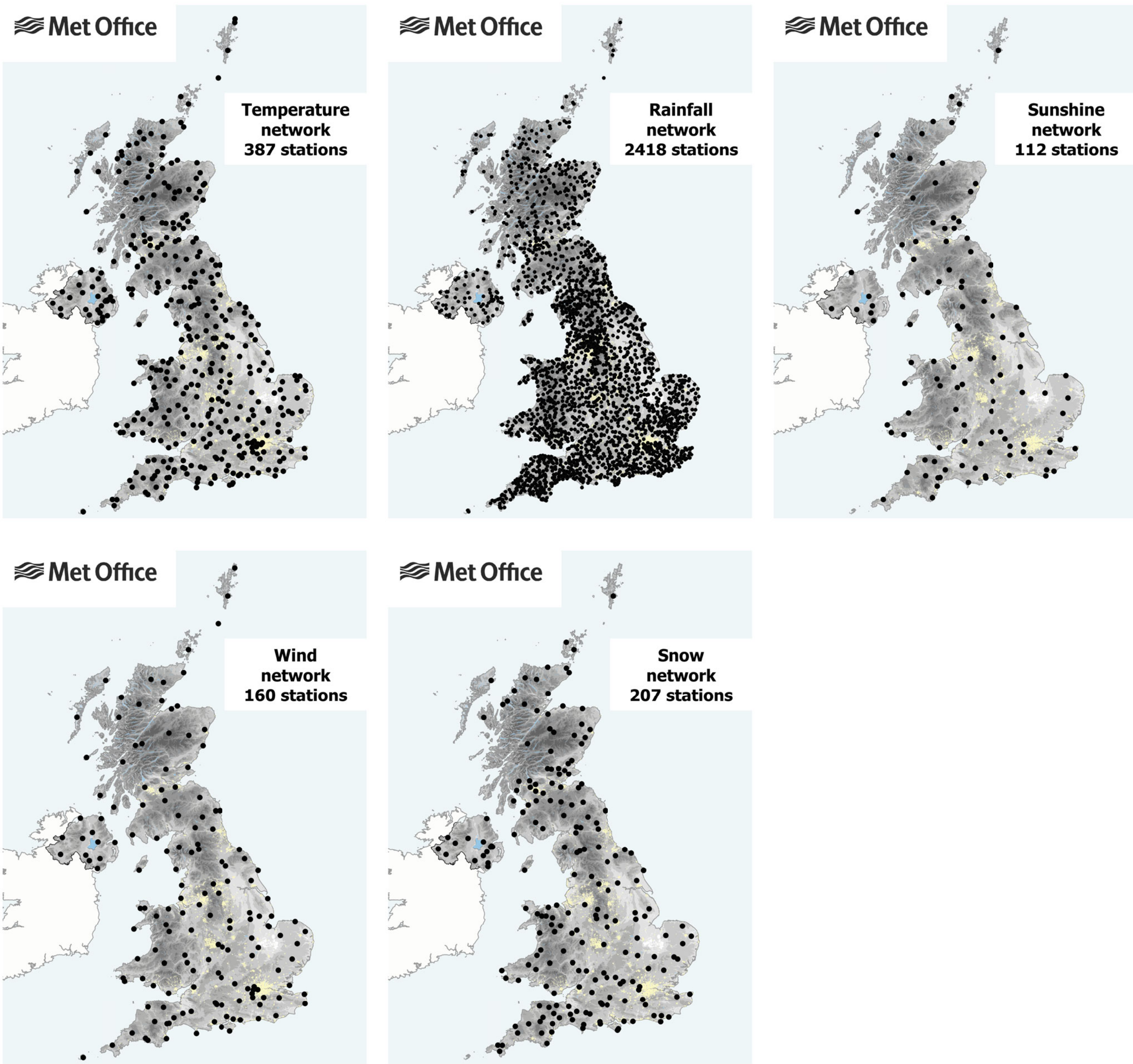

FIGURE A5 State of the UK observing network in 2023. The number of observations is indicative as these may vary on a daily basis due to data availability.

much denser for rainfall compared to 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 data-sparse than others, but these also tend to correspond to areas with a lower 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—that is, 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.

A4 | 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 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 1990 for the period 1991–2020) and omit the last December (December 2020)—although in practice any difference will usually be very small.

The introduction section explains of the choice of averaging periods used in this report. More background and discussion regarding averaging periods is provided in Hulme, 2020.

A5 | 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 $(T_{\mathrm{max}} + T_{\mathrm{min}})/2$. 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.

A6 | Consistency and quality control

Quality control of station observations held in the MIDAS database (the source of the majority of station data used in HadUK-Grid) 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. 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, enabling a closure check on the monthly totals. Development of the HadUK-Grid dataset and improvement in quality control processes to remove as much suspect data as possible, whilst avoiding the removal of good data (summarized by what in the field of machine learning is termed a "confusion matrix") remains an active area of research and development and will feed into future versions. Further details are beyond the scope of this report.

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

Condition: daily T_{max} T_{min} and T_{mean} above or below $T_{\mathrm{threshold}}$	Degree-day value
$T_{\mathrm{max}} \leq T_{\mathrm{threshold}}$	0
$T_{\mathrm{min}} \geq T_{\mathrm{threshold}}$	$T_{\mathrm{mean}} - T_{\mathrm{threshold}}$
$T_{\mathrm{mean}} \geq T_{\mathrm{threshold}}$ and $T_{\mathrm{min}} < T_{\mathrm{threshold}}$	$0.5\,(T_{\mathrm{max}} - T_{\mathrm{threshold}}) - 0.25\,(T_{\mathrm{threshold}} - T_{\mathrm{min}})$
$T_{\mathrm{mean}} < T_{\mathrm{threshold}}$ and $T_{\mathrm{max}} > T_{\mathrm{threshold}}$	$0.25\,(T_{\mathrm{max}} - T_{\mathrm{threshold}})$

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 $T_{\mathrm{threshold}}$	Degree-day value
$T_{\mathrm{min}} \geq T_{\mathrm{threshold}}$	0
$T_{\mathrm{max}} \leq T_{\mathrm{threshold}}$	$T_{\mathrm{threshold}} - T_{\mathrm{mean}}$
$T_{\mathrm{mean}} \leq T_{\mathrm{threshold}}$ and $T_{\mathrm{max}} > T_{\mathrm{threshold}}$	$0.5\,(T_{\mathrm{threshold}} - T_{\mathrm{min}}) - 0.25\,(T_{\mathrm{max}} - T_{\mathrm{threshold}})$
$T_{\mathrm{mean}} > T_{\mathrm{threshold}}$ and $T_{\mathrm{min}} < T_{\mathrm{threshold}}$	$0.25\,(T_{\mathrm{threshold}} - T_{\mathrm{min}})$

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 (v1.3.0.0 for this report). Details of the HadUK-Grid dataset are provided in Hollis et al. (2019).

A7 | Quality control of record values

Quality control of station observations is particularly important for potential new record values. While this is especially the case for high profile records such as the UK highest maximum temperature record of 40.3°C at Coningby Lincolnshire on 19 July 2022, all possible records must be carefully checked. 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. The monthly temperature records in Section 7.2 are examples of observations accepted as new records after verification by the SWAT process.

While SWAT reports are official Met Office documents primarily for internal use, publicly available versions of these documents are available as Weather Event Verification Reports from the Met Office digital library and archive at https://digital.nmla.metoffice.gov.uk/SO_cb95d84f-d807-4818-897c-687c2cdfc80b/.

A8 | 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, without any gaps. Daily area averages have similarly been calculated from the 1 km daily gridded datasets.

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. Long-term average statistics are consistent with the monthly statistics (although as noted in the Appendix A.4 winter is an exception to this).

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.

Some of the maps and analyses within this report are based on a set of county areas for the UK. These comprise ceremonial counties in England, Scottish lieutenancy areas in Scotland, and preserved counties in Wales, defined in 1997. More detail is provided at https://www.data.gov.uk/dataset/ad4fbd84-3185-4606-b619-b5317bc30a41/ceremonial-county. Northern Ireland is divided into six counties. The reason these county areas were chosen is that they provide a stable set of areas for long term monitoring, avoiding potential problems with boundary changes for other possible choices of areas which might be routinely updated (e.g., as a result of administrative changes). Area average statistics would otherwise need continual updating to keep in step.

There are 97 county areas in total (Figure A6). These are particularly useful for climate monitoring because they are generally similar in size, although inevitably some areas are much smaller than others. At this size these counties provide area average statistics which usually cover much of the spatial variation across the UK. Rainfall has such a large spatial variability that even at this scale the county areas may struggle to capture the detail. Statistics for county areas will also be much more sensitive to station network density (see Figures A1–A4). More work is required to evaluate the relationship between area size and uncertainty in the area average statistics. Uncertainties are discussed further in Appendix B.2.

A9 | Global surface temperature

HadCRUT.5.0.2.0 is a gridded dataset of global historical surface temperature anomalies relative to a

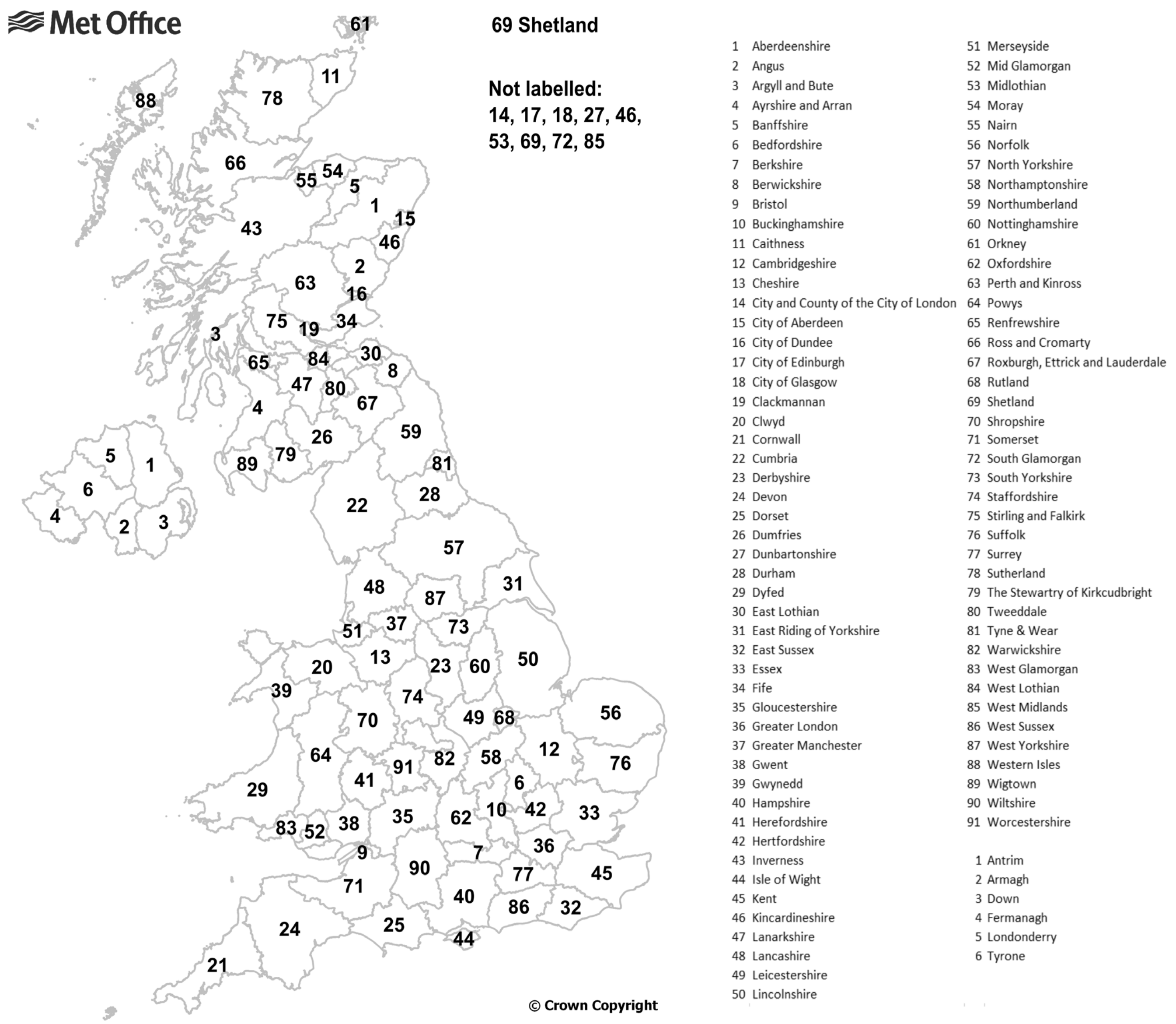

FIGURE A6 County areas for the UK used in this report. The Isle of Man is excluded.

1961–1990 reference period. Data are available for each month from January 1850 (Morice et al., 2021). The HadCRUT5 dataset of global surface temperature is produced from the station series of the CRUTEM5 land-surface air temperature dataset (Osborn et al., 2021) and the HadSST4 sea-surface temperature dataset (Kennedy et al., 2019).

The CRUTEM5 station series comprises monthly-mean temperature records from a global network of several thousand weather stations, from which CRUTEM5 anomaly fields are calculated. 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 realisations that sample the distribution of uncertainty. HadCRUT5 is one of several global surface temperature datasets, with other examples produced by NOAA, NASA, Berkeley Earth, and the German Climate Computing Centre DKRZ. Global temperature series based on reanalysis are also produced by ECMWF (ERA5) and Japan (JRA-55).

A10 | Central England temperature

The 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.

Last year's report used an updated version of the CET series, v2.0.0.0 (Legg et al., 2024). The version of the CET series presented in this report is v2.1.0.0, released May 2024. Updates to the CET series for this and the previous release (v2.0.1.0, April 2023) include substantial structural improvements to the underlying software, including addressing some historical issues. These changes have had negligible impact on the CET series overall (e.g., the rank of individual years). This series is updated on an annual basis. Detailed release notes for the CET series are available at https://www.metoffice.gov.uk/hadobs/hadcet/releases/cet_releases.html.

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).

A11 | 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 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 been adjusted to minimise 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 sea-surface temperature series in this report comprises the average of the 5° latitude-longitude grid-cells adjacent to the coast of the Great Britain, which at this spatial resolution comprises four grid-cells. Although this is much lower than the 1° latitude-longitude resolution of HadISST1 (Rayner et al., 2003), HadSST.4.0.1.0 has a more up to date homogenization so should be better for identifying long term trends, and it also has uncertainty information as shown in Figure 32.

A12 | England and Wales precipitation series

The England and Wales precipitation series (EWP) 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, 2000; Simpson & Jones, 2012; Wigley et al., 1984). Figure 41 shows that the EWP series is highly correlated with the England and Wales series (the areal-average for England and Wales combined) from the HadUK-Grid dataset from 1836.

A13 | 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 steadily diminished from a peak of over 5000 rain-gauges across the UK in the mid-1970s to fewer than 2500 in 2023 (i.e., halving in 50 years). 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, reaching a peak of over 500 stations in the 1990s. It subsequently reduced to around 200 stations in 2010 and has remained fairly steady thereafter.

A14 | Sunshine data

The UK's sunshine network in 2023 comprises two instrument types: just over a third Campbell-Stokes (CS) sunshine recorders which are read manually; the remainder Kipp and 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. The adjustment is made KZ to CS, not the other way round, because although KZ outnumbers CS for the current network, the majority of total historical sunshine observations, by far, are CS. Legg (2014) and references therein provide further details.

A15 | 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.

A16 | Sea level data

Sea-level changes around the British Isles are monitored by the UK national network of 42 tide gauges, which falls under the authority of the Environment Agency. 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.

In recent years, the State of the UK Climate report has included a UK sea level index for the period since 1901 computed from sea level data from five of the longest operating stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool), which provides a reliable 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 rate of 1.4 mm/year is reintroduced (Bradley et al., 2011; Woodworth et al., 2009).

However, creating this index relies on tide gauges following international best practice on operation and quality control to ensure reliability of the data, and long-term stability of the vertical reference frame (UNESCO/IOC, 2020). Unfortunately, from 2007 onward, there have been more gaps in observations throughout the network, including for the five long-running stations. We have been unable to update the index for 2023 as only Newlyn provided enough data to generate an annual mean. 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 distributed by the British Oceanographic Data Centre (BODC, https://www.bodc.ac.uk) having undergone full quality control, 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.

A17 | Skew surges from highlighted storms and other high levels in 2023

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

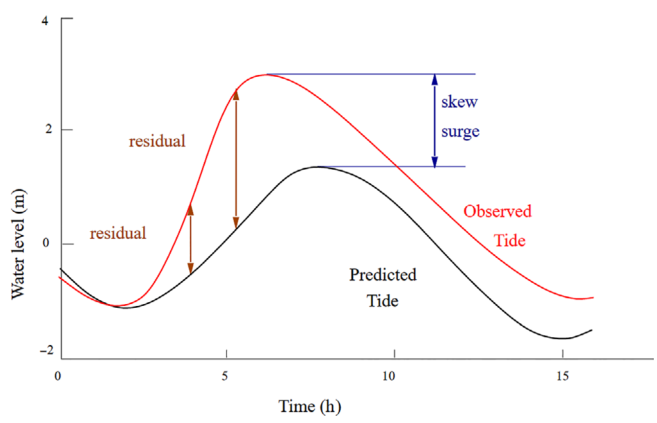

FIGURE A7 Diagram of skew surge showing the difference between predicted tide and observed tide.

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.

TABLE A5 Skew surges from highlighted storms.

Storm name	Dates	Storm surge
Unnamed	7–10 January	Widespread moderate (0.5–1 m) skew surge on west and east coasts of UK, but occurred during moderate tides, no especially high levels.
Gerard (Météo-France)	14–16 January	Surge mostly in southern North Sea, up to Sheerness 1.0 m skew surge.
Otto (DMI)	17–18 February	Small <0.5 m skew surge in west of Scotland and 0.5–1 m skew surge in east coast England later on 17 February. Surge residual in the North Sea was mostly due to phase shift and did not result in a substantial skew surge. Neap tide, small total water levels.
Larisa (Météo-France)	12–14 March	Surge in Irish Sea, skew surge over 0.5 m everywhere and Heysham 0.8 m, Newport 1.1 m. But due to the date being on neap tides, no high total water levels.
Unnamed	22–25 March	Widespread moderate (0.5–1 m) surge especially on west and north coast of UK. Although not the biggest surge, or a named storm, the coincidence of the March 23rd event with the spring tide led to this being the highest recorded level at 18 sites in Scotland and the west coast of England and Wales, as far south as the Severn.
Matthis (Météo-France)	29 March to 1 April	Skew surge approaching 1 m in English Channel, and widespread moderate skew surge on west coast of UK. Highest recorded 0.9 m (Jersey) but occurred during moderate tides, no especially high levels. Followed by negative surge particularly in Severn (−0.5 m negative skew surge at Hinkley, Avonmouth, Newport).
Noa (Météo-France)	11–12 April	Neap tide, no significant levels. Skew surge in Irish Sea, up to 0.9 m at Newport.
Antoni	5–6 August	No widespread storm surge resulting from this storm.
Betty	18–19 August	Moderate skew surge (~0.5 m) on west and south coasts. Negative surge all week in the Severn.
Unnamed	19–21 September	Skew surge (<1 m) western Scotland and negative skew surge in south east coast of England. Neap tides.
Agnes	27–28 September	High skew surge in north west England (Workington 0.9 m), Scotland (Millport 0.9 m, Portpatrick 0.8 m) and Northern Ireland (Bangor 0.8 m). Agnes led to the highest totals of the year in Northern Ireland where the tidal range is small. Close to 1 October spring tides, that is, 3 days later would have been 1 m higher at Heysham.
Babet	18–21 October	Widespread skew surge (0.5–1 m) in the west of the UK. This event notable for extreme low waters in the German Bight.
Ciarán	1–2 November	Widespread moderate (0.5–1 m) skew surge on all coasts of UK, however, tides were moderate by the day of this storm and the still water level was not significant at most sites. Modelled skew surge at Jersey around 1 m, and Jersey was severely affected by wave damage but unfortunately no tide gauge data was transmitted during that week. Highest level of the year recorded at Bournemouth.
Debi	12–13 November	Surge in the Irish Sea, west coast of England and Wales, 0.5–1 m skew surge and particularly at Heysham 1 m and Workington 1 m. However moderate tides so not extreme levels.
Elin	8–9 December	No widespread storm surge during this event, Fergus followed immediately.
Fergus	10–11 December	Skew surge 0.5–1 m in Irish Sea. Neap tides, no high levels.
Pia (DMI)	21–22 December	Pia had the highest skew surges of the year with >1 m widespread across the North Sea (observed 1.2 m Cromer, 1.5 m Lowestoft, 1.4 m Harwich, 1.2 m Sheerness and 1 m Dover). Neap tide, but still was the maximum total sea level for the year at Harwich and Lowestoft in East Anglia.
Gerrit	27–29 December	Gerrit had widespread positive skew surge (0.5–1 m) in the west of the UK, distinctive negative surges (approaching −1 m) in the North Sea. Combined with moderate spring tide this event led to the highest levels of the year at Millport (near Glasgow).

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 A7). 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).

Table A5 lists named storms and other events with a skew surge of more than 0.5 m observed at at least eight tide gauges. Table A6 lists other high levels (the counties of gauge locations are omitted).

Maximums at Avonmouth and Barmouth were not recorded in 2023, due to frequent gauge problems. In particular Avonmouth is reliant on a radar gauge and does not always record the top of the tidal cycle.

A18 | Phenology data

Nature's Calendar, run by the Woodland Trust, has been collating information on the timing of the seasons for 25 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 first and last lawn cutting dates in spring and autumn respectively. We

TABLE A6 Other high levels.

Vernal equinox spring tide	22 February	Highest levels of 2023 at Immingham, Lincolnshire. Coastal erosion at Hemsby, Norfolk.
Autumn spring tide	30 September	Highest levels of 2023 at several east coast sites (Dover, Cromer, Whitby, North Shields) and Newport. No particular storms but on September spring tides.
Autumn spring tide	28 October	Highest levels of 2023 in south and south-west England and Wales (except upper Severn). Milford Haven, Mumbles, Ilfracombe, St. Marys, Newlyn, Plymouth, Weymouth, Portsmouth, Newhaven, Sheerness. Not a named storm but a spring tide, combined with a sustained period of high sea-level throughout late October and early November.

FIGURE A8 Examples of phenology indicators: (a) Pedunculate Oak (*Quercus robur*) 'first leaf'; (b) Wood Anemone (*Anemone nemorosa*) first flowering; (c) Brimstone butterfly (*Gonepteryx rhamni*) first appearance; and (d) Common Frog (*Rana temporaria*) spawn first appearance.

report further 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 Speckled Wood butterfly (*Pararge aegeria*); first nest building by the Blackbird (*Turdus merula*), the appearance of Common Frog (*Rana temporaria*) spawn, first observation of Chiffchaff (*Phylloscopus collybita*) and of Swallow (*Hirundo rustica*). Figure A8 shows examples of some of these indicators. Dates are converted to day of the year (day numbers from 1 January) before manipulation and data analysis, with the mean date the average of all submitted records. No geographic adjustment is applied.

Dates for the baseline period (1999–2022), derived from annual means, are compared with those for 2023. To assess the relationships with temperature for each spring plant event, we have regressed the 1999–2023 annual mean dates on a three month mean CET for the month incorporating the mean date and the preceding 2 months. Past experience suggests that a 3-month block of temperatures is broadly appropriate for plants. For the animal events we have used the mean of those months that appear most influential. We report the response to a 1°C increase in the selected months. We also compare 1999–2023 annual means of bare dates, and last lawn cutting, 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. By necessity, the phenology data presented in this report are relatively short (i.e., <30 years), and therefore, in comparison to other climate series, less able to detect trends.

APPENDIX B: TIME-SERIES, TRENDS AND UNCERTAINTY

B1 | 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 to enable the trend lines to 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. Further discussion is provided in de Valk (2020).

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 urbanisation, 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 for such factors in climate monitoring is referred to as homogenization. This aims to ensure any biases introduced into the observations caused by these non-climatic factors are removed and the climate series are self-consistent through time. Homogenization may be considered as distinct from quality control—which is the identification and removal of errors in the observations (described in Appendix A.6). Some homogenization has been undertaken for some series presented in this report, such as the CET record, and the adjustment of sunshine records described in Appendix A.14. For most variables however the individual station data in this report have not been explicitly homogenized to account for these non-climatic factors.

B2 | 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; Legg, 2015). 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 the recent addition of Rainfall Rescue data).

A systematic reappraisal of the findings of Legg (2011, 2015) in order to update our estimates of uncertainties in HadUK-Grid is required. A change that has been made in this report is that annual mean temperatures for the UK and countries are quoted to two decimal places throughout, as one decimal place is judged as overly coarse precision. The UK annual mean temperature for 2023 was 9.97°C, 0.83°C above the 1991–2020 average, whereas the value for 2022 was 10.03°C and 0.89°C above. If rounded to one decimal place, these values would both correspond to 10.0°C, but with respective anomalies of 0.8°C and 0.9°C. Legg, 2015 supports uncertainty in annual mean temperature being <0.1°C.

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. For rainfall, this spatial sampling has recently been greatly improved pre-1960 due to the inclusion of Rainfall Rescue data. 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 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 (for monthly rainfall this step has been eliminated) and a relatively recent period in the dataset indicating current uncertainty. More comprehensive tables covering the full date range can be found in Legg (2015). We have applied a conservative reduction factor of √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 (2015). 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

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

TABLE B1 The 1σ uncertainty (standard error) ranges for annual T_{mean}, rainfall and sunshine for 5 km resolution 'legacy' gridded dataset.

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.

B3 | 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 41 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.

B4 | 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. 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 half 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. R^2 may also be expressed as a percentage.

B5 | 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. For internal processing purposes, unrounded values of area average statistics generated from the HadUK-Grid dataset are stored with a five decimal place precision for all variables and areas. See also Appendices A8 and B2.

APPENDIX C: USEFUL RESOURCES

C1 | 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 forecast model data are available via Weather DataHub https://datahub.metoffice.gov.uk/

Met Office UK Storm Centre for named storms https://www.metoffice.gov.uk/weather/warnings-and-advice/uk-storm-centre/index

Met Office digital library and archive (for scanned copies of Daily Weather Summaries, Monthly Weather

Reports, British Rainfall, etc.) https://digital.nmla.metoffice.gov.uk/

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

C2 | 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/4dc8450d889a491ebb20e724debe2dfb

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

Centre for Ecology and Hydrology, reports for major hydrological events https://nrfa.ceh.ac.uk/occasional-reports

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 Radcliffe Meteorological Station 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