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State of the UK Climate 2019

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Cover Images:

(Left) The Stevenson screen at Kew Gardens, London which recorded 21.2 °C on 26 February 2019. (Right) The Stevenson screen at Cambridge Botanic Garden which recorded 38.7 °C on 25 July 2019 – respectively the UK's highest winter and all-time temperatures on record. Both image Copyright Met Office.

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SPECIAL ISSUE ARTICLE

International Journal of Climatology RMetS

State of the UK Climate 2019

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INTRODUCTION

This report provides a summary of the UK weather and climate through the calendar year 2019, alongside the historical context for a number of essential climate variables. This is the sixth in a series of annual 'State of the UK Climate' publications and an update to the 2018 report (Kendon *et al*., 2019). 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 such that they conform to current best practice observational standards as defined by the World Meteorological Organization (WMO). The observations also pass through a range of quality assurance procedures at the Met Office before application for climate monitoring. Time series of near-coast sea-surface temperature (SST) and sea-level are also presented and in addition a short section on phenology which provides dates of first leaf and bare tree indicators for four common shrub or tree species.

National and regional statistics in this report are from the HadUK-Grid dataset (Hollis *et al*., 2019). Temperature and rainfall series from this dataset extend back to 1884 and 1862, respectively. Details are provided in the relevant sections and appendices.

The report presents summary statistics for the year 2019 and the most recent decade (2010–2019) relative to 1961–1990 and 1981–2010 averages. The period 2010–2019 is a non-standard reference period, but it provides a 10-year 'snapshot' of the most recent experience of the UK's climate and how that compares to historical records. This means differences between 2010 and 2019 and the baseline reference averages may reflect shorter-term decadal variations as well as long-term trends. These data are presented to show what has happened in recent years, not necessarily what is expected to happen in a changing climate.

The majority of maps in this report show the year 2019 relative to the 1981–2010 baseline reference averaging period—that is, they are anomaly maps which show the spatial variation in this difference from average. Maps of actual values are in most cases not displayed because these are dominated by the underlying climatology, which for this report is of a lesser interest than the year-to-year variability.

Throughout the report's text the terms ‘above normal’ and ‘above average’, and so on refer to the 1981–2010 baseline reference averaging period unless otherwise stated. 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 1981–2010), this difference is calculated from the original unrounded values.

Updates compared to State of UK Climate 2018

- A section on phenology has been added
- The method used to calculate rainfall percentiles (fig. 31) has been revised
- Updated climate data to HadUK-Grid version 1.0.2.0, including data rescue projects that have improved or extended early monthly sunshine and rainfall series.

Feedback

We would welcome suggestions or recommendations 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 BEIS and Defra.

EXECUTIVE SUMMARY

Land temperature

- 2019 was the 12th warmest year for the UK in a series from 1884, and 24th warmest for Central England in a series from 1659.
- Four national UK high temperature records were set in 2019: a new all-time record (38.7°C), a new winter record (21.2°C), a new December record (18.7°C) and a new February minimum temperature record (13.9°C). No national low temperature records were set.
- February 2019 was the second warmest February in the series from 1884 and the warmest February for daily maximum temperature.
- All the top 10 warmest years for the UK in the series from 1884 have occurred since 2002.
- The most recent decade (2010–2019) has been on average 0.3°C warmer than the 1981–2010 average and 0.9°C warmer than 1961–1990.
- The Central England Temperature (CET) series provides evidence that the 21st century so far has overall been warmer than the previous three centuries.

Air and ground frost

- 2019 was the sixth consecutive year where the number of air and ground frosts was below average. The number of ground frosts was 10th lowest in a series from 1961.
- The most recent decade (2010–2019) has had 6% fewer days of air frost and 10% fewer days of ground frost compared to the 1981–2010 average, and both 16% fewer compared to 1961–1990.

Energy demand and growing conditions indices

- Heating degree days (HDD) in 2019 were below average, and cooling and growing degree days (GDD) above average, although none exceptionally so.
- The most recent decade (2010–2019) has had 4% fewer HDD per year on average compared to 1981–2010 and 10% fewer compared to 1961–1990.
- The most recent decade (2010–2019) has had 5% more GDD per year on average compared to 1981–2010 and 15% more compared to 1961–1990.

Near-coast SST

- 2019 was the fourth warmest year for UK near-coastal SST in a series from 1870.
- The most recent decade (2010–2019) has been on average 0.3°C warmer than the 1981–2010 average and 0.6°C warmer than 1961–1990.
- Nine of the 10 warmest years for near-coast SST for the UK have occurred since 2002.

Precipitation

- 2019 rainfall for the UK overall was 107% of the 1981–2010 average and 112% of the 1961–1990 average.
- England and Wales had its fifth wettest autumn in a series from 1766, although much less wet overall than autumn 2000 (the wettest autumn in the series).
- Six of the 10 wettest years for the UK in a series from 1862 have occurred since 1998.
- The most recent decade (2010–2019) has been on average 1% wetter than 1981–2010 and 5% wetter than 1961–1990 for the UK overall.
- For the most recent decade (2010–2019) UK summers have been on average 11% wetter than 1981–2010 and 13% wetter than 1961–1990. UK winters have been 4% wetter than 1981–2010 and 12% wetter than 1961–1990.

Snow

- Snow fell fairly widely across the UK at the end of January and the start of February but this was not unusual for the time of year.
- 2019 was not a snowy year overall. It was not unusual in the context of the last two decades, but if compared to the last 60 years it was one of the least snowy years on record.
- Widespread and substantial snow events have occurred in 2018, 2013, 2010 and 2009, but their number and severity have generally declined since the 1960s.

Sunshine

- 2019 sunshine for the UK overall was 105% of the 1981–2010 average and 109% of 1961–1990 average.
- The most recent decade (2010–2019) has had for the UK on average 4% more hours of bright sunshine than the 1981–2010 average and 7% more than the 1961–1990 average.
- Winter and spring for the most recent decade (2010–2019) have had for the UK on average 5%/8% more sunshine than the 1981–2010 average and both 13% more than 1961–1990.

Wind

- Six named storms affected the UK in year 2019 (including ex-hurricane Lorenzo and storms Hannah and Atiyah named by Met Éireann).
- This was not a stormy year compared to recent decades.
- There are no compelling trends in storminess as determined by maximum gust speeds from the UK wind network over the last five decades.

Sea-level rise

- The UK mean sea level index for 2019 was the highest in the series from 1901, although uncertainties in the series mean caution is needed when comparing individual years.
- Mean sea level around the UK has risen by approximately 1.4 mm/yr from the start of the 20th century, when excluding the effect of vertical land movement.
- The 99th percentile water level (exceeded 1% of the time) at Newlyn, Cornwall for year 2019 was the third highest in the series from 1916, behind years 2014 and 2018.

Significant weather

- In late February, a new UK winter temperature record of 21.2°C was set during a record-breaking warm spell, breaking the previous winter record by a wide margin.
- In late July, a new UK all-time record of 38.7°C was set during a brief but exceptional heatwave.
- Flooding from persistent heavy rain affected parts of Lincolnshire in mid-June, and flash-flooding affected parts of the Pennines and northern England in late July.
- South Yorkshire, Derbyshire, Nottinghamshire and Lincolnshire experienced severe flooding in November 2019; at the time this event was the most severe flooding event in the UK since December 2015.

Phenology

- First leaf dates in 2019 were particularly early (on average 9.7 days earlier than the 1999–2018 baseline) for a range of common shrub/tree species. This was associated with relatively warm conditions in winter and early spring 2019.
- End of season bare tree dates in 2019 were slightly later (on average 2.4 days later than the baseline) for the same species.
- Overall, the 2019 leaf-on season was extended by 12.2 days on average compared with the baseline.

1 | SYNOPTIC SITUATION

Figure 1 shows seasonal mean sea-level pressure anomalies for the four seasons of 2019 relative to the 1981–2010 average, using the ERA5 reanalysis (Hersbach

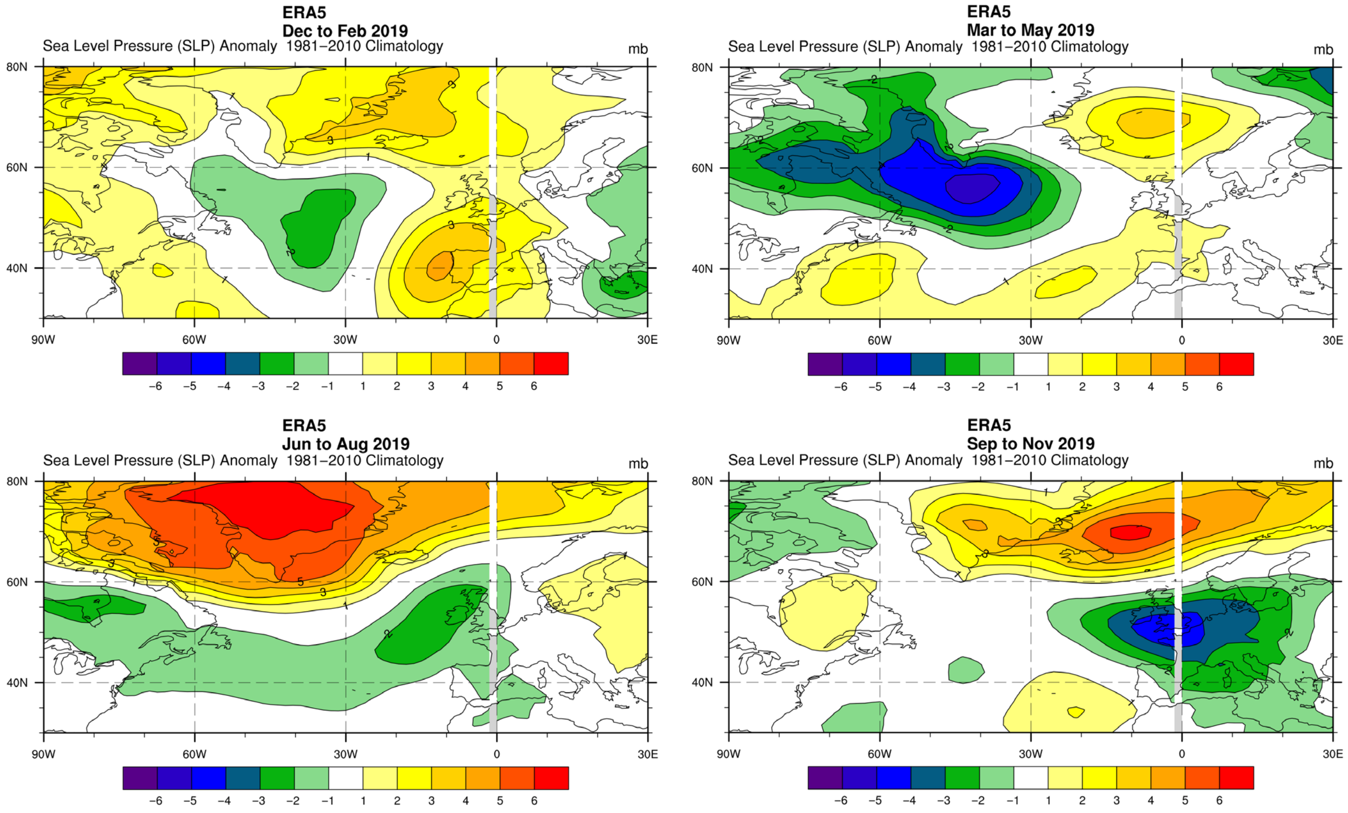
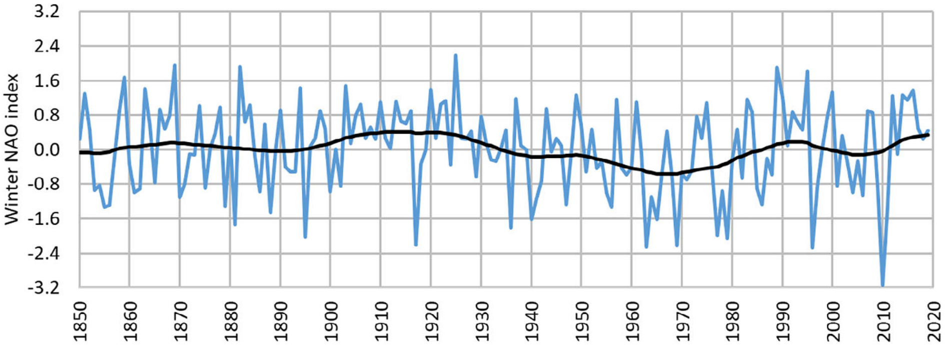


FIGURE 1 2019 seasonal mean sea-level pressure anomalies (hPa, relative to 1981–2010 average). Winter refers to the period December 2018–February 2019. Note that winter 2020 (December 2019–February 2020) will appear in State of the UK Climate 2020. Images provided by the NOAA-ESRL physical sciences division, Boulder, Colorado from their web site at http://www.esrl.noaa.gov/

FIGURE 2 Winter NAO index based on standardized monthly mean pressure difference between stations in Iceland and Gibraltar (see Annex 1 for details). Winter 2019 refers to the period December 2018–February 2019. Note that winter 2020 (December 2019–February 2020) will appear in State of the UK Climate 2020



et al., 2020). This provides an indication of atmospheric circulation patterns for each season overall.

January was a fairly quiet month with high pressure but cloudy and mild, although with increasing numbers of active frontal systems as the month went on. A northerly airflow brought the coldest spell of the winter at month end. February started cold but became very mild (exceptionally so toward month-end) with a southerly airflow from north Africa. December 2018 and February 2019 overall saw a low pressure anomaly to the west in the Atlantic with a high pressure anomaly across continental Europe, but this pattern reversed in January.

The seasonal pressure pattern for spring was similar to the long-term average pattern. The first half of March was unsettled with westerly low pressure systems including storms Freya and Gareth. However, high pressure over the near-continent brought drier weather from mid-month. After a wet start, the first half of April saw a period of easterly winds and dry but cool weather, followed by a period with high pressure to the east drawing warm continental air to the UK. May started cool with a northerly airflow but with a warmer spell and high-pressure building around mid-month.

The first two-thirds of June was generally cool and wet, with low pressure influencing the UK's weather. This was followed by a period of higher pressure and generally more settled weather for the latter part of June, extending through July and into early August. However, the remainder of August was unsettled, showery and cool as low pressure re-exerted its influence, with the exception of a few hot days late in the month coinciding with the August Bank Holiday.

For most of September the weather was relatively quiet with a period of high pressure over the UK around mid-month. However, after this the weather became much more unsettled and stormy at times, with the Jet Stream regularly tracking further south across England and Wales, particularly through October and November. The unsettled westerly weather type continued for much of the rest of the year, with any dry, setted interludes mainly short-lived. A deep low-pressure anomaly was centred across the south of the UK in November and northern Scotland in December.

1.1 | NAO index

Figure 2 shows the winter North Atlantic Oscillation (WNAO) index from 1850 to 2019 inclusive (Annex 1 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 Iceland and the Azores, which determines the strength of westerly winds across the Atlantic, and is thus 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 2019 was very slightly positive. The winter overall was mild and fairly dry—that is, neither characteristic of a WNAO +ve winter dominated by mild, wet westerly weather patterns (such as winter 2014 or 2016) or a WNAO –ve winter dominated by cold, dry blocked weather patterns (such as 2010). The 2019 WNAO index (+0.4) was similar to the 2017 WNAO index (+0.5) and this winter was similarly mild and fairly dry overall. Inevitably over this 3-month duration many if not most winters have a mixture of weather types and fall somewhere between these two extremes. Overall, the WNAO index shows a large annual variability but also decadal variability with periods of mainly positive phase (e.g., 1910s–1920s and 1990s) and negative phases (e.g., 1960s). Hanna *et al.* (2015) discusses recent changes in the NAO index and notes an increase in variability of WNAO within the last two decades.

Figure 3 shows the Summer North Atlantic Oscillation (SNAO) index from 1850 to 2019 inclusive (Annex 1 provides details of the SNAO index). Similar to the

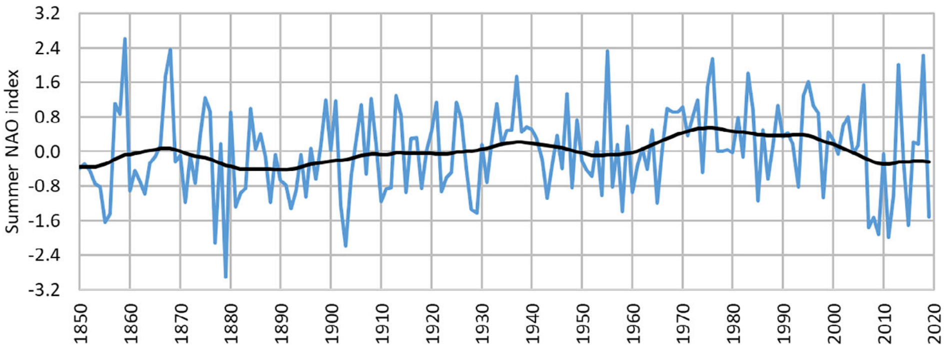


FIGURE 3 Summer NAO index based on standardized monthly mean pressure difference using HadSLP2 dataset (see Annex 1 for details). Summer 2019 refers to the period June to August 2019

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.

The UK's summer in 2019 was warmer but much wetter than average and the 2019 SNAO index was the tenth most negative in the series. For the UK, a negative SNAO tends to be associated with cool, wet summers. Other recent summers with a low SNAO index include 2007, 2008, 2009, 2011, 2012 and 2015 and these were all generally wetter than average (especially 2007, 2008, 2009 and 2012) with temperatures mostly near or below average (especially 2011, 2012 and 2015). Although summer 2019 was warmer than average overall, the hot spells of weather were relatively brief and the weather was often cool and unsettled during June and August.

As with its winter counterpart, the SNAO shows periods of mainly positive phase (e.g., 1970s–1990s) and negative phase (e.g., 1880s and 1890s), with Hanna *et al.* (2015) noting a striking recent decrease in SNAO since the 1990s, which includes the run of recent wet summers from 2007 to 2012. The summers of 2013 and 2018 were in marked contrast to this recent sequence.

2 | TEMPERATURE

Four new national high temperature records were set in 2019: a new UK all-time record, a new UK winter record, a new UK December record and a new UK February highest minimum record. Correspondingly, new temperature records were set at many individual stations. No new national low temperature records were set in 2019. The difference between the number of new high and low

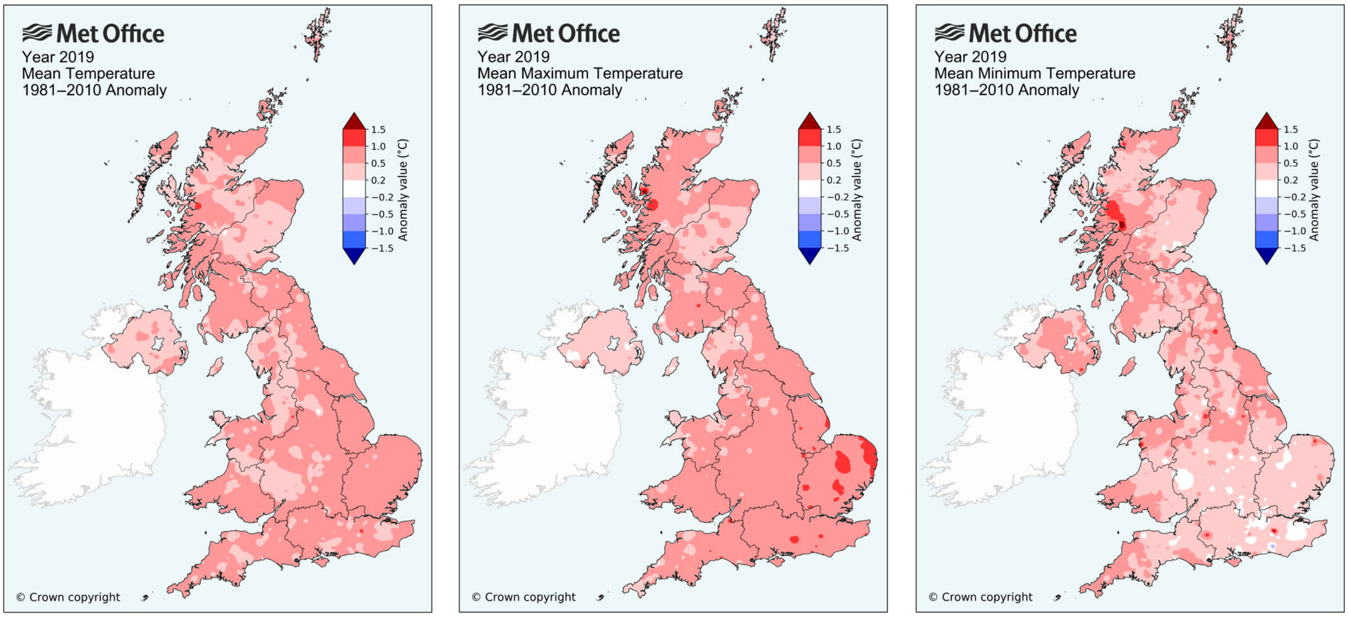


FIGURE 4 2019 annual average temperature anomalies (°C) relative to 1981–2010 average for mean, maximum and minimum temperature. Bulls-eye features present in the $T_{\min}$ map are likely to be due to localized micro-climate features, such as frost hollow effects, at individual weather stations which the gridding process is unable to fully represent

TABLE 1 Monthly, seasonal and annual mean temperature and anomaly values (°C) relative to 1981–2010 average for the UK, countries and CET for year 2019

	UK		England		Wales		Scotland		Northern Ireland		CET	
	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly
January	3.5	−0.2	3.8	−0.3	4.1	0.0	2.5	−0.2	4.8	0.6	4.0	−0.4
February	6.0	2.4	6.5	2.3	6.4	2.5	5.1	2.4	6.7	2.3	6.7	2.3
March	6.8	1.3	7.7	1.5	7.0	1.2	5.2	1.1	6.7	0.9	7.8	1.2
April	8.4	1.0	8.8	0.6	8.8	1.2	7.6	1.5	8.5	0.9	9.1	0.6
May	10.0	−0.3	11.0	−0.2	10.2	−0.4	8.3	−0.5	9.8	−0.4	11.1	−0.6
June	13.2	0.2	14.2	0.2	13.3	0.1	11.6	0.2	12.6	−0.2	14.2	−0.3
July	16.4	1.2	17.5	1.2	16.0	0.9	14.7	1.4	15.6	1.0	17.5	0.8
August	15.8	0.9	17.0	0.9	15.9	0.9	13.9	0.8	15.1	0.8	17.1	0.7
September	13.1	0.4	14.1	0.4	13.4	0.5	11.4	0.5	12.8	0.4	14.3	0.3
October	8.9	−0.5	10.0	−0.4	9.5	−0.4	7.2	−0.7	8.6	−0.8	10.0	−0.7
November	5.3	−0.9	6.2	−0.7	5.9	−0.8	3.6	−1.3	5.5	−1.0	6.2	−0.9
December	5.1	1.3	5.6	1.3	5.6	1.2	4.1	1.4	5.4	0.9	5.8	1.2
Winter	5.1	1.3	5.6	1.4	5.8	1.6	3.9	1.2	6.0	1.6	5.9	1.3
Spring	8.4	0.6	9.2	0.6	8.6	0.6	7.0	0.7	8.3	0.5	9.3	0.4
Summer	15.1	0.8	16.3	0.8	15.1	0.6	13.4	0.8	14.4	0.5	16.3	0.4
Autumn	9.1	−0.3	10.1	−0.2	9.6	−0.2	7.4	−0.5	9.0	−0.5	10.2	−0.5
Annual	9.4	0.5	10.2	0.6	9.7	0.5	7.9	0.5	9.4	0.4	10.3	0.3

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

Note: Colour coding relates to the relative ranking in the full series which spans 1884–2019 for all series except CET which is 1659–2019.

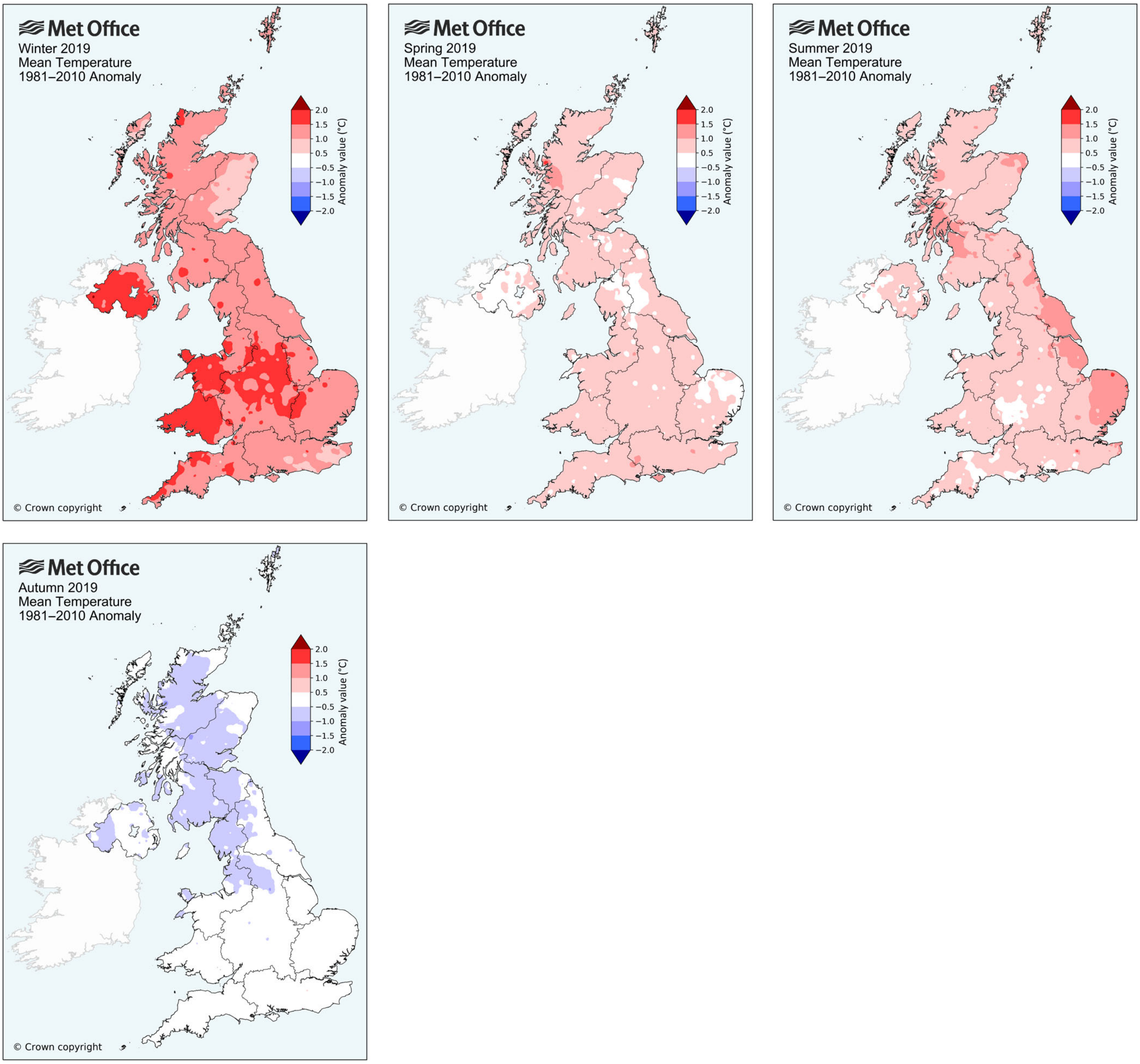


FIGURE 5 2019 seasonal average temperature anomalies (°C relative to 1981–2010 average). Winter refers to the period December 2018–February 2019. Note that winter 2020 (December 2019–February 2020) will appear in State of the UK Climate 2020

temperature records set is typical for what we might expect in a warming climate (although in any individual year the numbers may vary substantially). For more details of the record-breaking events, see Section 8.

In contrast to these records, the area-average statistics for the UK overall for the months, seasons and year 2019 were less exceptional. The UK mean temperature (T_{mean}) for 2019 was 9.4°C, which is 0.5°C above the 1981–2010 long-term average, making this the 12th warmest year in the UK series from 1884. Then, 2019 was ranked 24th warmest in the CET series from 1659. The annual mean temperature was around 0.5°C above normal across the UK (Figure 4, Table 1).

The UK annual mean daily maximum temperature (daily maximum temperature is hereafter referred to as T_{max}) for 2019 was 13.1°C, which is 0.6°C above average. The highest T_{max} anomalies of over 1.0°C were across East Anglia, with the lowest anomalies across Northern Ireland. The UK annual mean daily minimum temperature (daily maximum temperature is hereafter referred to as T_{min}) for 2019 was 5.7°C, which is 0.5°C above average. T_{min} anomalies were generally lower across the southern half of the UK and higher across the northern half (Figure 4, Table 1).

The UK seasonal T_{mean} for winter 2019 (December 2018–February 2019) was 5.1°C, which is 1.3°C above the

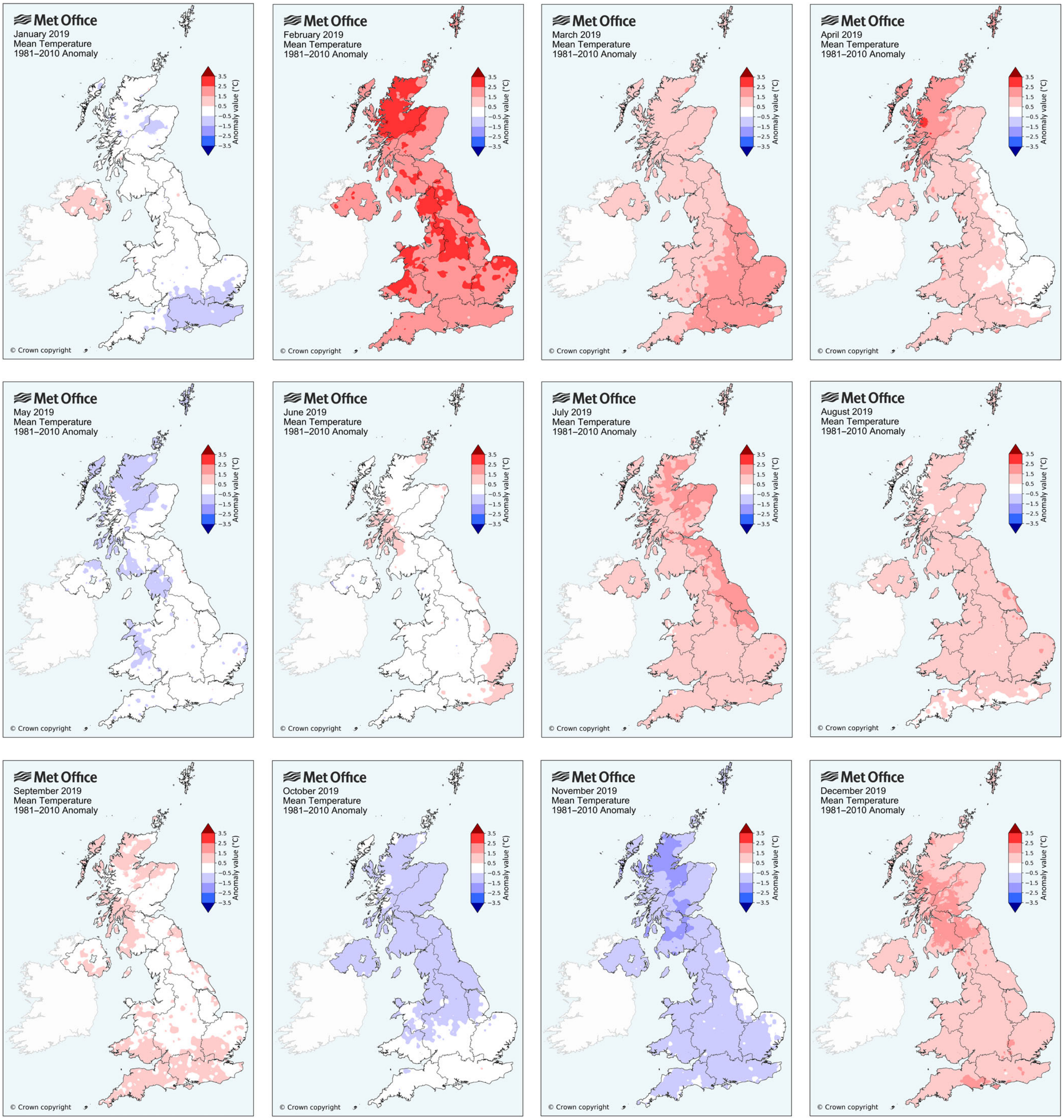
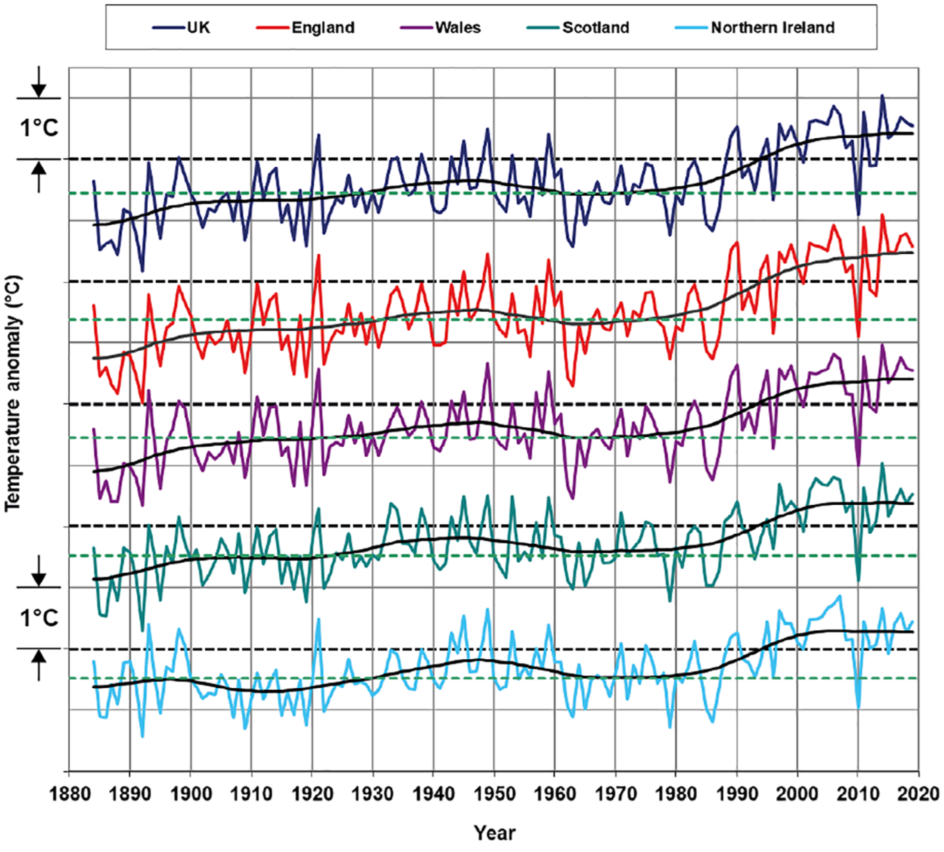


FIGURE 6 2019 monthly average temperature anomalies (°C) relative to 1981–2010 average

1981–2010 average. This was the eighth warmest winter for the UK in the series from 1884 (and ranked third and fifth warmest for Northern Ireland and Wales, respectively). Temperatures were slightly below normal in January but well above in December 2018 (anomaly +1.9) and February (+2.4°C)—the latter influenced by the exceptionally mild southerly airflow later in the month (Figures 5 and 6, Table 1). There were some sharp frosts and snowfalls at the end of January and the start of February. However, during the last week of February the UK experienced a record-breaking warm spell, setting a new UK winter temperature record, and monthly mean maximum temperature anomalies exceeded 4°C across central and eastern parts of England. This was the second-warmest February in the UK series from 1884 (with only February 1998 warmer) and for daily maximum temperatures the warmest February on record.

The UK seasonal T_{mean} for spring was 8.4°C, which is 0.6°C above the 1981–2010 average. Temperature anomalies were above normal in March (anomaly +1.3°C and the tenth warmest March in UK series from 1884) and also April (anomaly +1.0°C). There was a marked absence of cold spells in March. From 18th to 23rd April there was a spell of fine, warm, setted weather coinciding with the Easter weekend and temperatures widely at least 8°C above normal for the time of year. A maximum temperature of 25.8°C was recorded at Treknow, Cornwall on 19th—13°C above the 1981–2010 April average at this station—and temperatures reached the low 20s widely across the UK. On 20th, 22.9°C at Balmoral made this the warmest April day here since 1914, and on 23rd, 24.4°C was recorded at Port Henderson, Wester Ross in the far north-west of Scotland.

The UK seasonal T_{mean} for summer was 15.1°C, 0.8°C above normal. Despite the fact that temperatures in the UK reached 34.0°C in June, 38.7°C in July and 33.4°C in August on individual days, this was ranked only the equal-11th warmest summer in the UK series from 1884. In contrast to summer 2018 (ranked equal-warmest), the spells of hot weather during summer 2019 were relatively short-lived. Temperatures were near-normal overall in June (anomaly +0.2°C) but the month saw some dramatic temperature contrasts. On 11th June, daily maximum temperatures reached only 10°C across central England and 8–9°C across parts of Wales. Several stations recorded their coldest June day for more than 50 years. During a short spell of hot weather toward the end of the month, 30.0°C was recorded at Achnagart, Highland on 28th and 34.0°C at Heathrow and Northolt, both Greater London, on 29th. This was only the second time since 1976 that 34°C had been reached in the UK on a June day (the other being 21st June 2017). The brief hot spell in June was a result of a tropical continental air mass that saw exceptional temperatures further south, setting a new national temperature record for France with 46.0°C measured at Veragues on 28th. The UK experienced a record-breaking heat-wave in late July with a new UK temperature record of 38.7°C (for more details see Section 8). This was also associated with a heatwave in the near-continent where temperatures reached the low 40s, but, in contrast to the situation elsewhere in Europe, for the UK this heatwave was again relatively brief and the July temperature anomaly overall was



Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK	8.3	8.8	9.2	9.4
England	9.0	9.7	10.0	10.2
Wales	8.6	9.1	9.5	9.7
Scotland	6.9	7.4	7.7	7.9

FIGURE 7 Annual T_{mean} (°C) for the UK and countries, 1884–2019, expressed as anomalies relative to the 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±1°C. The table provides average values (°C). Smoothed trend lines used here and throughout the report are described in Annex 2

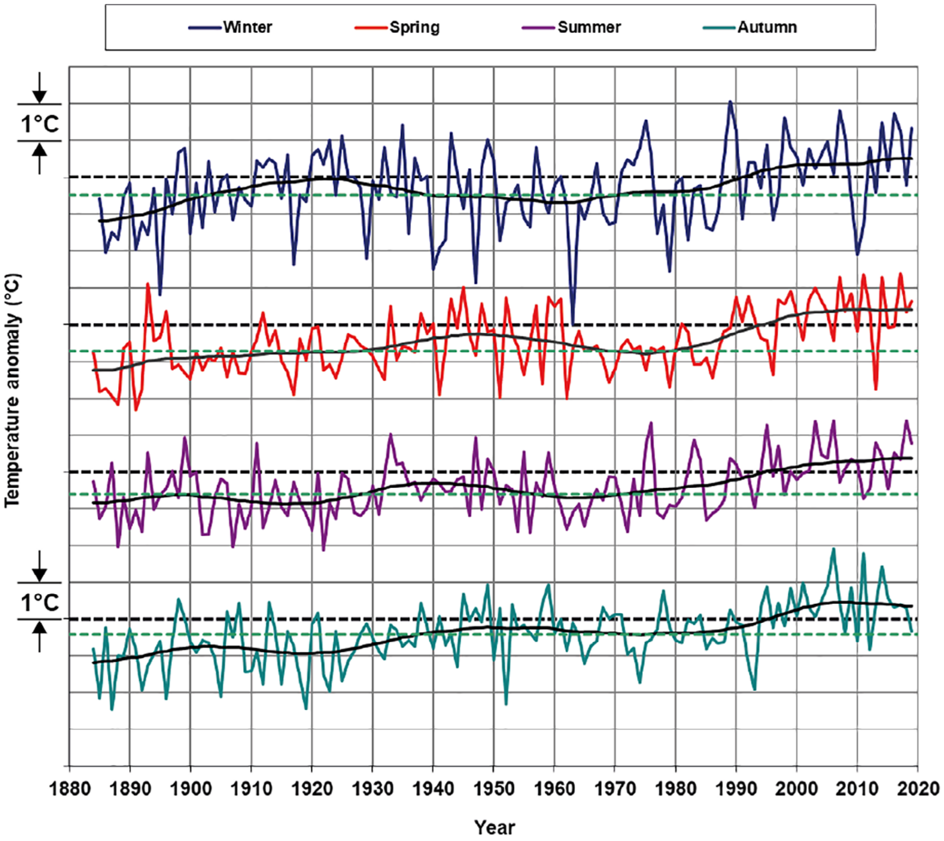


FIGURE 8 Seasonal T_{mean} (°C) for the UK, 1884–2019, expressed as anomalies relative to the 1981–2010 average (note winter from 1885 to 2019; year is that in which January and February fall. Winter 2020—which includes December 2019—will appear in next year's publication). The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±1°C. The table provides average values (°C)

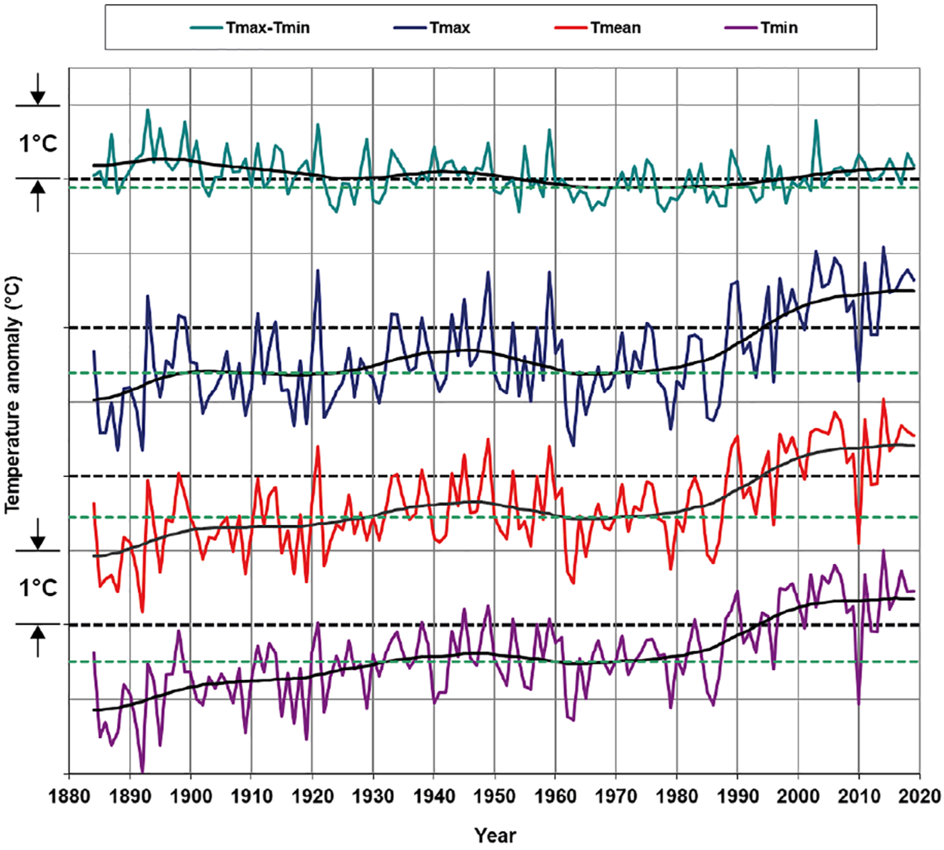
Season	1961–1990 average	1981–2010 average	2010–2019 average	2019
Winter	3.3	3.7	4.0	5.1
Spring	7.0	7.7	8.1	8.4
Summer	13.8	14.4	14.6	15.1
Autumn	9.0	9.4	9.8	9.1

a modest +1.2°C (the equal-seventh warmest July for the UK in a series from 1884, but not as warm as July 2018, ranked second). August was also warmer than average (anomaly +0.9°C) with a warm spell around the late August bank holiday and temperatures reaching 33.4°C at Heathrow, Greater London on the 27th.

While winter, spring and summer 2019 were all warmer than average for the UK, the autumn was cooler than normal (anomaly −0.3°C). September was warmer than average (anomaly +0.4°C) whereas both October (anomaly −0.5°C) and November (anomaly −0.9°C) were often cool, although not exceptionally so. December, which is included in Figure 6 but not Figure 5, was a mild month (anomaly +1.3°C). On 28th, a new UK December temperature record of 18.7°C was set in the far north of Scotland, due to a localized Foehn effect from a southerly flow across the Highlands (for more details see Section 8). In summary, for year 2019 overall, temperatures were above average for February to April, July to September and December, but near or below average in January, May to June and October to November (Figure 6, Table 1).

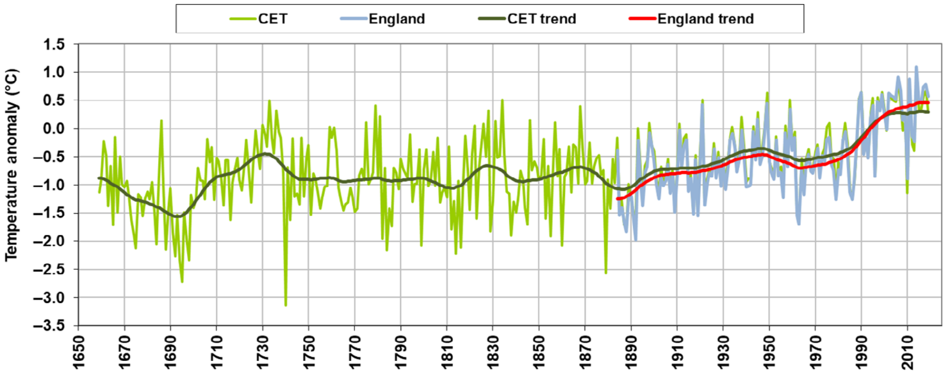
Figure 7 shows time series of annual T_{mean} anomalies for the UK and countries from 1884 to 2019 inclusive, and Figure 8 the seasonal UK T_{mean} anomaly series. There has been an increase in temperature from the 1970s to the 2000s with the most recent decade (2010–2019) being on average 0.9°C warmer than the 1961–1990 average and 0.3°C above 1981–2010. All the top 10 warmest years in the UK T_{mean} series have occurred since 2002 (Figure 7). Year 2019 is ranked 12th warmest and was warmer than any year in the series from 1884 to 1990. In contrast, none of the top 10 coldest years in the UK T_{mean} series have occurred this century. The coldest year this century (2010) is ranked 22nd coldest in the UK series.

All four seasons have seen 2010–2019 warmer than 1961–1990, with the largest change for spring at 1.1°C and winter, summer and autumn between 0.7 and 0.9°C above normal (Figure 8). 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 to the 2000s. Warming has been slightly greater for T_{max} than T_{min} in recent decades (Figure 9) resulting in a small increase in



Variable	1961–1990 average	1981–2010 average	2010–2019 average	2019
Tmax	11.8	12.5	12.9	13.1
Tmean	8.3	8.8	9.2	9.4
Tmin	4.8	5.3	5.5	5.7
Tmax minus Tmin	7.1	7.2	7.3	7.4

FIGURE 9 Annual $T_{\max}$, T_{mean} and $T_{\min}$ (°C) for the UK, and $T_{\max}$ minus $T_{\min}$, 1884–2019, expressed as anomalies relative to the 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±1°C. The table provides average values (°C)



Variable	1961–1990 average	1981–2010 average	2010–2019 average	2019
CET	9.5	10.0	10.2	10.3
England	9.0	9.7	10.0	10.2

FIGURE 10 Annual T_{mean} (°C) for CET series, 1659–2019, and England temperature series, 1884–2019, expressed as anomalies relative to the 1981–2010 average. The table provides average values (°C)

the average daily temperature range but to levels similar to those observed prior to the mid 20th century.

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

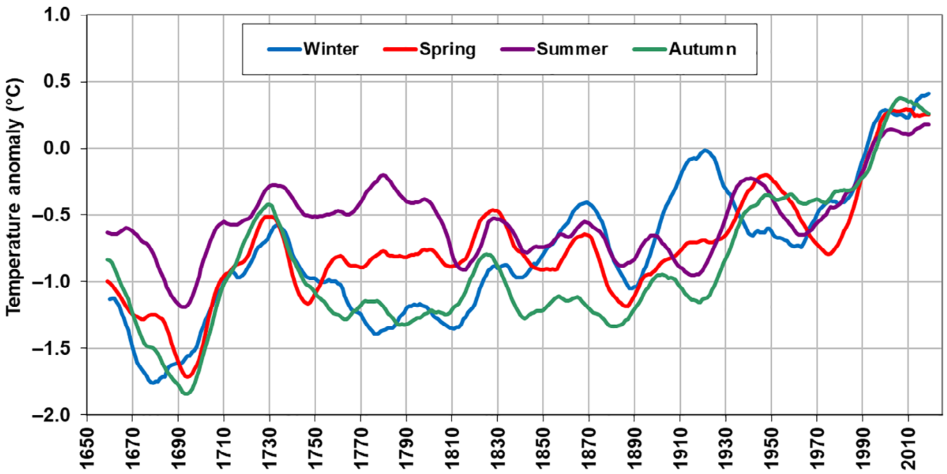


FIGURE 11 Seasonal CET series (°C), 1659–2019, expressed as anomalies relative to 1981–2010 average. The figure shows a smoothed trend for each series using a weighted kernel filter described in Annex 2

TABLE 2 Centennial averages for CET series (°C) 1659–2019 (winter from 1660 to 2019)

Season	1659–1700	1701–1800	1801–1900	1901–2000	2001–2019
Year	8.7	9.2	9.1	9.5	10.3
Winter	3.0	3.5	3.7	4.2	4.8
Spring	7.5	8.1	8.1	8.4	9.2
Summer	14.9	15.5	15.2	15.4	16.0
Autumn	9.1	9.6	9.5	10.1	11.0

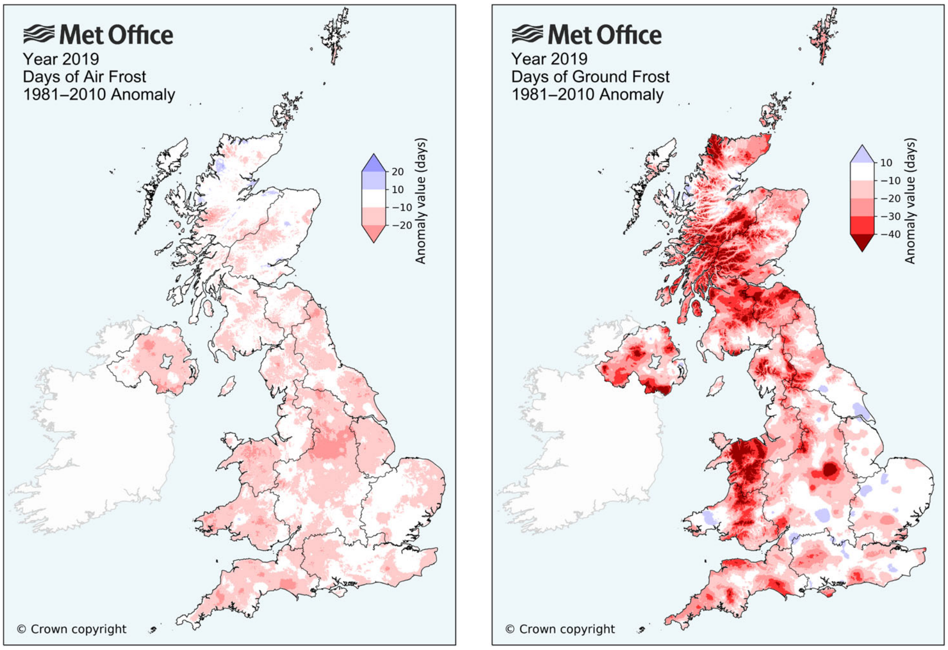
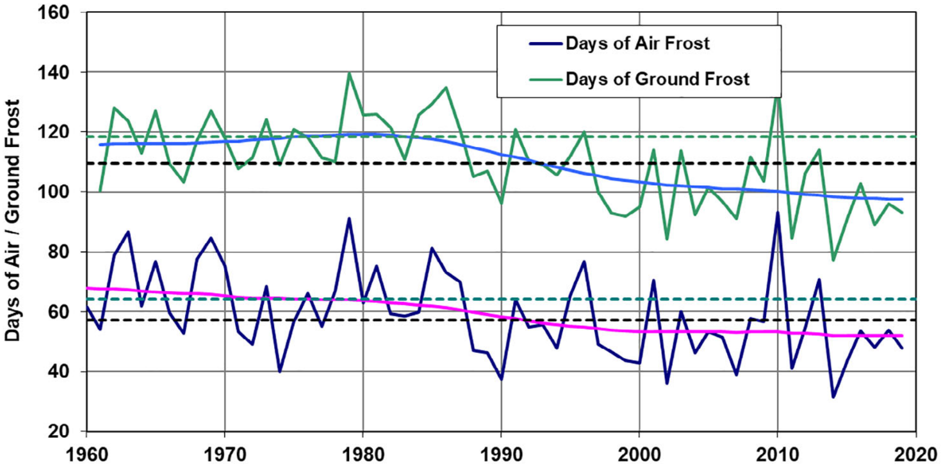


FIGURE 12 Days of air frost and days of ground frost for 2019, difference from 1981–2010 average. See Annex 1 for definitions. Bulls-eye features in these and the $T_{\min}$ maps are likely to be due to localized factors such as frost hollow effects at individual weather stations (present in the actual or long-term average grids) which the gridding process is unable to fully represent, particularly for ground frost

information relating to the uncertainties and how they are estimated is provided in Annex 2.

Figure 10 shows annual T_{mean} for England from 1884 to 2019 and CET series from 1659. The series are highly correlated for the period of overlap (R^2 value .98) and have a root-mean-square difference of 0.1°C which is comparable to the estimated series uncertainty as described in Annex 2. 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 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 are also warmer (Figures 10 and 11). When comparing the early 21st century (2001–2019) to previous centennial averages, the difference is typically 0.5–1.0°C compared to 1901–2000 and 0.5–1.5°C compared to 1801–1900 and



Variable	1961-1990 average	1981-2010 average	2010-2019 average	2019
Days of Air Frost	64	57	54	48
Days of Ground Frost	118	110	99	93

FIGURE 13 Annual number of days of air frost and ground frost for the UK, 1961–2019. The hatched black line is the 1981–2010 long-term average. The hatched green line is the 1961–1990 long-term average. The table provides average values (days)

1701–1800, with the greatest difference in autumn and the least in summer (Table 2)

2.1 | Days of air and ground frost

The year 2019 was the sixth consecutive year where the number of days of air and ground frosts were below the 1981–2010 average. The average number of days of air frost for the UK for 2019 was 48 days, 9 days below average. The number of air frosts was around 5 days below average across much of Scotland but typically 10–15 days below across England, Wales and Northern Ireland. The number of days of ground frost for 2019 was 93 days, 16 days below the 1981–2010 average and 10th lowest in a series from 1961. Some locations recorded at least 30 fewer days of ground frost for the year overall compared to normal but with considerable spatial variation across the UK (Figure 12). The low number of ground frosts seen in Wales is consistent with the winter of 2019 being in the top 10 warmest years for Wales. The number of air and ground frosts was well below average in February, March

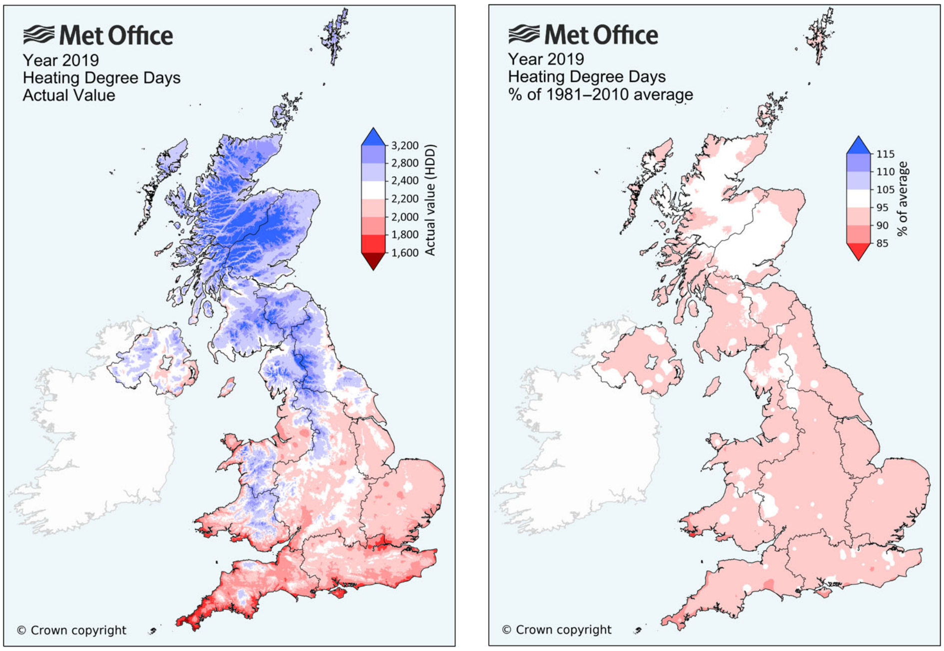


FIGURE 14 Heating degree days for 2019 (left) actual and (right) % of 1981–2010 average

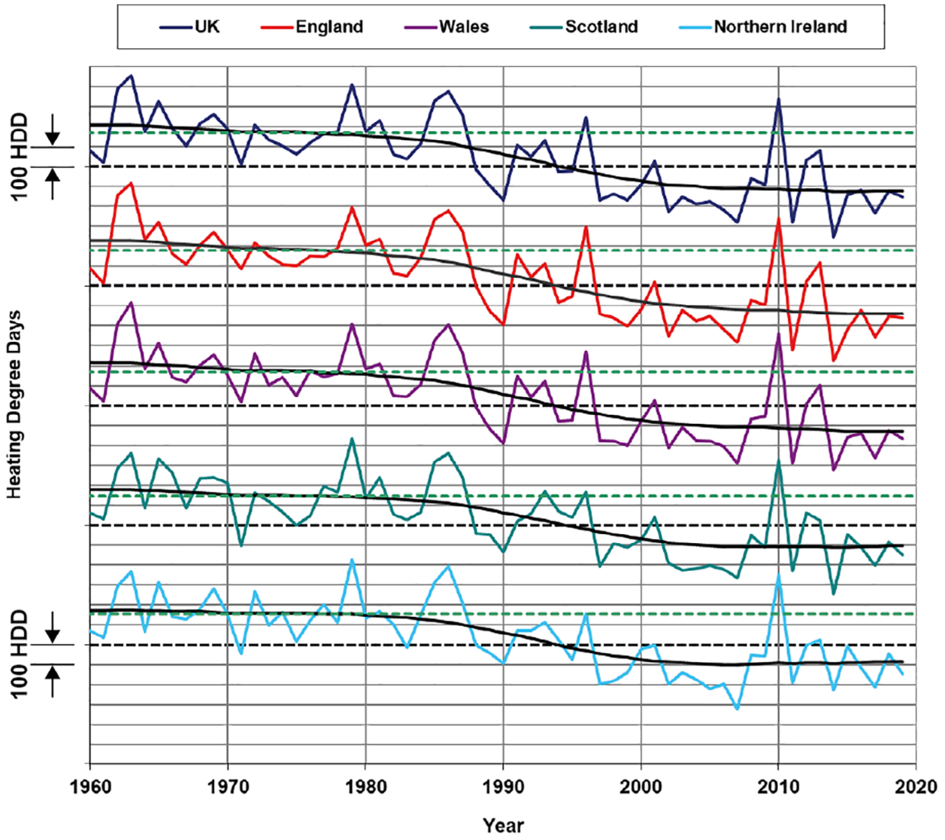


FIGURE 15 Heating degree days for the UK and countries, 1960–2019, expressed as anomalies relative to the 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±100 HDD. The table provides average values (HDD)

Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK	2736	2570	2474	2414
England	2520	2342	2229	2183
Wales	2616	2447	2348	2280
Scotland	3142	2994	2919	2844
Northern Ireland	2649	2495	2438	2348

and December but slightly above in January, and well above average in Scotland in both October and November, consistent with those latter months falling in the lowest third of years since 1884 for temperature (Table 1).

The annual numbers of days of air and ground frost for the UK overall for 2019 was slightly below the average for the most recent decade, with the series showing a reduction through the 1980s and 1990s. The most recent decade, 2010–2019, has recorded 16% fewer annual days of air frost and ground frost per year than the average for 1961–1990, and 6%/10% fewer, respectively than 1981–2010 (Figure 13). The most recent years with above average days of air and ground frosts were 2013 and 2010. Annex 1 explains how these areal-series are calculated.

2.2 | Degree days

A degree day is an integration of temperature over time and is commonly used to relate temperature to particular impacts. It is typically estimated as the sum of degrees above or below a defined threshold each day over a fixed period of time. The standard degree days monitored by the Met Office are heating, cooling and GDD which relate to the requirement for heating or cooling of buildings to maintain comfortable temperatures, or 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 definitions and thresholds used are described in Annex 1.

HDD for 2019 were between 90 and 95% of average across most of the UK but nearer average across Scotland (Figure 14). Averaged across the UK, HDD for 2019 were 94% of the 1981–2010 average although near the average for the most recent decade. The lowest 10 HDD years for the UK in a series from 1960 have all occurred since 1990, with the lowest eight since 2002, and year 2019 ranked 12th lowest (Figure 15).

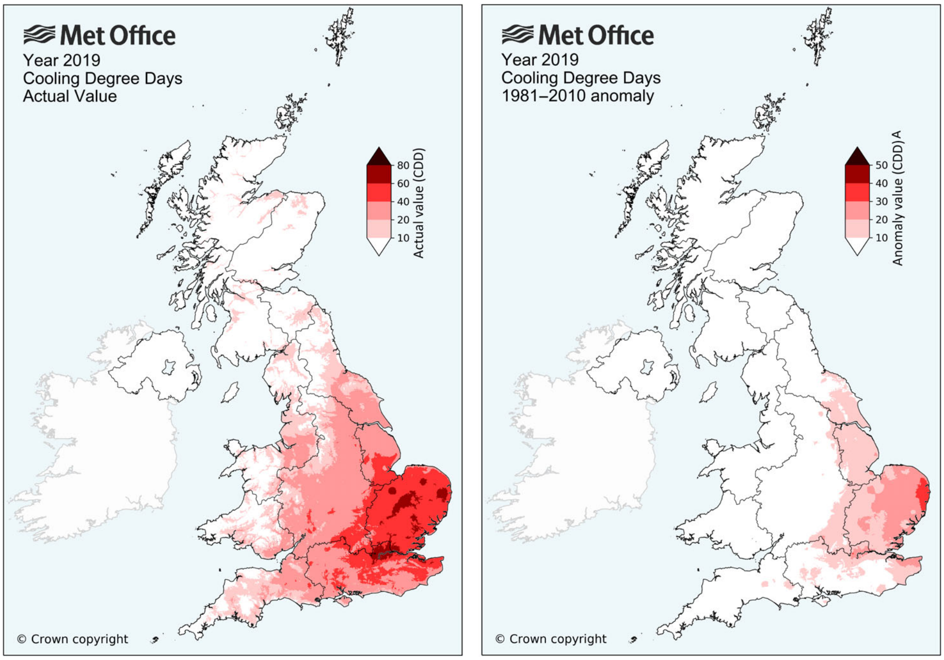
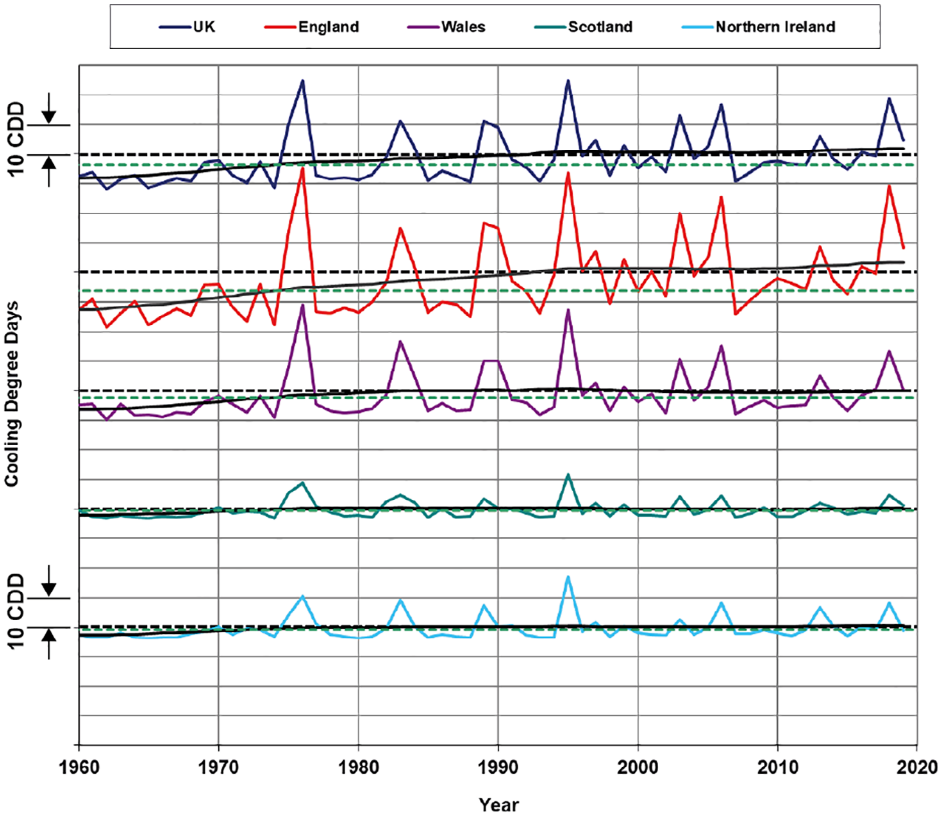


FIGURE 16 Cooling degree days for 2019, (left) actual and (right) anomaly. The anomaly is presented as a difference from, rather than percentage of, average. This is because CDD long-term averages are close to zero over much of Highland Scotland



Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK	9	13	14	18
England	14	21	23	29
Wales	8	10	9	10
Scotland	3	3	3	4
Northern Ireland	3	4	4	2

FIGURE 17 Cooling degree days for the UK and countries, 1960–2019, expressed as anomalies relative to the 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±10 CDD. The table provides average values (CDD)

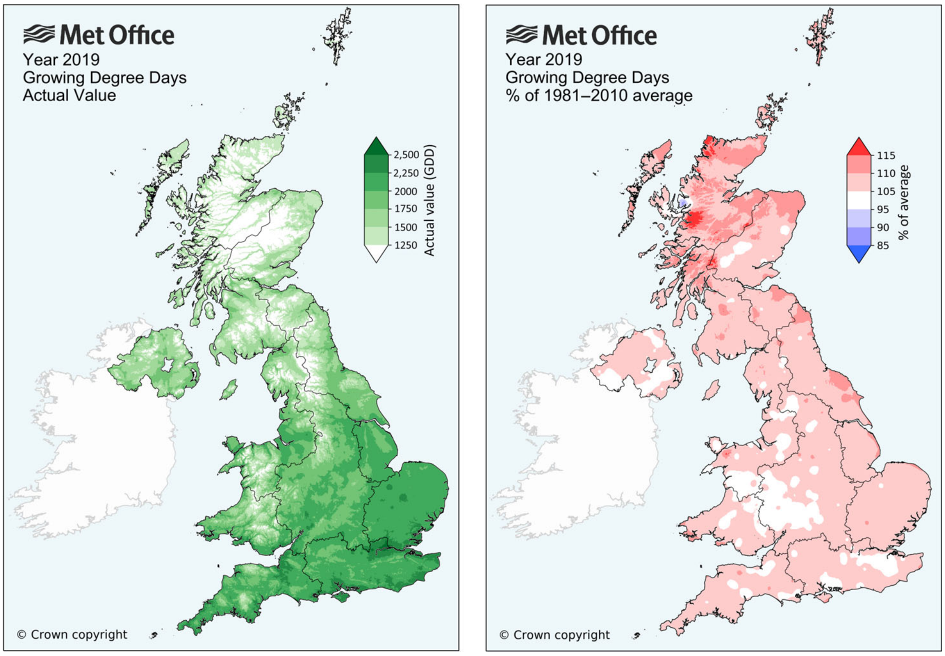


FIGURE 18 Growing degree days for 2019 (left) actual and (right) % of 1981–2010 average

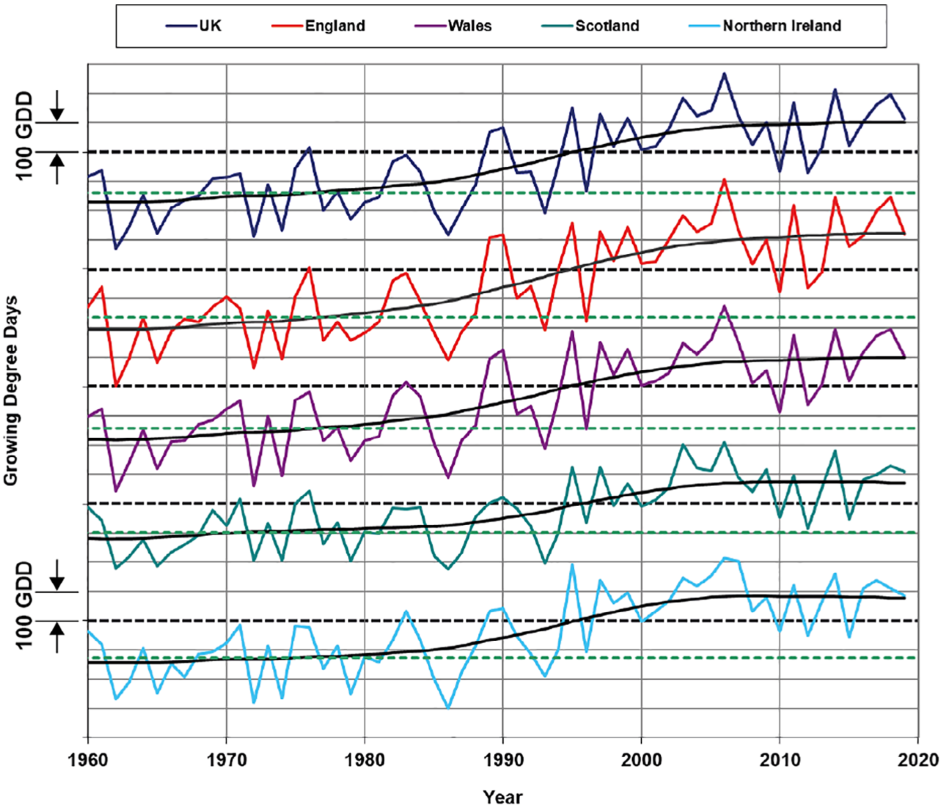


FIGURE 19 Growing degree days for the UK and countries, 1960–2019, expressed as anomalies relative to the 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The hatched green line is the 1961–1990 long-term average. Light grey gridlines represent anomalies of ±100 GDD. The table provides average values (GDD)

Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK	1472	1611	1697	1724
England	1678	1842	1949	1963
Wales	1520	1663	1746	1765
Scotland	1127	1226	1281	1333
Northern Ireland	1427	1553	1618	1639

For the UK, the most recent decade 2010–2019 has had an annual average HDD 10% lower than 1961–1990 and 4% lower than 1981–2010. Nevertheless, recent years such as 2010 and 2013 demonstrate it is still possible for UK climate to experience well above average HDD values.

The UK experienced three spells of hot weather in late June, late July and late August 2019. However, these spells were relatively short-lived with temperatures exceeding 28°C fairly widely on only 1 day in June and 4 days in July and August, respectively. Since cooling degree days (CDD) are an integration of temperature over time, CDD for 2019 (18) were not exceptional, and much less than year 2018 (32)—although they were well above the 1981–2010 average (13). As is typically the case, the spells of hot weather during 2019 were mainly located across central and south-east England, where there were typically 40–60 CDD, and this was well above average across parts of eastern England, notably East Anglia (Figure 16).

Across England and Wales the significant peaks in CDD depend on when the heat-waves have occurred historically (including 1976, 1995, 2003, 2006 and 2018). Although these time-series are dominated by annual variability, there is an underlying rising trend. For England, the most recent decade 2010–2019 CDD value of 23 compares to 21 for 1981–2010 and 14 for 1961–1990. The cooler climate of Scotland and Northern Ireland means that CDD are much lower, each with long-term averages of less than 5 CDD (Figure 17).

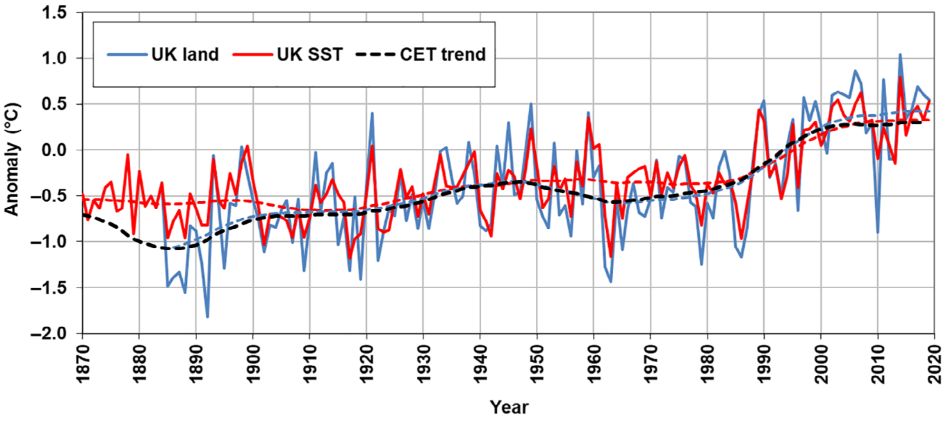
GDD for 2019 were between 105 and 110% of average across much of the UK, but with some regional variation (Figure 18). UK GDD overall were 107% of the 1981–2010 average. The most recent decade has had an annual GDD 15% higher than 1961–1990 and 5% higher than 1981–2010, and the similar (downward) trend in HDD and (upward) trend in GDD from 1960 to date each reflect the underlying warming of the UK's climate (Figure 19). The year 1993 was the last year with GDD below the 1961–1990 average for the UK overall.

2.3 | Coastal waters

The annual mean SST for 2019 for near-coast waters around the UK was 12.0°C, 0.5°C above the 1981–2010 long-term average. This was the fourth-warmest year for UK near-coast SST (Figure 20). For UK near-coast SST, the most recent decade, 2010–2019, is 0.6°C warmer than the 1961–1990 average and 0.3°C above 1981–2010. Nine of the 10 warmest years in the series have occurred since 2002, and all 10 since 1989. Every year this century has fallen within the warmest third of the series.

Over the past 30 years, warming has been most pronounced in the north of Scotland and the North Sea, with SSTs increasing by up to 0.24°C per decade. However, shorter-term variations are superimposed on the longer-term trend, for example, a period of cooler SSTs from 2010 to 2013. Recent years have seen warmer conditions return (Tinker and Howes, 2020).

Near-coast SST data are highly correlated with the land observations (R^2 value .82, see Annex 2) with a root mean square difference of less than 0.3°C. Some differences between historical trends in these series are apparent, notably the 1960s and 1970s and the period pre-1900. However, these differences are also apparent in the CET series, also shown in Figure 20, which closely follows the UK series. Uncertainties in the SST dataset will generally be larger at smaller scales (such as UK near-coast) and



Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK land	8.3	8.8	9.2	9.4
UK near-coast SST	11.1	11.5	11.7	12.0

FIGURE 20 UK annual mean temperature over land 1884–2019, CET trend and UK annual mean SST across near-coastal waters around the UK 1870–2019, expressed as anomalies relative to the 1981–2010 long-term average. Hatched blue and red lines are the UK land and SST trends. The table provides average values (°C)

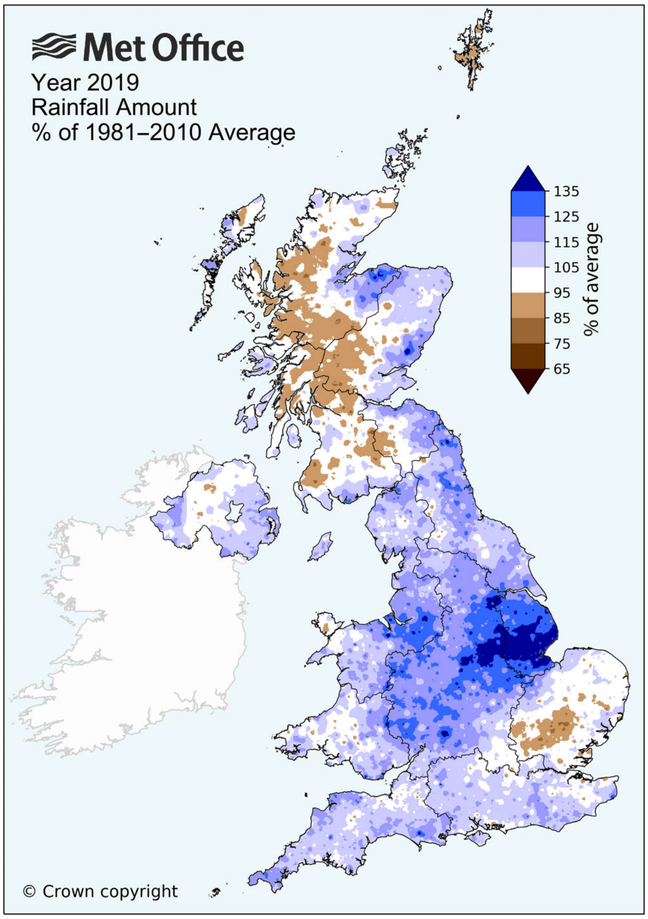


FIGURE 21 Rainfall anomalies (%) for year 2019

can include uncertainty in the bias adjustments applied to minimize the effect of instrumentation changes.

3 | PRECIPITATION

The UK rainfall total for 2019 was 1,227 mm, 107% of the 1981–2010 average. Most of the UK received above average rainfall, with the exception of parts of East Anglia and the Home Counties, western and northern Scotland and Shetland. It was a particularly wet year across parts of central and northern England—notably Lincolnshire, Nottinghamshire, Derbyshire, Leicestershire and Cheshire which received 125–135% of the long-term average widely and 140–150% at a few individual locations (Figure 21). For northern England (north of a line from the Wash to North Wales) this was the ninth wettest year in a series from 1862.

The wettest and driest observed locations for the year generally reflected the long-term climatology. Several rain-gauges across the Lake District, Snowdonia and the West Highlands recorded over 3,000 mm with 4,123 mm at Ennerdale, Black Sail, 4,025 mm at Honister Pass and 5,217 mm at Styhead—the latter a monthly raingauge—all in the English Lake District. The driest locations in Essex, Cambridgeshire and Suffolk recorded less than 500 mm.

Figures 22 and 23 and Table 3 show seasonal and monthly rainfall anomalies across the UK for 2019. Inevitably, as is always the case, the annual map conceals the detail behind significant monthly and seasonal variations which occurred in rainfall patterns over the course of the year.

The UK rainfall total for winter was 254 mm, 77% of the 1981–2010 long-term average and totals were below average throughout the UK, particularly parts of north-east England and south-east Scotland with less than 50% fairly widely. December 2018 rainfall totals were broadly close to average across many areas but parts of northern and eastern Britain were drier whereas some areas of England and Wales had a rather wet month (not shown). January was a dry month with less than 50% of normal rainfall widely and less than 10 mm fell in the driest locations across Fife, Edinburgh and Lothian. February rainfall totals were near or rather below average with 81% for the UK overall.

Spring rainfall was near average for the UK overall but it was relatively wet across Wales, Scotland and Northern Ireland and dry across southern and eastern England with less than 70% of the average rainfall here. March was a wet month across much of Wales, north-west England and southern Scotland and Northern Ireland. The first half of the month was wet and unsettled with persistent heavy rain from frontal systems including named storms Freya and Gareth. Northern Ireland recorded 169% of the 1981–2010 average rainfall making this the wettest March in a series from 1862. April was notably dry across western Scotland and south-east England. May was very wet in north-east Scotland (with around twice the normal rainfall across Nairn and Moray) but dry across Wales and southern Engand.

The UK rainfall total for summer was 326 mm, 135% of the 1981–2010 average. June was a particularly wet month with over 200% of average rainfall across a swathe from eastern Wales, through the Midlands and Lincolnshire; England had its ninth wettest June on record (although the Junes of 2007 and 2012 were around 40% wetter). July was also a wet month across the northern half of the UK – and in particular parts of Cheshire, Derbyshire and the Manchester area but drier across southern England and Wales. August rainfall was almost twice the average aross much of Scotland from generally unsettled weather; Scotland had its third wettest August in a series from 1862. The summer of 2019 was notable for the extent to which it was both warm and wet. All summers warmer than 2019 were very dry summers, and all summers wetter than 2019 were cool summers, whereas 2019 was both the equal-11th warmest and 14th wettest summer in series from 1862.

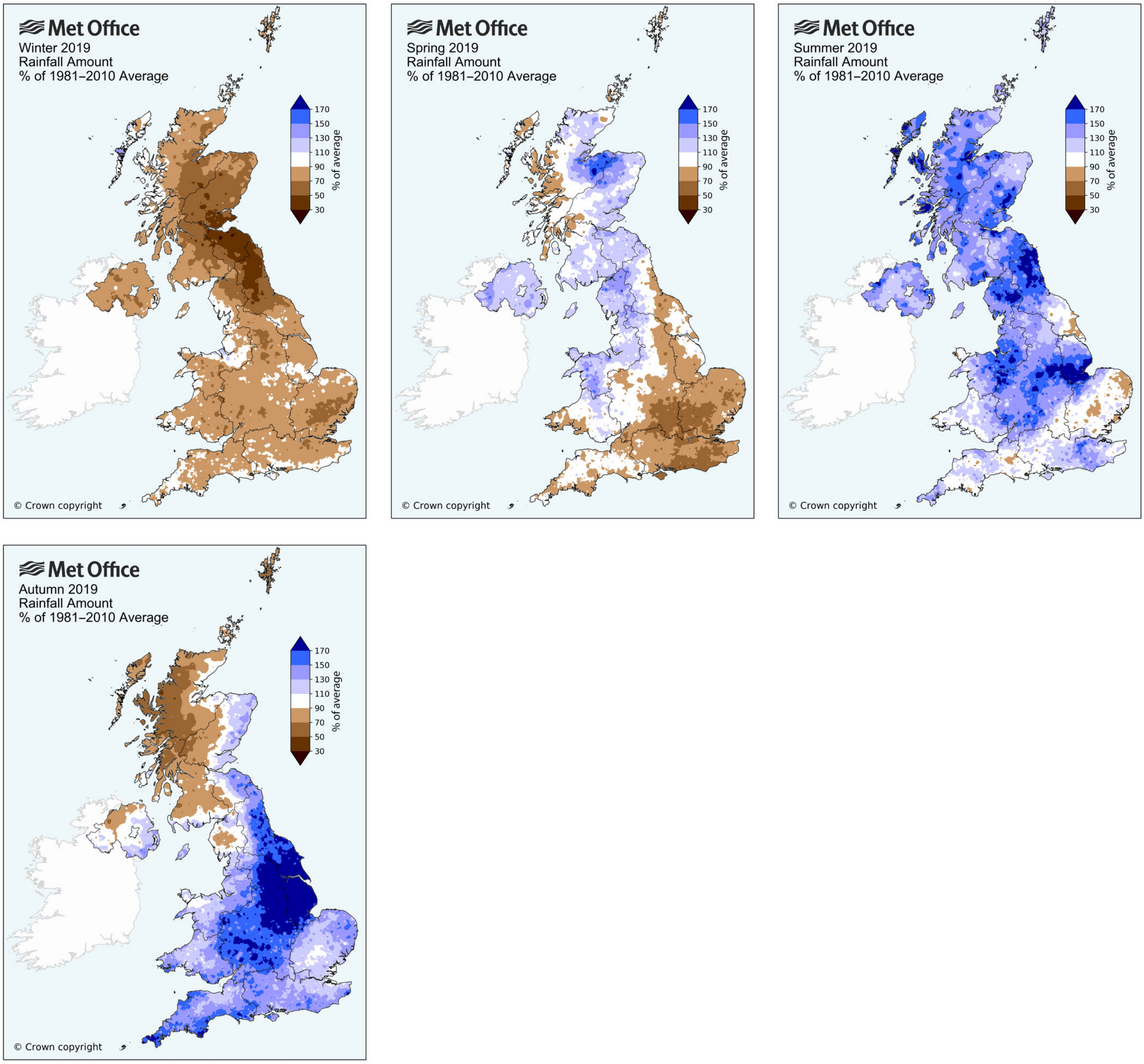


FIGURE 22 Rainfall anomalies (%) for seasons of 2019. Winter refers to the period December 2018–February 2019. Note that winter 2020 (December 2019–February 2020) will appear in State of the UK Climate 2020

From late September and through the autumn, the jet stream tracked further south than usual, meaning that much of England and Wales were wetter than average, whereas Scotland and Northern Ireland were drier—especially during November (western Scotland being remarkably dry). The focus of the wettest areas further south were across the south Pennines and Lincolnshire, which received well over twice the normal rainfall amount. For northern England this was the wettest Autumn since 2000 and seventh wettest on record, while Lincolnshire, South Yorkshire, and Nottinghamshire all recorded their wettest autumn on record. The England and Wales autumn rainfall total was 411 mm, 146% of the 1981–2010 long-term average and the fifth-wettest autumn in a 253-year series from 1766 (summer 2000 with 503 mm was the wettest autumn in this series). The station at Sheffield recorded more than twice the seasonal 1981–2010 long term average rainfall and it was the wettest autumn here in records from 1883. December was a wet month for East Anglia and southern England, but fortunately totals were near or below average across northern England.

Various flood events occurred during 2019. On February 8–9, there were reports of flooding on Orkney and across parts of Northern Ireland and Wales associated with storm Erik. Early March was also very wet

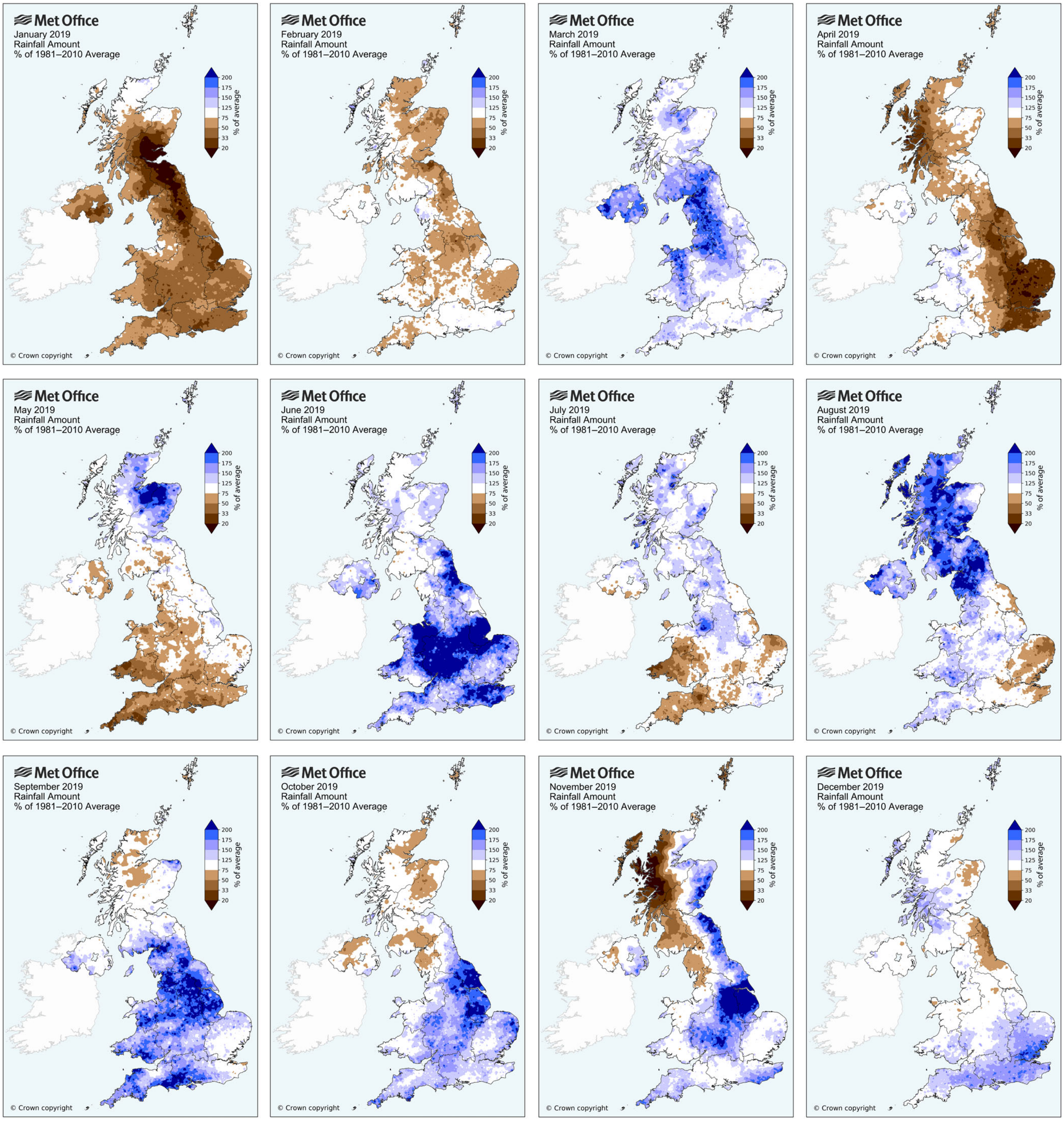


FIGURE 23 Rainfall anomalies (%) for months of 2019

across the north and west, with storm Freya on third and the succession of low pressure systems from 10th to 16th including storm Gareth bringing localized flooding problems, notably across parts of North Wales, West Yorkshire, Greater Manchester and York, while temporary flood barriers were installed in the Midlands on the River Severn. In early June, around 2.5 times the monthly average rain fell across Lincolnshire from 10th to 12th from a slow-moving front, causing severe flooding problems (for more details, see Section 8). There was also some flash-flooding in Stirling associated with the hot weather at the end of the month.

The most severe flooding events of the year occurred during the second half of the summer and through the autumn. During the second half of July, thunderstorms and lightning associated with the record-breaking temperatures had numerous impacts bringing transport disruption, power cuts and flash-flooding. From 30 to

TABLE 3 Monthly, seasonal and annual rainfall actual (mm) and anomaly values (%) relative to 1981–2010 for the UK, countries and England and Wales precipitation series (EWP) for year 2019

	UK		England		Wales		Scotland		Northern Ireland		EWP	
	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly	Actual	Anomaly
January	65	53	38	46	81	52	107	61	55	47	47	51
February	71	81	48	79	87	79	105	81	78	94	54	82
March	129	136	88	138	176	151	179	127	160	169	95	132
April	49	67	35	60	98	110	53	58	73	98	46	71
May	64	91	42	73	47	55	104	124	59	82	46	72
June	109	149	107	174	146	170	102	116	106	140	116	175
July	84	108	63	101	58	62	126	127	83	103	72	107
August	133	149	84	121	143	133	208	179	153	157	87	115
September	126	131	113	163	193	165	132	97	110	121	124	161
October	140	110	128	140	208	123	148	85	99	83	149	143
November	119	99	119	136	177	109	102	62	121	108	138	138
December	140	117	106	121	184	111	190	117	111	97	121	125
Winter	254	77	184	80	358	83	343	73	242	77	217	84
Spring	241	102	166	92	321	110	335	107	293	121	187	93
Summer	326	135	254	131	347	121	436	144	343	135	275	131
Autumn	385	112	361	145	577	129	382	80	330	102	411	146
Annual	1,227	107	972	114	1,598	110	1,555	100	1,210	107	1,095	116

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

Note: Colour coding relates to the relative ranking in the full series which spans 1862–2019 for all series except EWP which is 1766–2019.

31 July there was severe flash-flooding across North Yorkshire, south Manchester and Cheshire and the impacts from this extended into early August (for more details, see Section 8). Bouts of wet and windy weather caused further localized flooding problems through August.

The last 10 days of September brought an unsettled and wet period of weather which continued through much of the autumn. From 22nd to 23rd a number of properties were flooded across Northern Ireland, there was flooding on roads in Wales, Northern Ireland and north-west England and four central stations in London were affected by flooding. Renewed heavy rain affected parts of England and Wales from 28 September, onwards. In North Yorkshire, a cycle race was cut short due to the very wet conditions, and the railway line flooded at Harrogate. There was also some flooding from the River Ouse in York. Various flooding problems continued into early October. Torrential dowpours brought localized flooding and disruption across England and Wales on 1st October, and there was severe flooding in the village of Laxey on the Isle of Man.

On 25–26 October a slow-moving front brought persistent heavy rainfall across England and Wales. Fifty to eighty milli metre of rain fell across a swathe from north Devon through Wales to the Peak District; around 50–75% of the monthly average and locally 75–100%. There was significant flooding disruption across Shropshire, Staffordshire and Manchester, including flooding of the Manchester Airport relief road. The most severe flood event of the year occurred on 7 November, when 50–100 mm of rain fell in a swathe from the Humber to Sheffield, around the whole-month average rainfall or more in a 24-hr period. All this rain followed the late October rainfall event, and generally unsettled weather from late September onwards. The result was severe flooding in parts of Derbyshire and South Yorkshire (for more details see Section 8). This was at the time arguably the UK's most significant flood episode since the severe flooding across northern England from storms Eva and

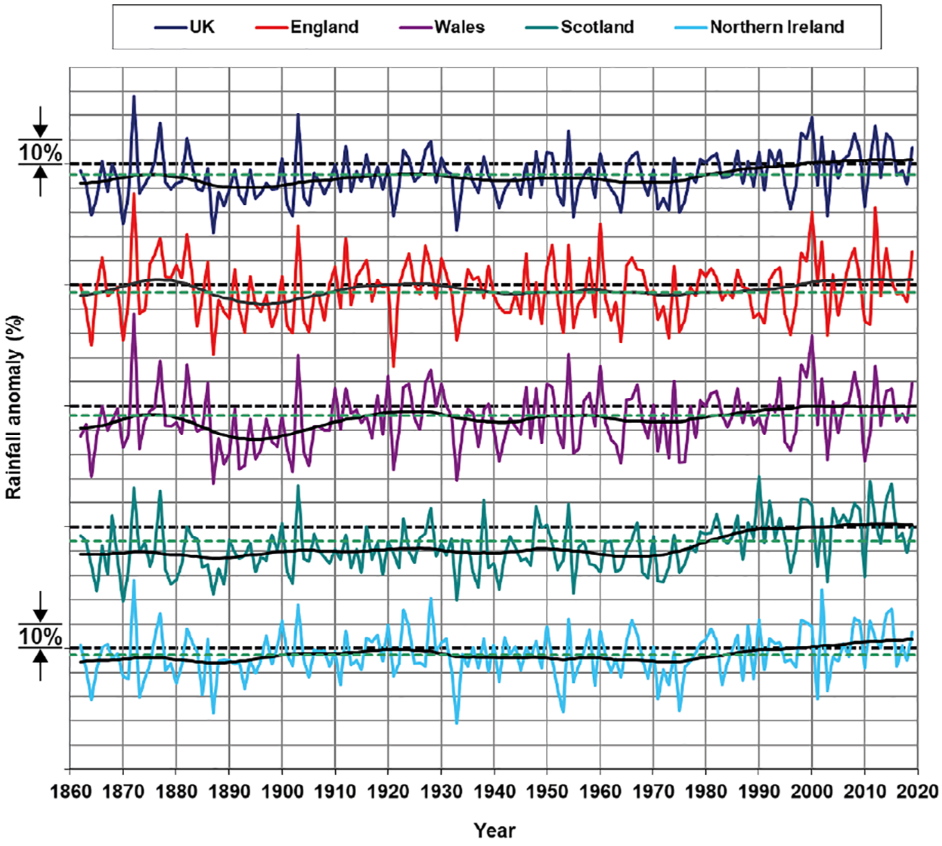
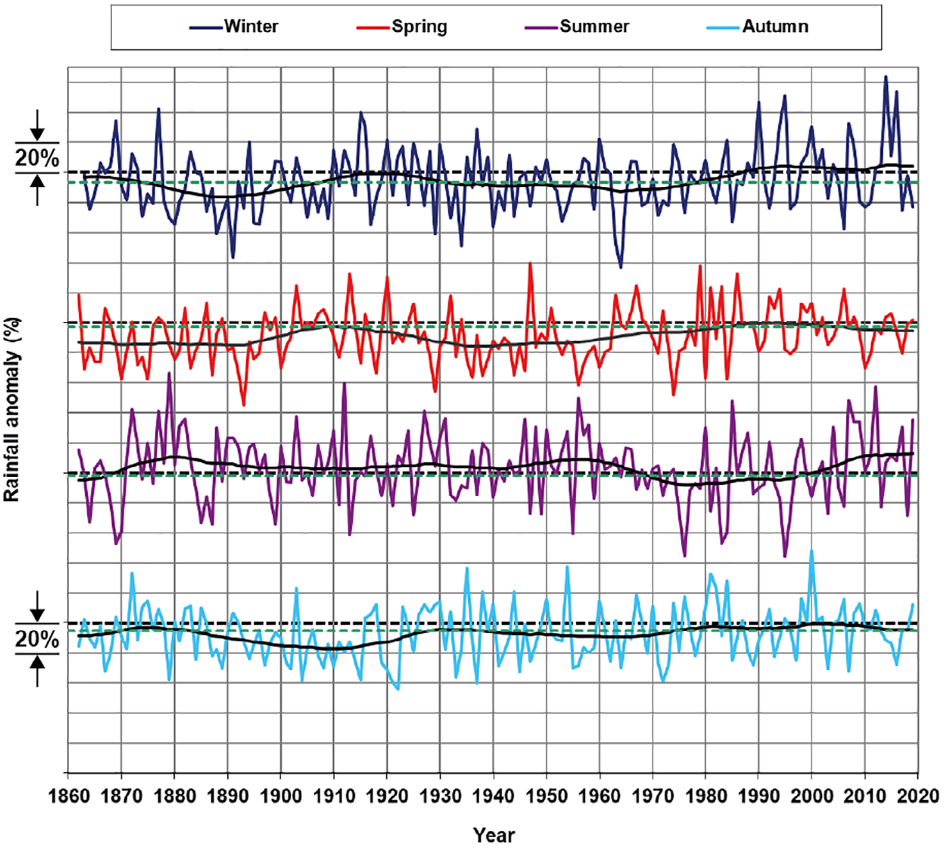


FIGURE 24 Annual rainfall, 1862–2019, expressed as a percentage of 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±10%. The table provides average values (mm)

Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK	1100	1150	1158	1227
England	827	853	864	972
Wales	1402	1459	1430	1598
Scotland	1470	1562	1570	1555
Northern Ireland	1099	1133	1169	1210



Season	1961–1990 average	1981–2010 average	2010–2019 average	2019
Winter	307	329	344	254
Spring	231	237	219	241
Summer	236	240	267	326
Autumn	326	343	325	385

FIGURE 25 Seasonal rainfall for the UK, 1862–2019, expressed as a percentage of the 1981-2010 average (note winter from 1863 to 2019; year is that in which January and February fall. Winter 2020—which includes December 2019—will appear in State of the UK Climate 2020). The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961-1990 long-term average. Light grey grid-lines represent anomalies of ±20%. The table provides average values (mm)

Frank in December 2015. Fortunately the weather was generally quieter for the remainder of the month. There were further flood impacts in December from spells of wet and windy weather but these were generally fairly localized in nature.

The precipitation data show large annual variability, with a slight increase from the 1970s onwards (Figure 24). The most recent decade (2010–2019) has been on average 5% wetter than 1961–1990 although 1% wetter than 1981–2010; this increase is most pronounced for Scotland and Northern Ireland, being 7% wetter than 1961–1990. The wettest year for the UK overall is 1872 (128% of average) and the driest 1887 (71%). The year 2019 was ranked the 16th wettest year in the UK series from 1862. Six of the 10 wettest years in the UK series from 1862 have occurred since 1998 (2000, 2012, 1998, 2014, 2008 and 2002).

Figure 25 shows seasonal rainfall series for the UK from 1862 to 2019 (for winter 1863–2019). The two recent winters of 2013–2014 and 2015–2016 stand out, each with over 150% of the 1981–2010 average UK rainfall overall. Similar to the annual series, the seasonal series are dominated by large annual variability with some decadal variability about a relatively stable long-term mean. Since 2000 eight seasons have been in the top-10 wettest in UK seasonal series (winter 2014, 2016, 2007 and 2000, spring 2006, summer 2012 and 2007 and autumn 2000) whereas two have been in the top-10 driest (winter 2006 and autumn 2007).

The annual rainfall total for 2019 in the long running England and Wales precipitation (EWP) series was 1,095 mm (Figure 26), which is 116% of the 1981–2010 average and ranked 18th wettest in the series from 1766 (recent wetter years including 2014, 2012, 2002 and 2000). Figure 26 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) highlighting the value of rainfall series before the 20th Century for understanding the full historical context of UK rainfall. The most recent decade is a relatively wet decade in this series, being 3% wetter than 1981–2010 and 7% wetter than 1961–1990. The England and Wales areal rainfall series based on 1 km resolution gridded data

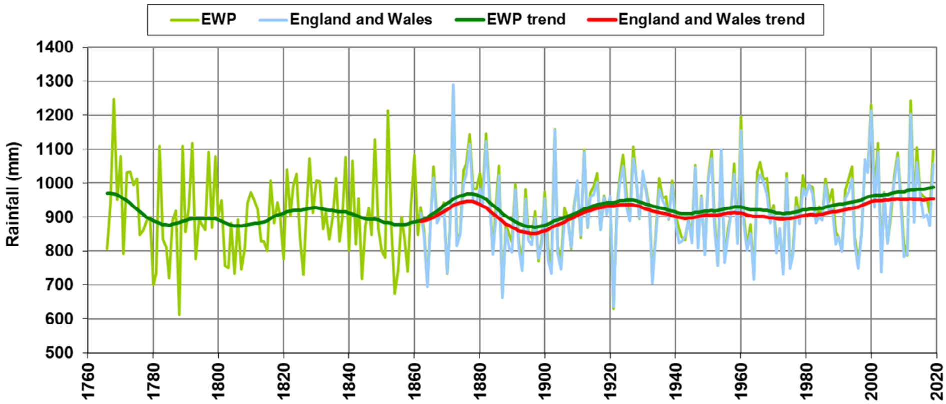


FIGURE 26 Annual rainfall for EWP series, 1766–2019, and England and Wales areal series, 1862–2019 (mm). The table provides average values (mm)

Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
EWP	915	948	977	1095
England and Wales	906	936	942	1058

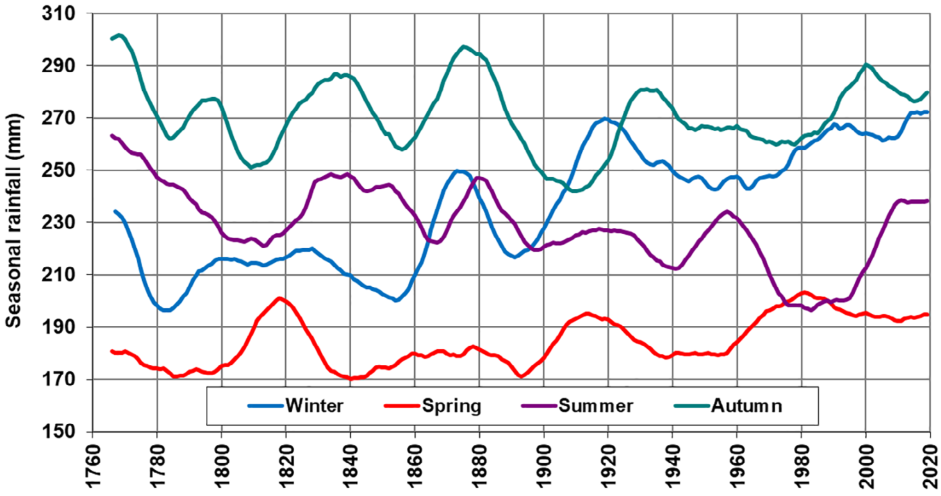


FIGURE 27 Seasonal rainfall trends for EWP series in mm, 1766–2019 (note winter from 1767). The figure shows a smoothing trend for each series using a weighted filter (see Annex 2)

is highly correlated to EWP for the period of overlap, with an R^2 value of .98 and root mean square difference of 1.6%. 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 27 shows trends in seasonal EWP rainfall amounts from 1766 to date. While there is little change in the long-term mean for the annual EWP series, this is certainly not the case for the seasonal series. EWP shows a marked increase in winter rainfall (winter 2014 is the wettest winter in this series and 2016 ranked eighth wettest). Before 1900, EWP winter rainfall was substantially lower than autumn rainfall, but the increase in winter rainfall has meant that during the 20th century autumn and winter rainfall were roughly equal on average. However there are potential issues with the estimation of early winter rainfall in the series relating to the treatment of snow before systematic meteorological observing networks were established which could be associated with an underestimation of early winter rainfall (Murphy *et al.*, 2020).

The increasing winter rainfall has been offset by a slightly smaller reduction in summer rainfall, although a run of recent wet summers from 2007 demonstrates that these trends are very sensitive to the choice of start and end dates, and summer rainfall trends in the 18th and early 19th Century are also subject to some uncertainty and possibly over estimated (Murphy *et al.*, 2020). Spring/autumn rainfall have each remained fairly steady with only a slight increase/decrease, respectively.

The rainfall statistics throughout are presented to the nearest whole mm, but the uncertainties of the

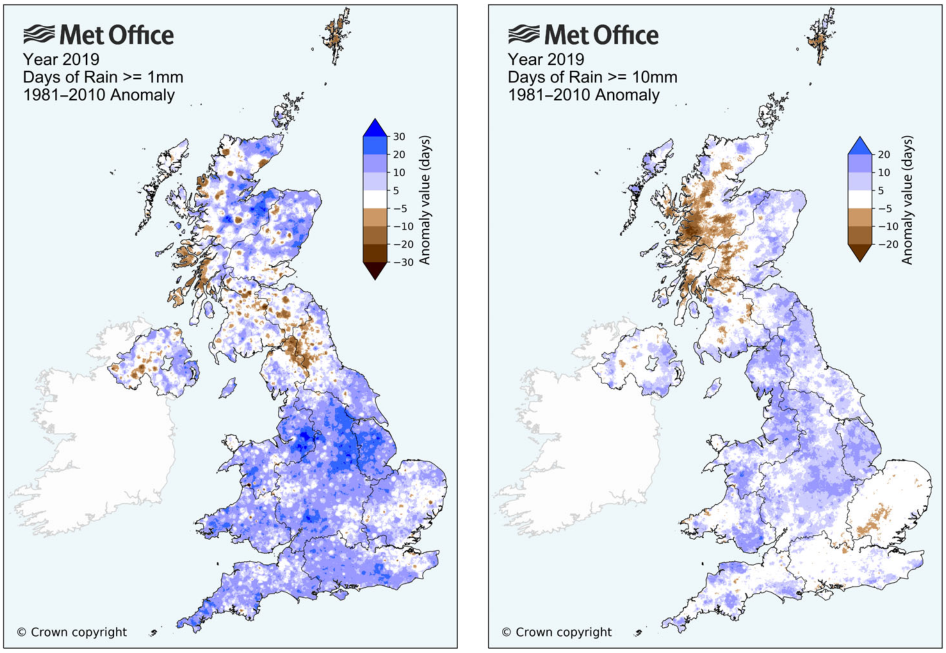
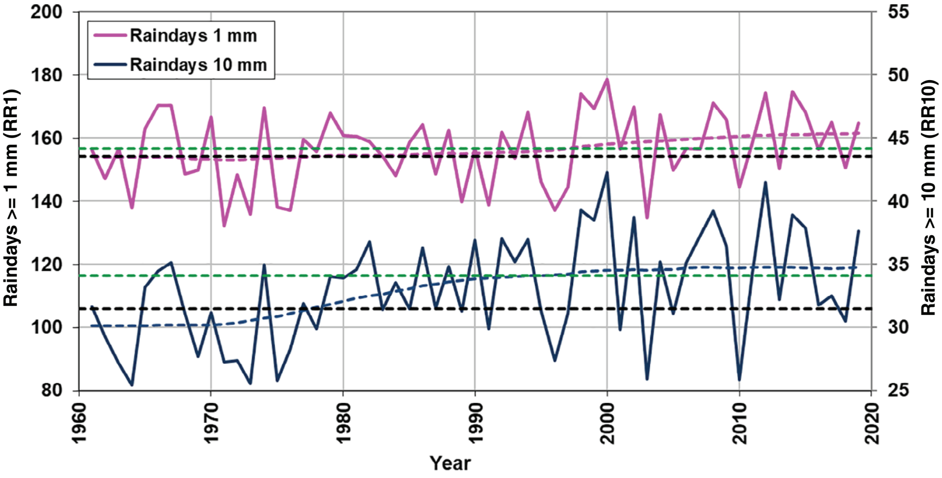


FIGURE 28 Days of rain ≥1 mm (RR1) and 10 mm (RR10) for 2019, difference from 1981–2010 average



Climate variable	1961–1990 average	1981–2010 average	2010–2019 average	2019
Raindays >= 1mm	154	157	161	165
Raindays >= 10mm	31	34	34	38

FIGURE 29 Annual average number of days of rain ≥1 (RR1) and 10 mm (RR10) for the UK, 1961–2019. The hatched green line is the 1981–2010 long-term average. The hatched black line is the 1961–1990 long-term average. The table provides average values (days)

areal statistics relating to changes in the observing network change over time. The standard error can approach 1–4% depending on region in early decades, but less than 1 or 2% for the comprehensive network of rain gauges in the years since 1960. The uncertainties are therefore much smaller than the year to year variability and more detail on this can be found in Annex 2. However it is non-trivial to determine the robustness or significance of observed trends in rainfall as they are quite sensitive to region, season and choice of start and end dates.

3.1 | Days of rain and rainfall intensity

The number of days of rain greater than or equal to 1 mm (RR1) during 2019 was more than 10 days above the long-term average fairly widely across the UK, and locally 20–30 days more than average, particularly across a swathe from Cheshire to Lincolnshire (Figure 28). In general, the monthly variation was comparable to the rainfall anomaly pattern (Figure 23). There were fewer days of rain than average across the UK in January and April but more than average in June

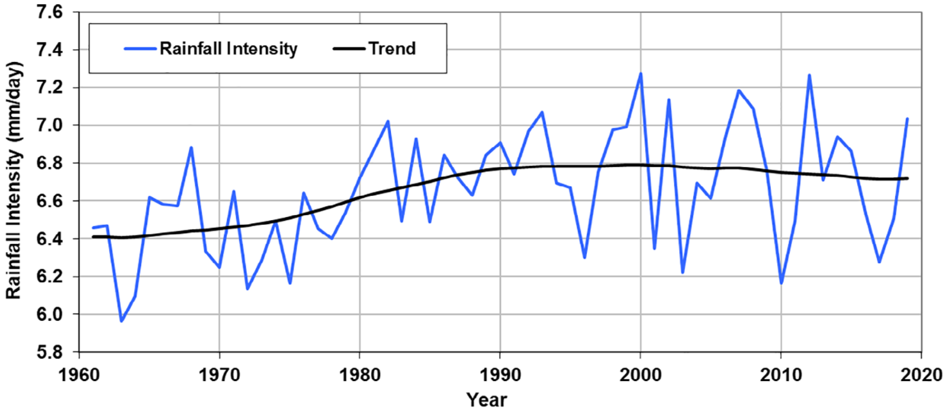


FIGURE 30 Annual average rainfall intensity for the UK on days of rain ≥1 mm, 1961–2019. The table provides average values (mm/day)

	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK rainfall intensity	6.5	6.8	6.7	7.0

and fairly widely from August to December—but with significant regional variation. The number of days of rain greater than or equal to 10 mm (RR10) was above normal across much of Wales, northern England, Northern Ireland and southern and eastern Scotland—but significantly below normal across the West Highlands with a marked absence of rain-bearing fronts here in November (Figure 28).

Figure 29 shows the annual area-average RR1 and RR10 for the UK for 1961–2019. Overall, 2019 was above the 1981–2010 average for both RR1 and RR10. For both RR1 and RR10 the year with the most days was 2000, and this year was also the third-wettest in the UK series from 1862, with only 1872 and 1903 wetter. While the RR1 series is broadly flat, the RR10 series shows a slight increase from around 31 days for 1961–1990 to 34 days for the period 1981–2010, an increase of around 10%. 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 because both time-series are relatively short and with large annual variability.

Figure 30 shows an estimate of the areal-average rainfall intensity (see Annex 1 for definition) across the UK for each year from 1961 to 2019. The figure is indicative of trends in rainfall intensity across the UK on wet days although, as with RR1 and RR10, it neither provides a seasonal break-down, nor distinguishes between upland and lowland areas, Overall, 2019 was slightly above the 1981–2010 average for this metric, and consistent with RR1 and RR10 also being above average. The two years

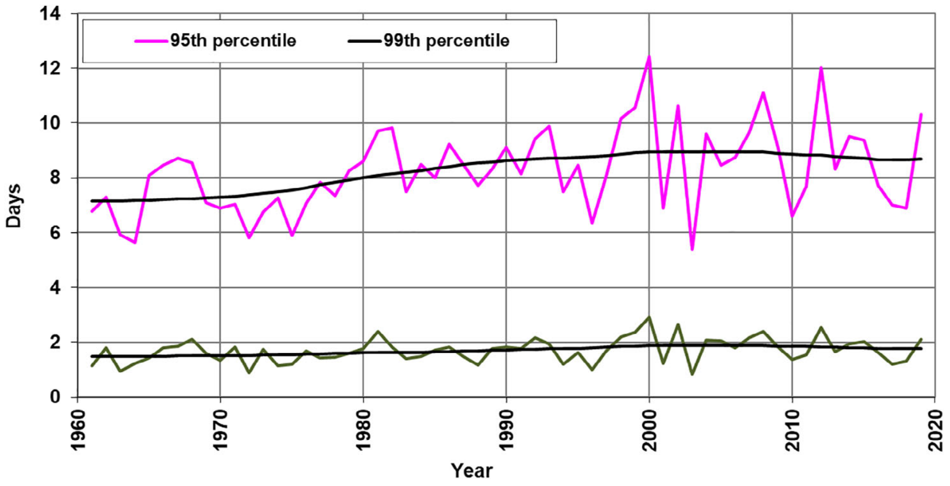


FIGURE 31 The number of days each year where rainfall totals have exceeded the 95th and 99th percentile (the 95th and 99th percentiles are calculated based on the period 1961–1990 for 'wet days'—exceeding 1 mm; the UK value is the areal-average of the number of days calculated at each grid point. Based on Figure 29 we would therefore expect about 154/20 = 7.7 days per year for the 95th percentile for the period 1961–1990—which is indeed the case). The table provides average values (days)

Percentile	1961–1990 average	1981–2010 average	2010–2019 average	2019
95th	7.7	8.8	8.5	10.3
99th	1.6	1.8	1.7	2.1

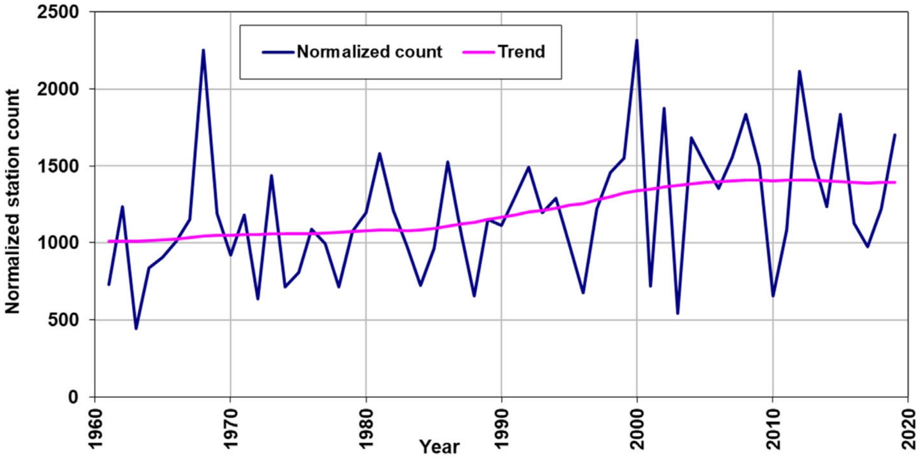
with highest rainfall intensity in the series (2000 and 2012) also correspond to the wettest years in the UK series since 1961. There is a slight upward increase of 0.2 mm (approximately 3%) when comparing the 1961–1990 and 1981–2010 averages, but again this is a short time-series dominated by year-to-year variability. The rainfall intensity series is well correlated with the RR10 series (R^2 value .70), as would be expected because in years with a large number of very wet days the average rainfall intensity on wet days is higher. In contrast, there is low correlation between the rainfall intensity series and the RR1 series (R^2 value .21) because in years with a large number of days exceeding 1 mm (a much lower threshold) we would not necessarily expect the rainfall intensity on wet days to be higher.

3.2 | 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. These metrics adopt two different methods: a percentile approach and an absolute threshold. The ranking of individual years is quite sensitive to the choice of definition used and the series are relatively short given the variability of rainfall. However there are some consistent features across these different metrics—most notably, more heavy rain events have been recorded in the most recent decade than in earlier decades in the series.

Figure 31 shows the number of days each year where the rainfall total has exceeded the 95th and 99th percentile for wet days. The percentiles and daycounts are calculated for each grid point with the UK value as the areal-average of the daycount values across all grid points. As with rainfall intensity, this neither includes a seasonal breakdown, nor does it distinguish between orographically enhanced frontal rain and convective rain. Note that the calculation of this metric has changed since the previous State of UK Climate report (Figure 31, Kendon *et al.*, 2019) The revised metric is based on a percentile approach with thresholds that vary geographically so that all parts of the UK will have an equal influence (since the climatologically wetter parts of the UK in the north and west will have higher percentile values than the drier parts of the south and east). Both series show large annual variability with some decadal variability, but with a rising trend for the 99th/95th percentiles from 1.6/7.7 days for the period 1961–1990 to 1.8/8.8 days for the period 1981–2010. The 2019 values for both percentiles were above the 1981–2010 and 1961–1990 long term average which is likely to be influenced by the relatively large number of flood events during the year—particularly in the second half.

Figure 32 provides a count of the number of times each year any rain gauge in the observing network below



	1961–1990 average	1981–2010 average	2010–2019 average	2019
Number of station-days	1050	1256	1350	1703

FIGURE 32 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 2019, adjusted for station network size and excluding stations above 500 m above sea level. The table provides average values (station-days). Note that the number of station-days for the 1961–1990 and 1981–2010 averages has changed slightly from last year's report (1,056, 1,263). This is because the adjustment for station network size has altered as a result of inclusion of year 2019. However, historical observations held within the climatological database also 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

500 m elevation has recorded a daily rainfall total greater than or equal to 50 mm. We refer to this type of metric as a count of station-days. This metric cannot distinguish between a small number of widespread events recorded at many stations, or more frequent but localized events, but is a useful gauge of the occurrence of extreme heavy rainfall overall. This series has been adjusted to take into account the changing size of the UK rain-gauge network which reached over 5,000 gauges in the 1970s and has reduced to fewer than 3,000 in the 2010s (Figure A1.2a). The dense network of several thousand rain gauges across the UK means that widespread heavy rain events will tend to be well captured, although highly localized convective events may still be missed. The adjustment is made by applying a scaling factor to the station-day counts for each year, so that earlier years are scaled down and later years scaled up and the apparent number of stations in the network remains constant throughout. 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.

3.3 | Snow

Frost and snow were quite widespread between 17 and 23 January. On 17th, snow contributed to some road closures in Scotland and there was some disruption in Northern Ireland. Snow fell more widely on 22–23 January. There were numerous road traffic accidents and airport delays in Scotland and school closures in Wales. Accidents, road closures and transport disruption also occurred in north-west and south-east England (16 cm at Malham Tarn, North Yorkshire, 6 cm at High Wycombe, Buckinghamshire on 23rd).

The most significant snow of the year occurred at the end of January extending into the start of February. Snow fell widely on 30–31 January and snow showers continued to affect many northern and eastern areas in early February. There were a large number of road accidents, road closures and treacherous driving conditions. Major roads affected included the M8 and A9 in Scotland and the A1(M) in County Durham, while 100 people were stuck overnight on the A30 in Cornwall. On January 30, Liverpool and Manchester Airport runways were closed for several hours due to snow. On 1 February, part of the M3 was closed and flights at Bristol and London airports were delayed or cancelled. Power supplies were affected across parts of mid-Wales and the London Overground service. On 2 February, some of the higher snow depths recorded across the network included 33 cm at Tomnavoulin, Moray, 12 cm at Tulloch Bridge, Highland, 9 cm at Lough Navar Forest, County Fermanagh, 16 cm at Copley, County Durham, 8 cm at Ipstones Edge, Staffordshire, 16 cm at Odiham, Hampshire 11 cm at Huntsham, Devon and 6 cm at Bodmin, Cornwall. However, depths were more typically 1 or 2 cm across many parts of the UK.

There were further impacts from snow during the first half of March, with a north-westerly weather type bringing snow across higher ground. On fourth, storm Freya brought snow across higher routes in the Pennines, stranding vehicles on the A595 in Cumbria, while between 10th and 16th, snow again blocked some higher roads. Three climbers were killed in an avalanche on Ben Nevis. On 3 April, snow again led to traffic accidents on the M74 and the A9 was closed for a time. Traffic delays were widespread across higher parts of Cumbria and north-east England. Icy conditions at the start of December caused numerous road traffic accidents across Wales and on 15th–16th colder weather led to roads across higher ground being affected by snow. However, in general any snow impacts toward the end of 2019 were limited.

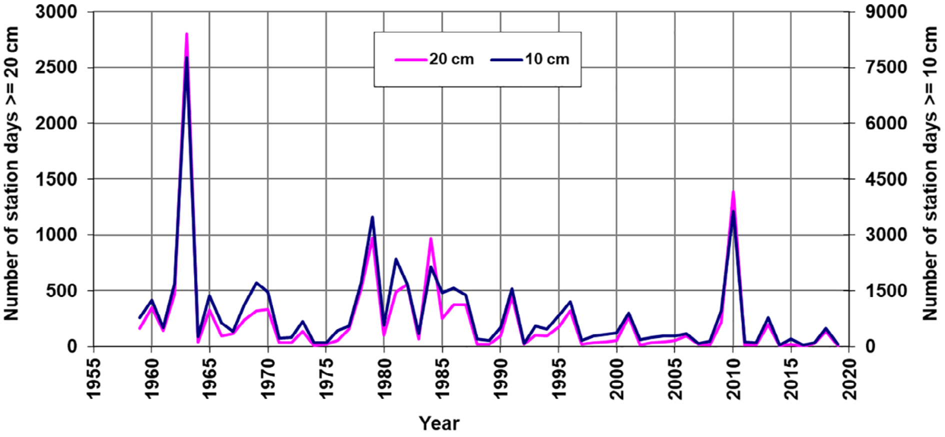


FIGURE 33 Count of number of station-days per year in the UK with recorded snow depths exceeding 10 and 20 cm, excluding stations above 500 m above sea level. This series has not been adjusted for network size. The 2019 values are 59 (10 cm) and 8 (20 cm)

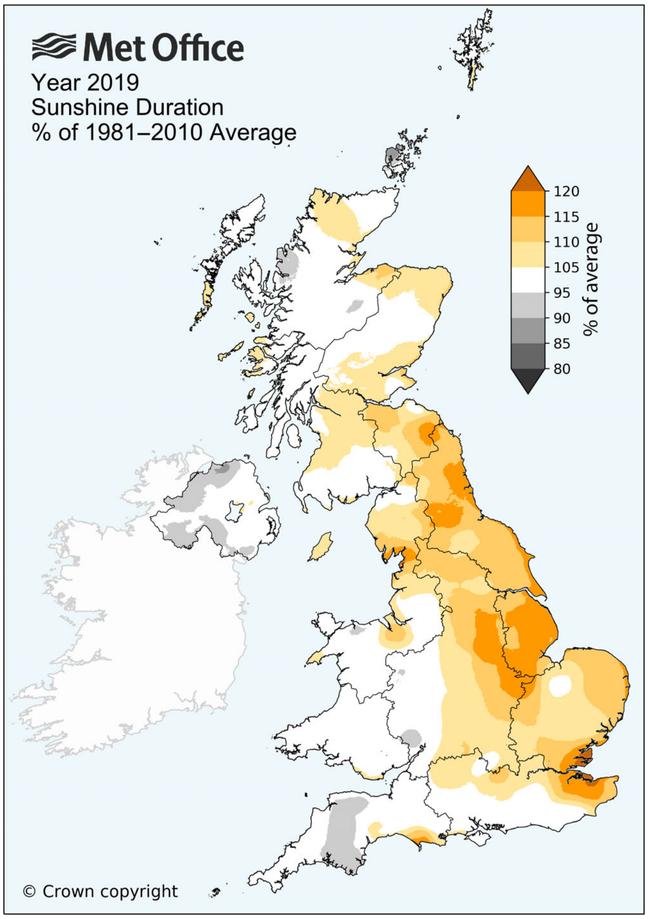


FIGURE 34 Sunshine anomalies (%) for year 2019 relative to 1981–2010

The last spells of significant and widespread lying snow across lowland parts of the UK were in February to March 2018 (the 'Beast from the East' event, see Kendon *et al.*, 2019), January and March 2013 and January and December 2010. The year 2010 was the snowiest year by far for the UK in the last two decades, and was comparable to several snowy years in the 1970s and 1980s. Figure 33 shows the count of station-days where snow depth sensors recorded greater than or equal to 10 or 20 cm of lying snow. The series has not been adjusted for network size, consequently it is indicative but not homogeneous (with the 2019 network size roughly half that of the 1960s–1990s, see Annex1). The year 2019 was one of the least snowy years in the series—comparable with 2016 and 2014, but even so would not be considered unusual in the context of the last two decades. However, there was a notable absence of snow in 2019 if compared to the period 1960–2000. The 1960s had a greater frequency of snowfalls and blizzards than any decade since the 1860s and 1870s (Wild *et al.*, 2000).

4 | SUNSHINE

The UK sunshine total for 2019 was 1,447 hr, 105% of the 1981–2010 average and the 14th sunniest year for the UK in a series from 1919. Sunshine totals were above average across much of England, with the exception of the west Midlands and south-west, but near normal across Wales and Scotland, and slightly below normal for Northern Ireland (Figure 34). The highest sunshine anomalies were generally in the east, with 110% or more at 13 stations across the network from north-east Scotland to the south coast. Three stations recorded over 2,000 hr; 2,110 hr at Preston Cove House, Dorset, 2099 hr at Shoeburyness, Essex and 2016 hours at Faversham, Kent—around 120% of average in these locations. The lowest total was at Loch Glascarnoch, Ross-shire with 969 hr (this station was also the dullest location in 2018).

Winter 2019 (December 2018–February 2019) was dull across western parts of the UK but totals were 125% of average or more widely across central and eastern areas. This was the sixth sunniest winter for the UK in a series from 1919 (recent winters 2015 and 2018 were sunnier) and for northern England (north of a line from the Wash to North Wales) it was the sunniest winter in the series. December 2018 was rather dull, particularly in western areas—notably Wales—and January was also dull across Wales, Northern Ireland and south-west England but sunny across northern Britain. However, February was a sunny month widely—except for the far north—and for England the sunniest February in the series. During the record-breaking warm spell late in the month, skies across central and south-east England were largely cloud free with 9–10 hr of sunshine per day-and approaching half of the normal monthly average recorded in just 4 days widely across England and Wales.

Spring was a sunny season across most of the UK, again with the exception of Northern Ireland. March and April were relatively sunny. Sunshine totals for May were near-normal across England and Wales but rather below across Scotland and Northern Ireland. Summer sunshine totals were variable but June was a rather cloudy, dull month across a swathe of England and Wales. However, it was sunnier later in the month, and this brighter weather extended through July and early August, with much of September too being relatively sunny across England and Wales.

From late September through the rest of the autumn, low pressure systems tracking across England and Wales often brought cloudy conditions. It was an especially dull November across England, Wales and eastern Scotland, whereas the easterly flow to the

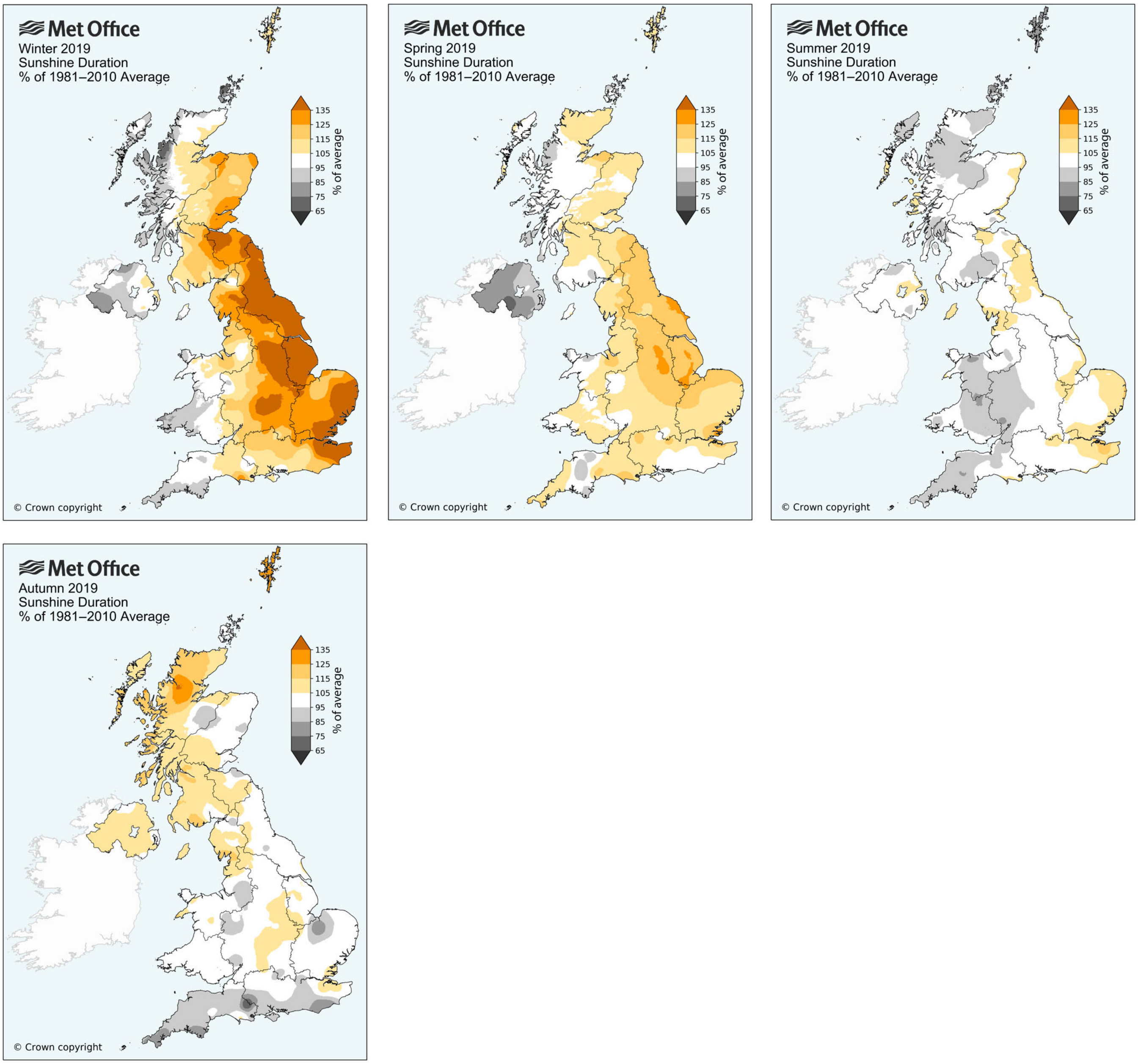


FIGURE 35 Sunshine anomalies (%) for seasons of 2019. Winter 2019 refers to the period December 2018–February 2019

north of the low pressure systems and the shelter of the mountains often brought sunny and dry conditions across western Scotland. By December the low pressure systems resumed their track further north and it was a dull month across north-west England and the West Highlands—with for example, only 8 hr of sunshine at Poolewe, Wester Ross for the month (Figures 35 and 36).

Figures 37 and 38 show annual sunshine anomalies for the UK and countries, and seasonal sunshine anomalies for the UK, from 1919 to 2019 inclusive. The smoothed trend shows a slight increase in sunshine from a low during the 1960s to 1980s to a sunnier period from 2000 onwards. The most recent decade (2010–2019) has had for the UK on average 7% more hours of bright sunshine than the 1961–1990 average and 4% more than the 1981–2010 average. This trend is apparent across all countries but is most prominent during the winter and spring, where the most recent decade is 13% higher than 1961–1990 for both seasons.

The sunshine network is relatively sparse, with the 2019 network comprising around 110 stations (Figure A1.4). This means that some parts of the UK such as Highland Scotland and central Wales have few observations. Sunshine stations may be affected by exposure issues, particularly in the winter months when the sun is at a low elevation and topographic shading may be important. The sunshine statistics throughout are presented to the nearest whole hour,

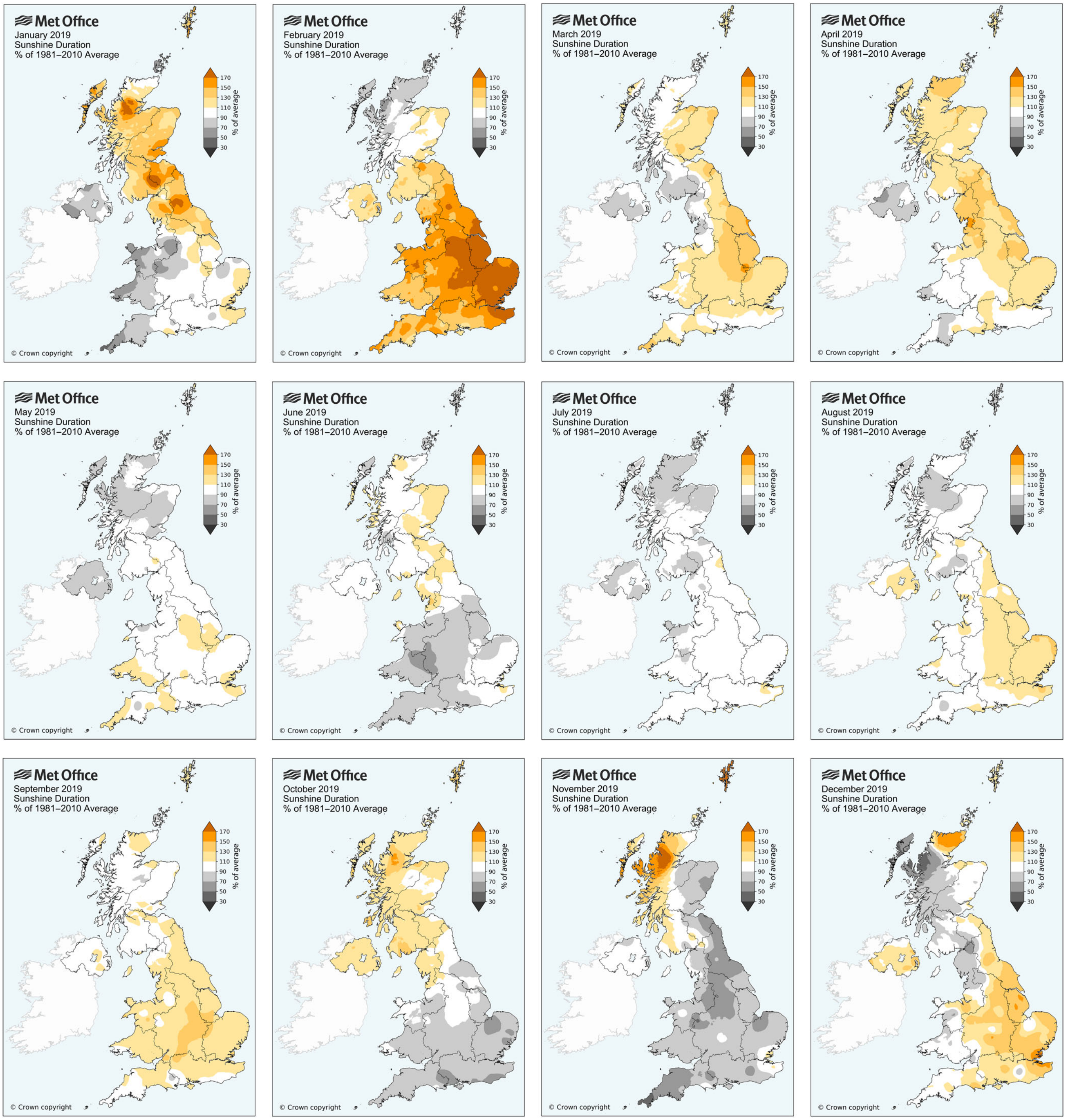


FIGURE 36 Sunshine anomalies (%) for months of 2019

but the uncertainties of the areal statistics relating to changes in the observing network over time can approach 2%. More details can be found in Annex 2.

5 | WIND

The windiest days of 2019 are listed in Table 4. Storms in 2019 were named as part of an initiative between the Met Office and Met Eireann, with other European national meteorological agencies running similar schemes. The naming of storms was aimed at improving the communication of approaching severe weather through the media and government agencies by using a single authoritative system. This scheme was introduced in autumn 2015 with storms named if they had the potential to cause medium or high impacts from wind on the UK and/or Ireland. The naming system was subsequently adjusted

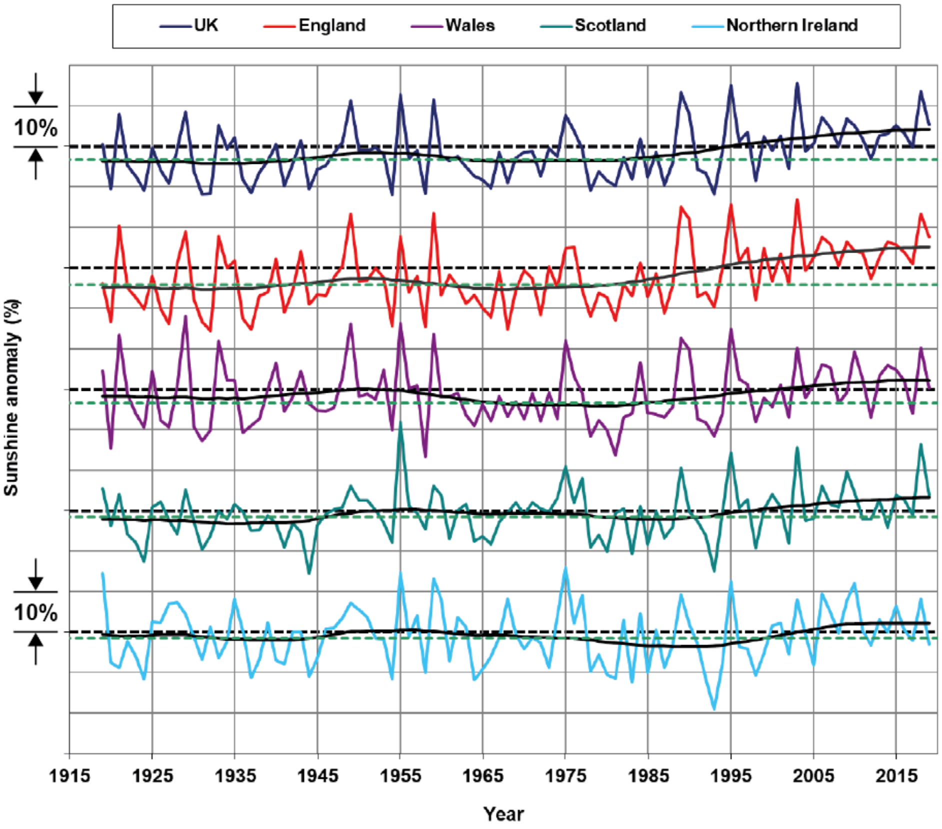


FIGURE 37 Annual sunshine duration (hours) for UK and countries, 1919–2019, expressed as a percentage of 1981–2010 average. The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±10%. The table provides average values (hours)

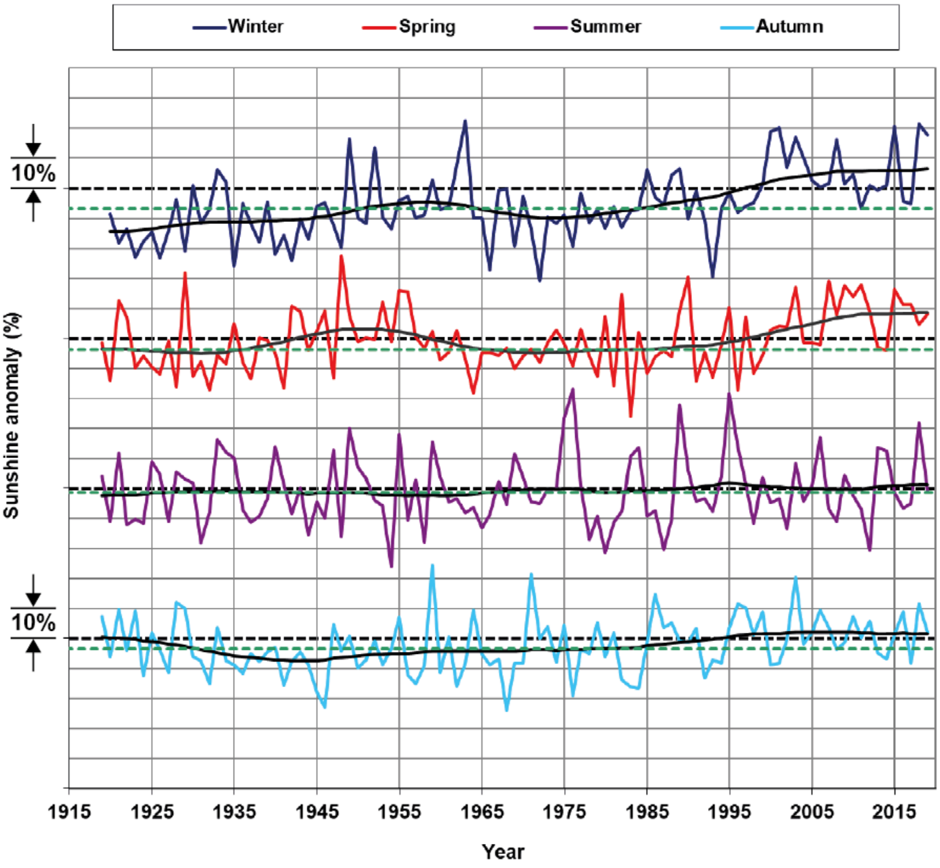
Area	1961–1990 average	1981–2010 average	2010–2019 average	2019
UK	1328	1373	1424	1447
England	1430	1493	1562	1608
Wales	1355	1402	1438	1406
Scotland	1167	1184	1214	1229
Northern Ireland	1240	1260	1289	1223

to take into account other weather types, so storms could be named on the basis of impacts from wind but also include impacts of rain and snow. The change in convention means that the number of named storms from year-to-year should not be used as a climate index in its own right. For 2020 the Royal Netherlands Meteorological Institute, KNMI, have also joined the scheme.

Named storms (Table 5) and windy spells are described below, but 2019 was not an especially stormy year overall; weather-related impacts from heavy rain were generally much greater than those from wind. Storm Erik on 8–9 February was a deep area of low pressure with winds gusting at over 50 Kt (58 mph) across much of the UK, with some exposed coastal locations exceeding 60 Kt (69 mph). A kitesurfer died in high winds off the north Devon coast and two people were killed in their vehicles by falling trees in Devon and Wales. This was a fairly typical winter storm and caused widespread transport disruption.

The UK experienced a turbulent spell of weather during the first half of March, in contrast to much calmer conditions in late February. Storm Freya on 3 March, was a rapidly deepening area of low pressure which brought strong winds to England and Wales, and rapidly followed another deep low which brought very strong winds across Scotland. A sequence of four further low pressure systems brought strong winds from 10–16 March, including storm Gareth which tracked across Scotland overnight 12–13 March . This spell brought transport disruption to road and rail with some reports of fallen trees. Ferry services were delayed or cancelled and large waves battered exposed coastlines.

Storm Hannah brought some very strong winds to England and Wales overnight 26–27 April. Exposed locations in west Wales recorded gusts of over 60 Kt, including 71 Kt (82 mph) at Aberdaron, Lleyn peninsula. There were reports of fallen trees (coming into leaf at this time of year), power cuts and transport disruption with the M48 Severn Bridge closed. The worst impacts were across Ireland, where a Red Warning was issued by Met Eireann for parts of the south-west. For west Wales, this was arguably the third most severe April storm in the last 50 years. However, the storms of 1 April 1994 and 11 April 1989, although much more severe, occurred much earlier in the month.



Season	1961–1990 average	1981–2010 average	2010–2019 average	2019
Winter	147	158	166	186
Spring	419	436	473	471
Summer	498	505	507	501
Autumn	264	274	279	279

FIGURE 38 Seasonal sunshine duration for the UK, 1919–2019, expressed as a percentage of 1981–2010 average (note winter from 1920 to 2019; year is that in which January and February fall). The hatched black line is the 1981–2010 long-term average. The lower hatched green line is the 1961–1990 long-term average. Light grey grid-lines represent anomalies of ±10%. The table provides average values (hours)

There were relatively few storms during the start of the 2019/2020 season. On 4 October, storm Lorenzo crossed the UK. Lorenzo was a mid-Atlantic hurricane but weakened rapidly as it tracked north-east past the Azores to the west coast of Ireland. An area of low pressure brought some very strong winds to south Wales and south-west England on 2 November. This storm was not named, but winds gusted at 60–70 Kt in exposed coastal locations with 95 Kt at Needles Old Battery, the UK's highest gust of the year at a low level station. One person was killed by a falling tree in Dorset and there were reports of other fallen trees. This same part of the UK was again affected by storm Atiyah overnight 8–9 December. Atiyah was named by Met Eireann with the worst impacts across Ireland, but winds gusted over 50 Kt across inland parts of the south-west and 60 Kt or higher around exposed coastlines. The storm caused some fallen trees, power outages and transport disruption. Large waves overtopped sea walls around coastal parts of Wales and the south-west.

As a measure of storminess Figure 39 counts the number of days each year on which at least 20 stations recorded gusts exceeding 40/50/60 Kt (46/58/69 mph). Most winter storms have widespread effects, so this metric will reasonably capture fairly widespread strong wind events. The metric will consider large-scale storm systems rather than localized convective gusts. There are no compelling trends in max gust speeds recorded by the UK wind network in the last five decades, particularly bearing in mind the year-to-year and decadal variations and relatively short length of this time series. Overall 2019 was an unexceptional year for storminess when compared to previous decades and does not stand out in terms of the 50 or 60 Kt metrics, while the 40 Kt metric was notably low. There were many windier years than 2019, particularly in the 1980s and 1990s.

Note that higher 40 Kt counts from the mid-1980s through the 1990s as shown in Figure 35 is broadly consistent with a period of positive phase of the winter NAO as shown in Figure 2. This earlier period also included among the most severe storms experienced in the UK in the observational records including the 'Burns' Day Storm' of 25 January 1990, the 'Boxing Day

TABLE 4 The windiest days of year 2019

	England	Wales	Scotland	N Ireland	Total	
Date	**(96)**	**(15)**	**(34)**	**(12)**	**(157)**	**Named storm**
07 January 2019			16		16	
27 January 2019	13	4	4	2	23	
07 February 2019	7	8			15	
08 February 2019	11	7	7	5	30	Erik
09 February 2019	19	9	7	2	37	Erik
03 March 2019	20	8	6		34	Freya
10 March 2019	26	2	2	1	31	
12 March 2019	10	5	14	5	34	Gareth
13 March 2019	12	2	9	4	27	Gareth
14 March 2019	5	3		2	10	
16 March 2019	8	7		1	16	
27 April 2019	5	8		1	14	Hannah
02 November 2019	18	2			20	
08 December 2019	11	7	9		27	Atiyah
09 December 2019	13	5	1	1	20	Atiyah
10 December 2019	12	9	13		34	
14 December 2019	6	7	1		14	
15 December 2019	6	5			11	
18 December 2019	6	2	6	5	19	

Note: The table lists dates where 10 or more stations across the UK recorded a maximum wind gust greater than or equal to 50 knots (58 mph) on that day. The table also gives a count of affected stations by country. The number of wind observing sites in 2019 for each country (based on data availability) is also given in brackets.

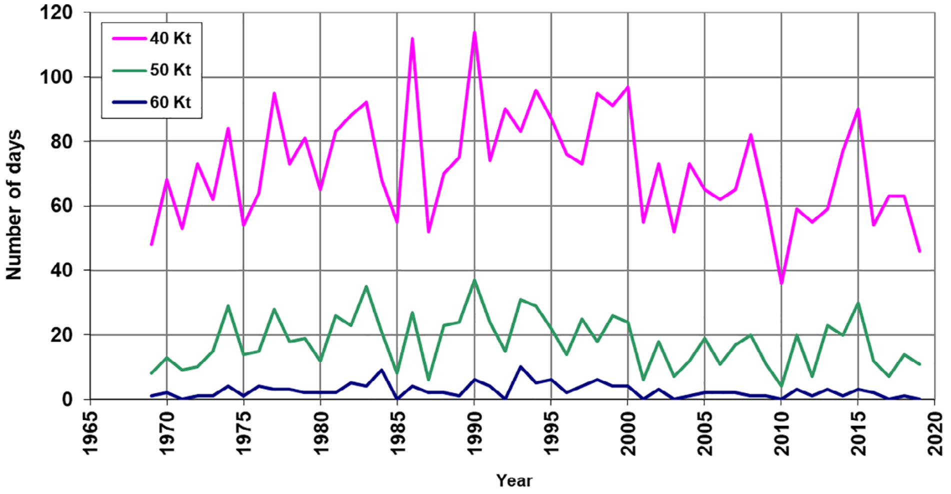


FIGURE 39 Count of the number of individual days each year during which a max gust speed ≥ 40, 50 and 60 Kt (46, 58, 69 mph; 74, 93, 111 kph) has been recorded by at least 20 or more UK stations, from 1969 to 2019. Stations above 500 m above sea level are excluded

Storm' of 26 December 1998 and the 'Great Storm' of 16 October 1987. In the last decade the most significant major winter storms have been on 5 December 2013, 3 January 2012 and 8 December 2011, and none of the storms of 2019 compared with these for overall severity across the UK.

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 39 is based comprises

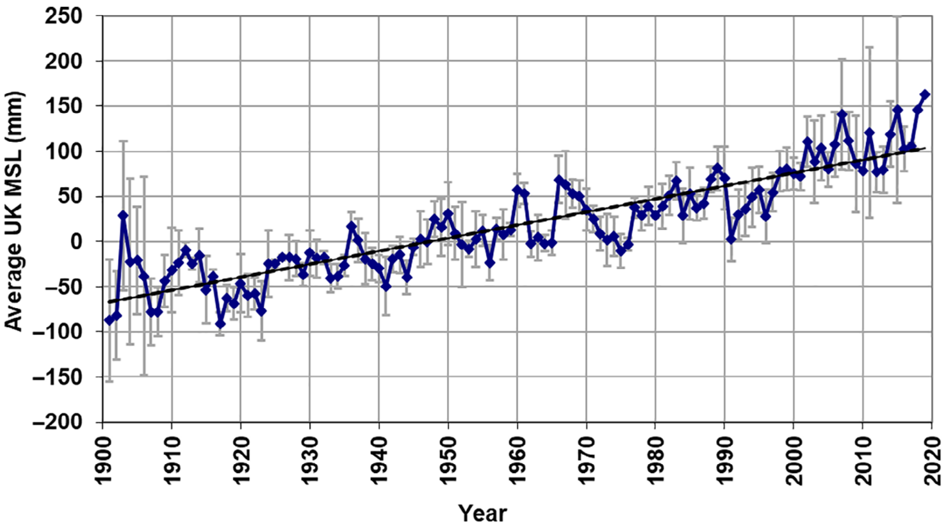


FIGURE 40 UK sea level index for the period since 1901 computed from sea level data from five stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool) from Woodworth *et al.* (2009). The linear trend-line has a gradient of 1.4 mm/year

TABLE 5 UK named storms of 2019

Name	Date of impact on UK and/or Ireland
Erik	8–9 February
Freya	3–4 March
Gareth	12–13 March
Hannah	26–27 April
Lorenzo (ex-hurricane)	4 October
Atiyah	8–9 December

around 130 stations in the 1970s, 150 in the 1980s, 190 in the 1990s and 2000s and 160 in the 2010s. Figure 39 has not been adjusted to take into account this changing network but this may partly account for the higher station counts in 40 Kt gusts through the 1980s and 1990s. Although data from the land network as presented in this report show no compelling trends in maximum gust speeds in the UK, Matthews *et al.* (2014) notes an increase in cyclone intensity and wind speeds across the North Atlantic since the 1950s based on the NCEP reanalysis (Kalnay *et al.*, 1996).

6 | SEA LEVEL

A UK sea level index (Figure 40) for the period since 1901 provides a best-estimate trend of 1.4 ± 0.2 mm/yr for sea level rise, when excluding the effect of vertical land movement (Woodworth *et al.*, 2009). When vertical land movement is included, the net rate of sea level rise is slightly higher in the south of England and slightly lower in some parts of Scotland. The rate of sea level rise for the UK is close to the estimate of

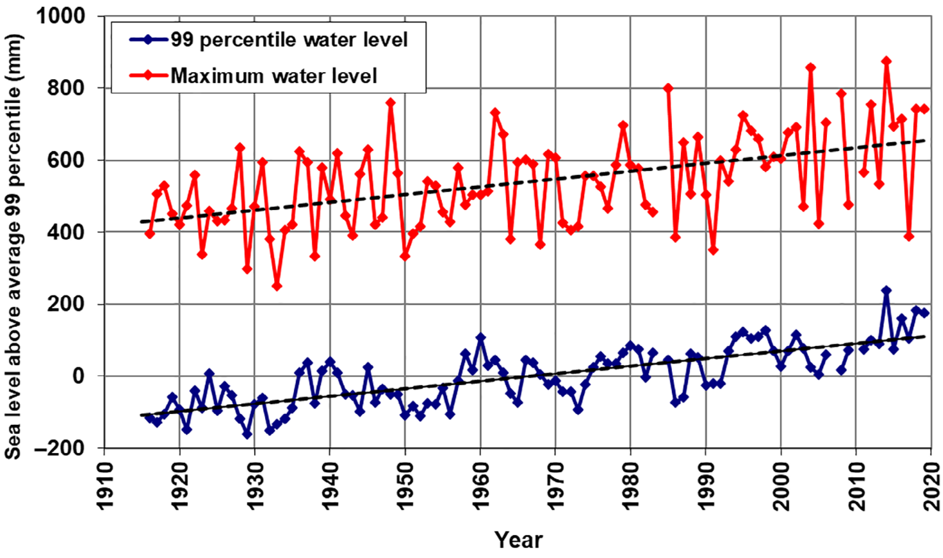


FIGURE 41 Extreme sea levels at Newlyn, Cornwall (1916–2019), in mm. The blue and red time-series are annual 99 percentiles and maximum water levels, respectively. Levels are relative to the long-term average for the 99 percentile, computed for the whole period 1916–2019

TABLE 6 Annual extremes for the UK for year 2019, excluding stations above 500 m above mean sea level (masl)

Extreme	Observation	Date	Station
Highest daily maximum temperature (09-09 UTC)	38.7°C	25 July	Cambridge Botanic Garden, 12 masl
Lowest daily minimum temperature (09-09 UTC)	−15.4°C	1 February	Braemar, Aberdeenshire, 327 masl
Lowest daily maximum temperature (09–09 UTC)	−5.0°C	31 January	Balmoral, Aberdeenshire, 283 masl
Highest daily minimum temperature (09-09 UTC)	22.6°C	26 July	Carlton-in-Cleveland, North Yorkshire, 103 masl
Lowest grass minimum temperature (09-09 UTC)	−18.1°C	30 January	Balmoral, Aberdeenshire, 283 masl
Highest daily rainfall (09-09 UTC)	143.0 mm	21 July	Ennerdale, Black Sail, Cumbria, 300 masl
Greatest snow depth (09 UTC)	33 cm	2 February	Tomnavoulin, Moray, 264 masl
Highest daily sunshine	17.0 hr	27 June	Kinloss, Moray, 5 masl
Highest gust speed	95 Kt 109 mph	2 November	Needles Old Battery, Isle of Wight, 80 masl
Highest gust speed (mountain)	105 Kt 121 mph	7 January 18 December	Cairngorm Summit, Inverness-shire 1,237 masl

Note: Stations above 500 masl are considered as mountain stations and therefore not representative of low-level areas. Channel Island values are also quoted if these exceed UK values.

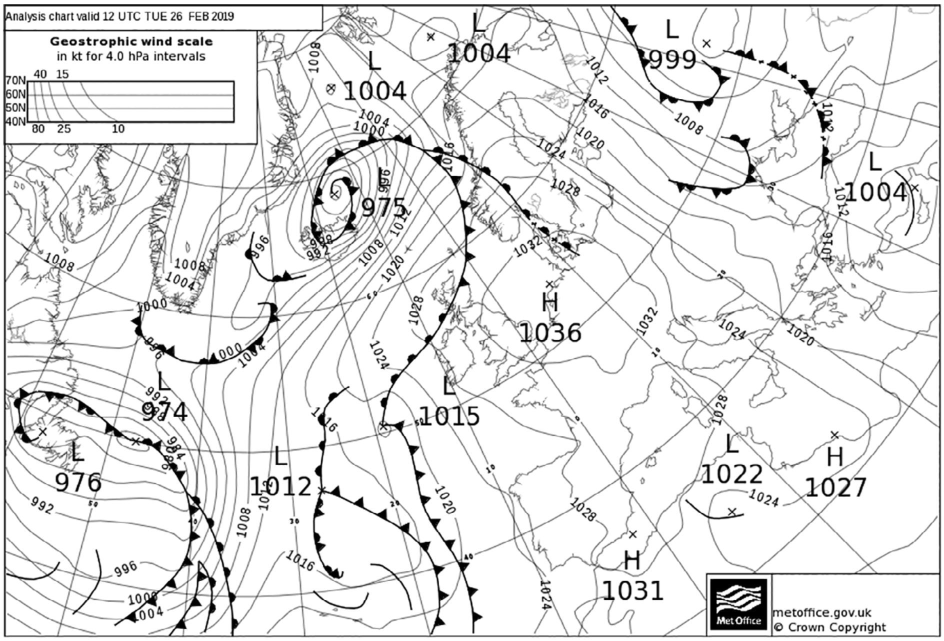


FIGURE 42 Analysis chart at 1200 UTC 26 February 2019

1.7 ± 0.2 mm/yr estimated for the global sea-level rise suggested by the Fifth Assessment Report of Intergovernmental Panel on Climate Change (Church *et al.*, 2013). However, UK sea level change is not a simple linear increase, but also includes variations on annual and decadal timescales. A number of large-scale atmospheric and ocean processes contribute to non-uniform sea-level rise around the coast of the UK.

The UK sea level index for 2019 was the highest on record in this series. The UK index is based on five long-running stations dating back to the beginning of the 20th century. The 2019 and 2018 values are based on only one of these stations (Newlyn) due to missing data at the others at various times during the year.

Error bars shown in the UK index indicate uncertainty (one standard deviation) in values for individual

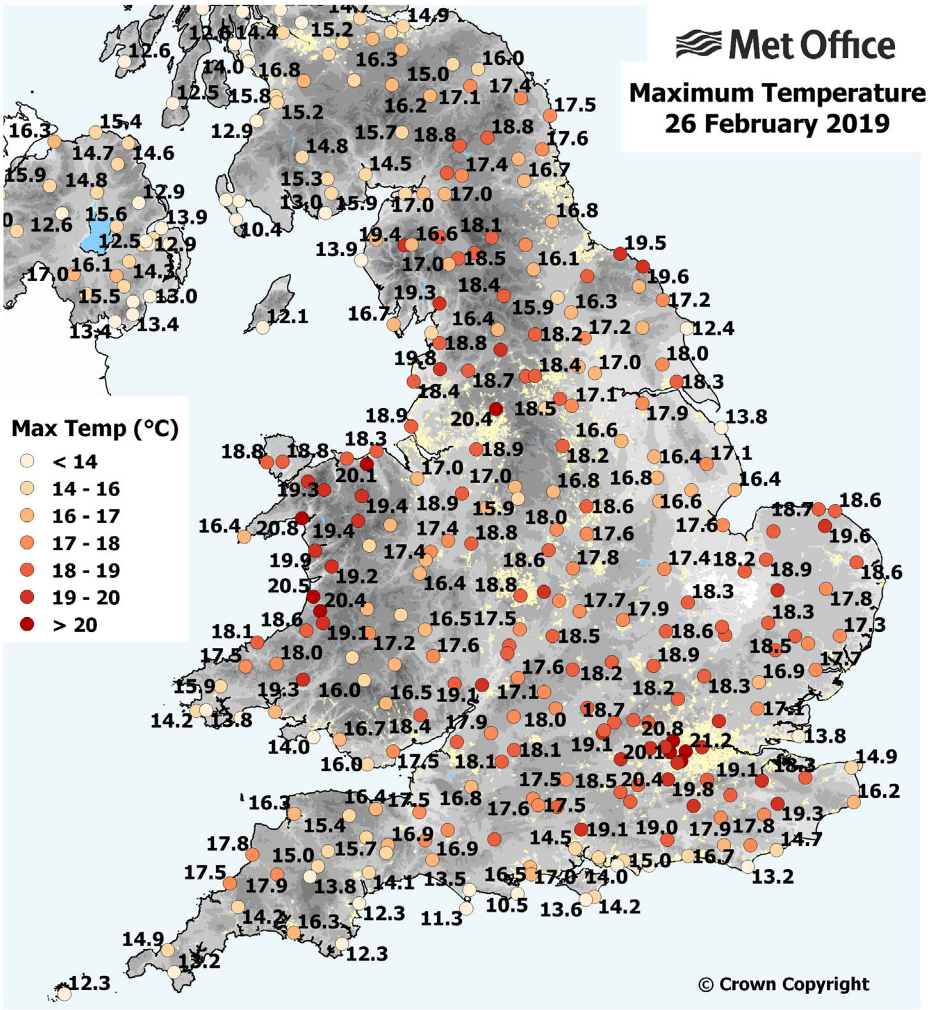


FIGURE 43 Daily maximum temperature station values (°C) on 26 February 2019

TABLE 7 National highest maximum and minimum temperature records set in February 2019 compared to previous temperature records

Station	Value	Date	National record	Previous station	Previous value	Previous date
Kew Gardens (London)	21.2°C	26 February 2019	Feb and winter max temp record for UK and England	Greenwich Observatory (London)	19.7°C	13 February 1998
Porthmadog (Gwynedd)	20.8°C	26 February 2019	Feb max temp record for Wales	Velindre (Powys)	18.6 °C	23 February 1990
Aboyne (Aberdeenshire)	18.3°C	21 February 2019	Feb max temp record for Scotland	Aberdeen	17.9°C	22 February 1897
Achnagart (Highland)	13.9°C	23 February 2019	Feb min temp record for UK and Scotland	Aboyne (Aberdeenshire)	13.7°C	13 February, 1998

years. Uncertainties in the UK sea level index for several recent years, notably 2007, 2011 and 2015, are large; it is suspected that these relate to data quality issues at the Liverpool gauge. The method for calculating uncertainties does not currently take into account missing stations. The 2010, 2018 and 2019 values are based on only one gauge so error bars are not available. Given issues with data availability in the network a review of the method used to calculate the UK index may be required to derive an index based on the complete network of 44 stations, rather than restricting this to long-running stations only.

Figure 41 presents a 100-year record of sea level at Newlyn, Cornwall showing time-series of the annual

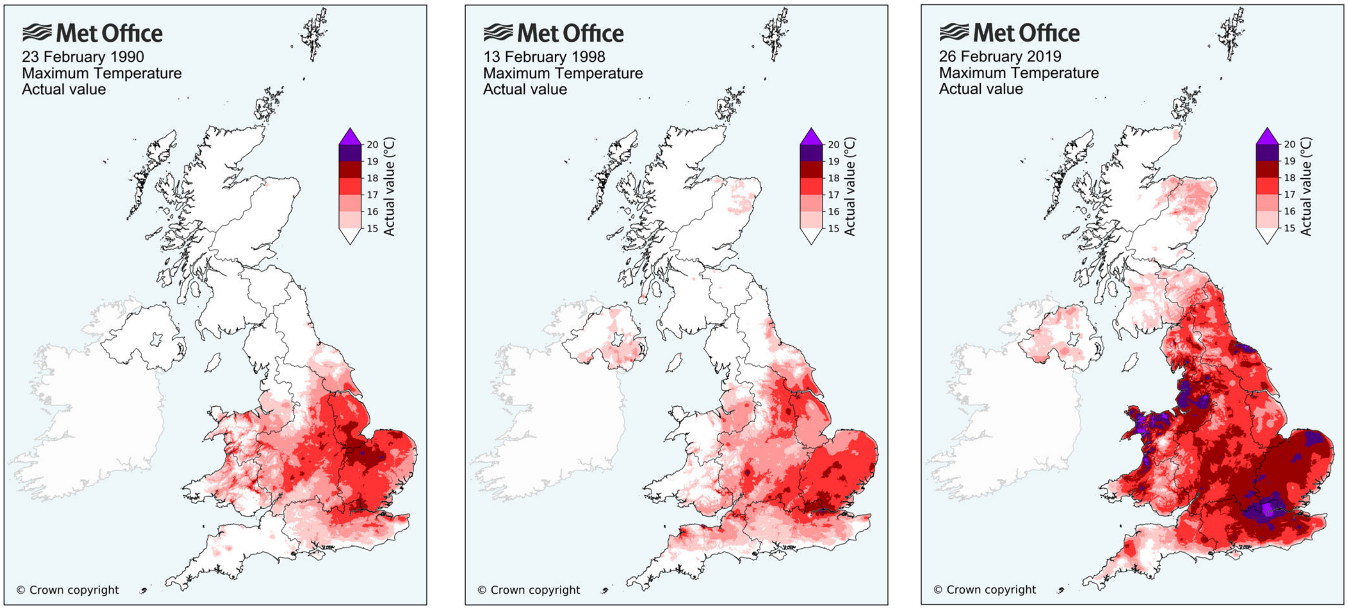
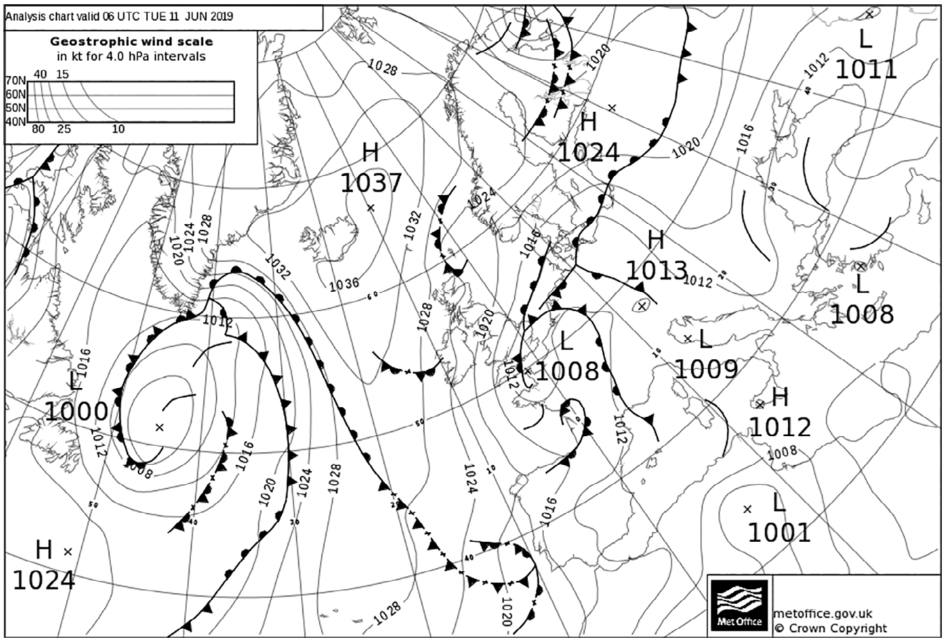


FIGURE 44 Daily maximum temperatures (°C) compared for (a) 23 February 1990, (b) 13 February 1998 and (c) 26 February 2019

FIGURE 45 Analysis chart at 0600 UTC 11 June 2019



99th percentile water level and annual maximum water levels, relative to the long-term mean for the 99th percentile. The 99th percentile is the level which is exceeded 1% of the time, or for about 88 hr in any given year. Any periods of high tides and storm surges in the year are likely to be in the 88 hr above the 99th percentile. The annual maximum water level shows greater annual variability than the 99th percentile series. Consequently the 99th percentile time-series is sometimes preferred because it provides a description of change in high and low water characteristics without the greater year-to-year variability inherent in the true extremes.

The 99th percentile water level at Newlyn for year 2019 was the third highest in the series, with year 2014 highest. The highest maximum water level during 2019 was equal-seventh highest (with 2018). The long-term trends in 99 percentile level and highest maximum water levels are 2.1/2.2 mm/year, respectively for the period 1916–2019. At many locations, extreme sea levels that exceed critical flood-thresholds are being experienced more frequently than in the past, due to sea level rise (MMCIP, 2020).

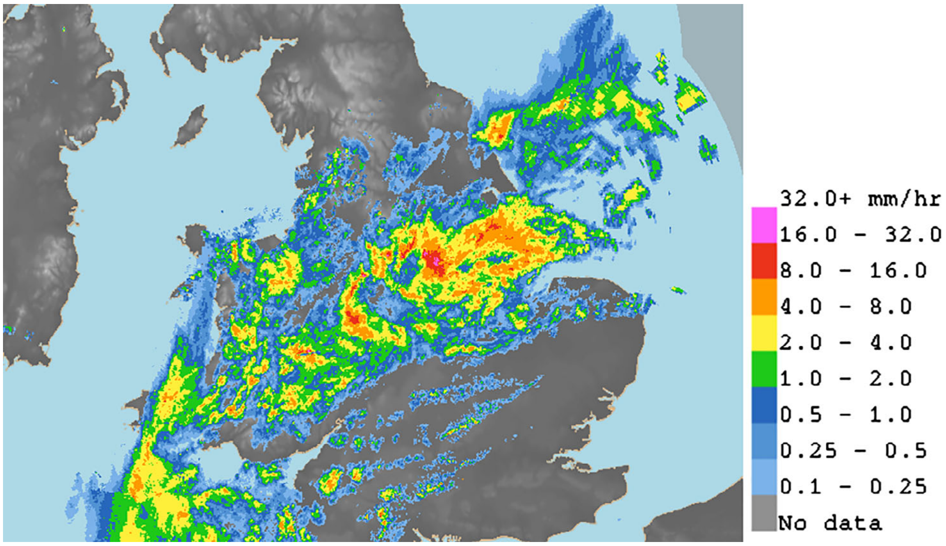


FIGURE 46 Rain-radar image at 0600 UTC 11 June 2019

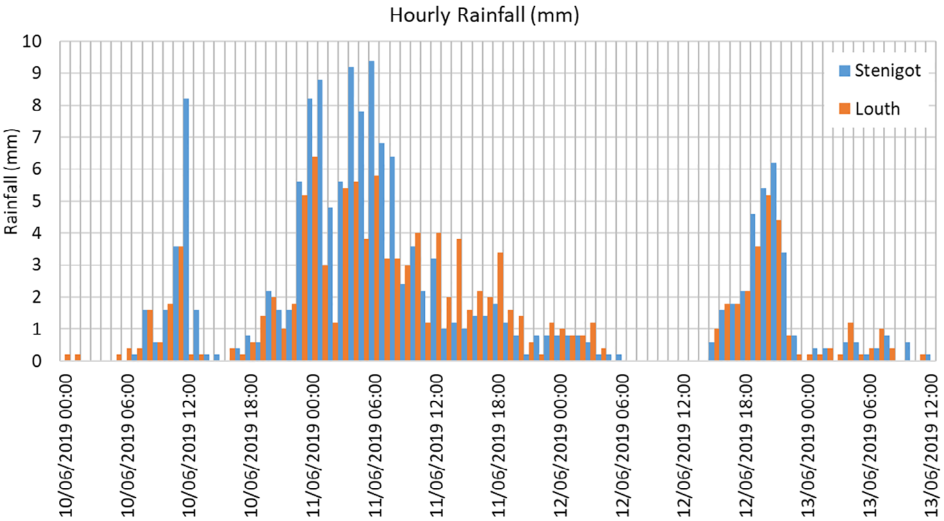


FIGURE 47 Hourly rainfall totals (mm) from 10–13 June 2019 at two stations in the Lincolnshire Wolds—Stenigot and Louth

7 | EXTREMES FOR YEAR 2019

Table 6 shows the UK weather extremes for year 2019. The highest temperature of the year, 38.7°C at Cambridge Botanic Garden on 25th July was a new all-time temperature record, exceeding the previous record by 0.2°C. More than 10 stations in the network exceeded 37°C with three exceeding 38°C. (For more details of this event see Section 8). The following night was very mild with the highest daily minimum temperature of the year, 22.6°C at Carlton-in-Cleveland within 1.3°C of the UK record.

The lowest maximum, minimum and grass minimum temperatures occurred during the coldest spell of the year at the end of January into early February. These were fairly typical for the lowest values of the year—the lowest minima occurring under clear skies and light winds with lying snow. Braemar, located in the Dee valley, is often the coldest location in the UK, associated with cold air flowing off the Cairngorms and pooling in the valley. The greatest snow depth of 33 cm at Tomnavoulin, Moray, also occurred during this cold spell but is likely to have been significantly influenced by drifting; nearby Cromdale (also Moray) recorded 14 cm.

The highest daily rainfall total of 143.0 mm at Ennerdale, Black Sail was on 21st July. This was a very wet day across the English Lake District with over 100 mm recorded at several rain-gauges in the western fells. The highest gust speed of 95 Kt (109 mph) at Needles Old Battery was due to an area of low pressure bringing some very strong winds to south Wales and the south coast. However, this station has a uniquely exposed location on the western end of the Isle of Wight. Elsewhere exposed coastal locations of south Wales and the south coast saw gusts of 60–70 Kt (69–81 mph).

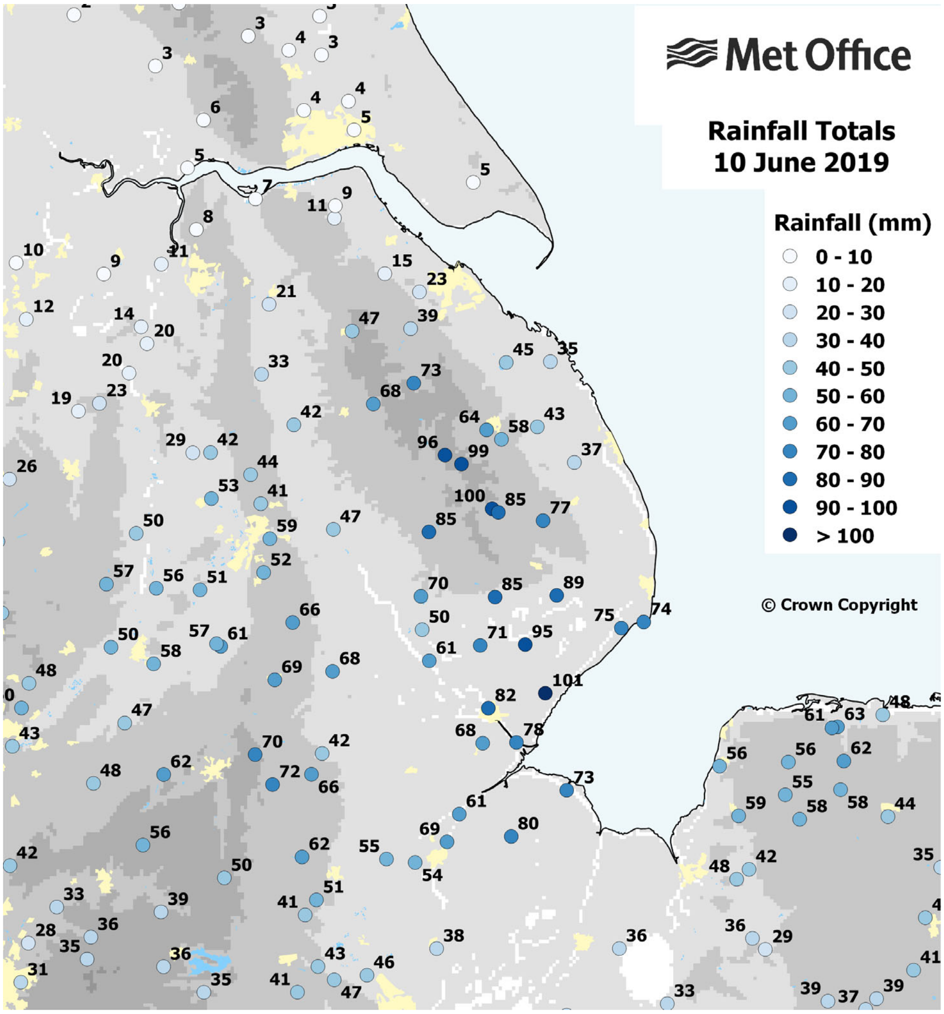


FIGURE 48 Daily rainfall totals (mm) across Lincolnshire 10 June, 2019 (0900 UTC 10th–0900 UTC 11th)

TABLE 8 Rainfall totals (mm) at selected rain-gauges in Lincolnshire 10–12 June, 2019

Date	Cadwell	Tetford	Lade Bank	Holbeach S Wks	Wainfleet
10/06/2019	81.0	99.5	95.0	79.6	74.6
11/06/2019	58.0	34.0	16.5	26.8	20.0
12/06/2019	29.0	38.7	23.0	23.0	24.8
3-day total	168.0	172.2	134.5	129.4	119.4
1981–2010 average	62.2	59.0	49.5	50.6	53.1
3-day total as % of 1981–2010 June average	270	292	272	256	225

8 | SIGNIFICANT WEATHER EVENTS OF 2019

This section describes notable weather events which occurred during 2019. The choice of event is determined by the National Climate Information Centre based on our experience of monitoring the UK's climate through the year, 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 2019 is also included in the wind section of this report.

8.1 | Exceptional warmth, February

In late February 2019, the UK experienced a flow of exceptionally mild Tropical Maritime air originating from

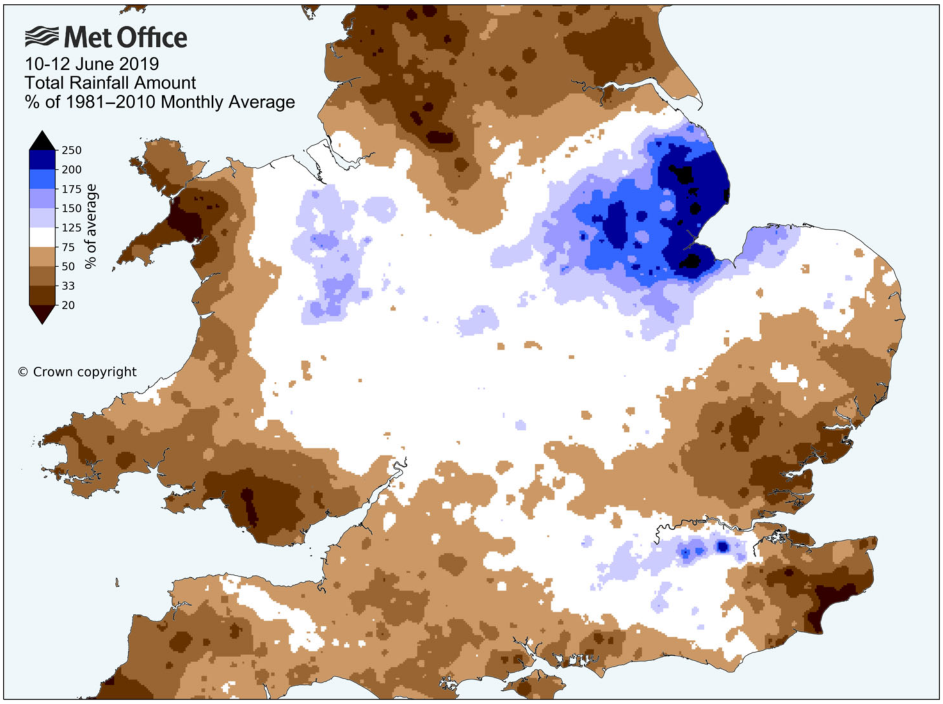


FIGURE 49 Rainfall totals 10–12 June 2019 as a percentage of the 1981–2010 June average

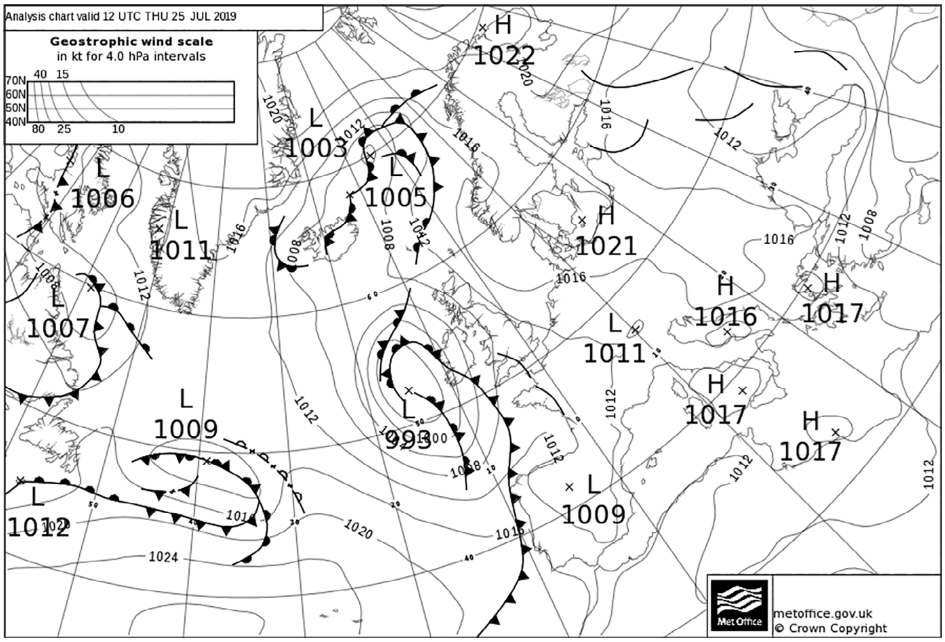


FIGURE 50 Analysis chart at 1200 UTC 25 July 2019

the Canaries and North Africa (Figure 42). Daily maximum temperatures responded to clear skies and long spells of late winter sunshine with 18°C reached somewhere in the UK on every day from 21 to 27 February and exceeded widely on 25th to 27th. This was the first time 20°C was exceeded in the UK in a winter month with the highest temperature recorded 21.2°C at Kew Gardens on the 26th.

Figure 43 shows daily maximum temperatures on the 26th. 20°C was reached in London, west and north Wales and the Manchester area, with 19°C also across parts of Wales, north-west England, East Anglia and North-East England and 18.8°C as far north as Northumberland. Across England and Wales daily maximum temperatures were widely 10°C more than the February 1981–2010 average, with anomalies locally over +13°C in parts of Wales and northern England. For example, at Hunt Hall Farm in upper Teesdale, the daily maximum of 18.1°C on 26 February 2019 compared to a February 1981–2010 long term average of 4.5°C. Large fires broke out in West Yorkshire across the moorland of the Pennines. These occurred

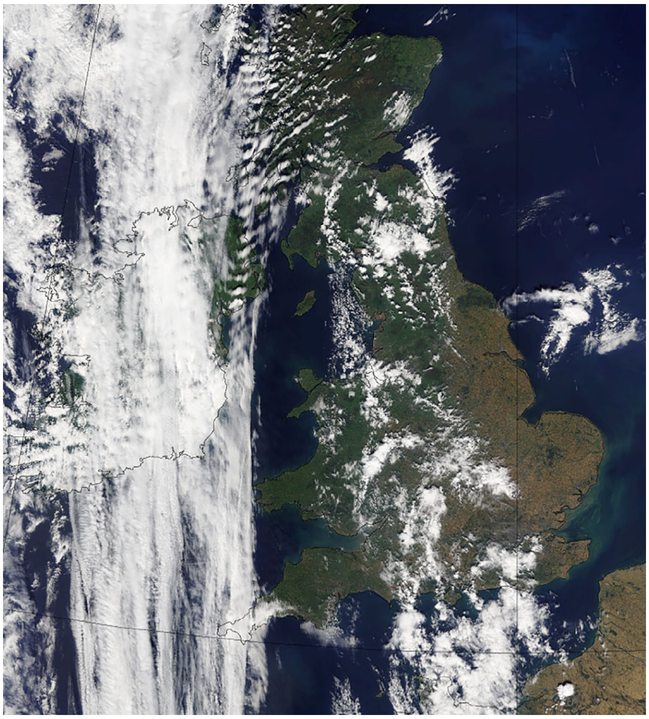


FIGURE 51 Visible satellite image at 1252 UTC 25 July 2019. Image copyright Met Office/NOAA/NASA

unusually early in the year as a result of the warmth and dry ground.

Four new national temperature records were set during this spell. Normally temperature records tend to be broken by small margins (e.g., the UK all-time record was exceeded in July 2019 by 0.2°C, see later in this section), but during this spell a new UK winter temperature record was set with a margin of 1.5°C and the Wales winter temperature record with a margin of 2.2°C. New highest daily maximum and daily minimum temperatures were also set in Scotland—the former a long-standing 122-year record (Table 7).

Figure 44 compares the daily maximum temperatures from 26 February 2019 against the previous warmest winter days for the UK based on temperatures widely reaching 18°C: 23 February 1990 (19.4°C at Santon Downham, Suffolk); and 13 February 1998 (19.7°C at Greenwich Observatory, London). On 26 February 2019 temperatures were generally much higher and the warmth covered a much greater extent across the UK compared to these previous dates.

An analysis of the February 2019 warm spell in the UK by Young and Galvin (2020) demonstrates that multiple meteorological factors combined to result in these exceptional temperatures, in particular subsidence of air resulting in a warm-dry layer near the surface. Further analysis based on the UK Climate Projections (UKCP18) has shown that this event was due to exceptional synoptic conditions, and would likely have been record-breaking even without the influence of the warming UK climate (Kendon *et al.*, in press). However, these model simulations also show that under a high greenhouse gas emissions scenario, by the late 21st century 20°C in winter may occur as a result of much less rare synoptic conditions, perhaps every 2–3 years (Christidis and Stott, in press; Kendon *et al.*, in press).

8.2 | Wet weather and flooding across Lincolnshire, June

The UK experienced a spell of very wet weather in mid-June as a low pressure system and associated fronts brought widespread and slow moving heavy rainfall. The worst affected area was Lincolnshire, with around 600 homes evacuated in Wainfleet and 130 flooded when the River Steeping burst its banks. Figure 45 shows low pressure to the south-east of the UK with a north-easterly flow at the boundary between colder, drier air to the north-west and warm, moist air across the near continent. The stalled front on the boundary between these air masses brought persistent heavy rainfall across south Lincolnshire, particularly the Lincolnshire Wolds (Figure 46). This type of rainfall might more normally be expected across western upland areas of the UK in a prevailing westerly Atlantic flow, but is much more unusual in an easterly flow, affecting areas of the UK normally in the rain-shadow of upland areas and climatologically much drier. The main event occurred from 10 to 11 June but the low pressure system was slow to clear and brought further rain on 12 June exacerbating the flooding problems.

Figure 47 shows hourly rainfall totals for two rain-gauges in the Lincolnshire Wolds at Stenigot and Louth. 123 mm of rain fell in 48 hr at Stenigot, followed by a further 25 mm only 8 hr later. On 10 June, 50–70 mm fell widely across southern Lincolnshire with up to 100 mm from the Lincolnshire Wolds to the Wash (Figure 48). Table 8 lists daily totals for selected rain-gauges across this area. More than 2.5 times the June 1981–2010 average rainfall fell in just 3 days, and this period was also very wet across parts of east Wales, south London and Surrey (Figure 49). This was the third wettest June for Lincolnshire in a series from 1862 (based on HadUK-Grid with 138.4 mm, 247% of the June 1981–2010 long term average overall)—but even so June 2007—when there was major and widespread flooding—was much wetter (180.8 mm, 323%).

8.3 | Record-breaking heatwave, July

The UK experienced a short but exceptional heatwave in late July, setting a new all-time UK temperature record of

38.7°C. The analysis chart on 25 July shows much of the UK in light southerly flow drawing exceptionally hot air from the near continent (Figure 50). New national temperature records were set in Belgium, the Netherlands and Germany, and in Paris the temperature reached 42.6°C. The British Isles was largely cloud-free, but with weather fronts bringing cooler, fresher air to the west. Temperatures peaked in the early afternoon, but to the west and north-west of London areas of cloud moved north from France (Figure 51). Thunderstorms brought torrential downpours during the evening to parts of East Anglia and the far south-east.

The rail network was severely affected by the heat across south-east England with train cancellations and main lines closed out of London due to concerns with rail buckling. Damage occurred to overhead electric wires as they sagged in the heat, and trackside vegetation caught fire in several locations. The exceptionally hot weather made conditions difficult, particularly for the frail and elderly, with over 500 estimated excess deaths in England above the baseline in 65+ year olds during this spell (Public Health England heatwave mortality monitoring, summer 2019, see Annex 3).

Figure 52 shows daily maximum temperatures on 25 July 2019. 38.7°C at Cambridge Botanic Garden set a

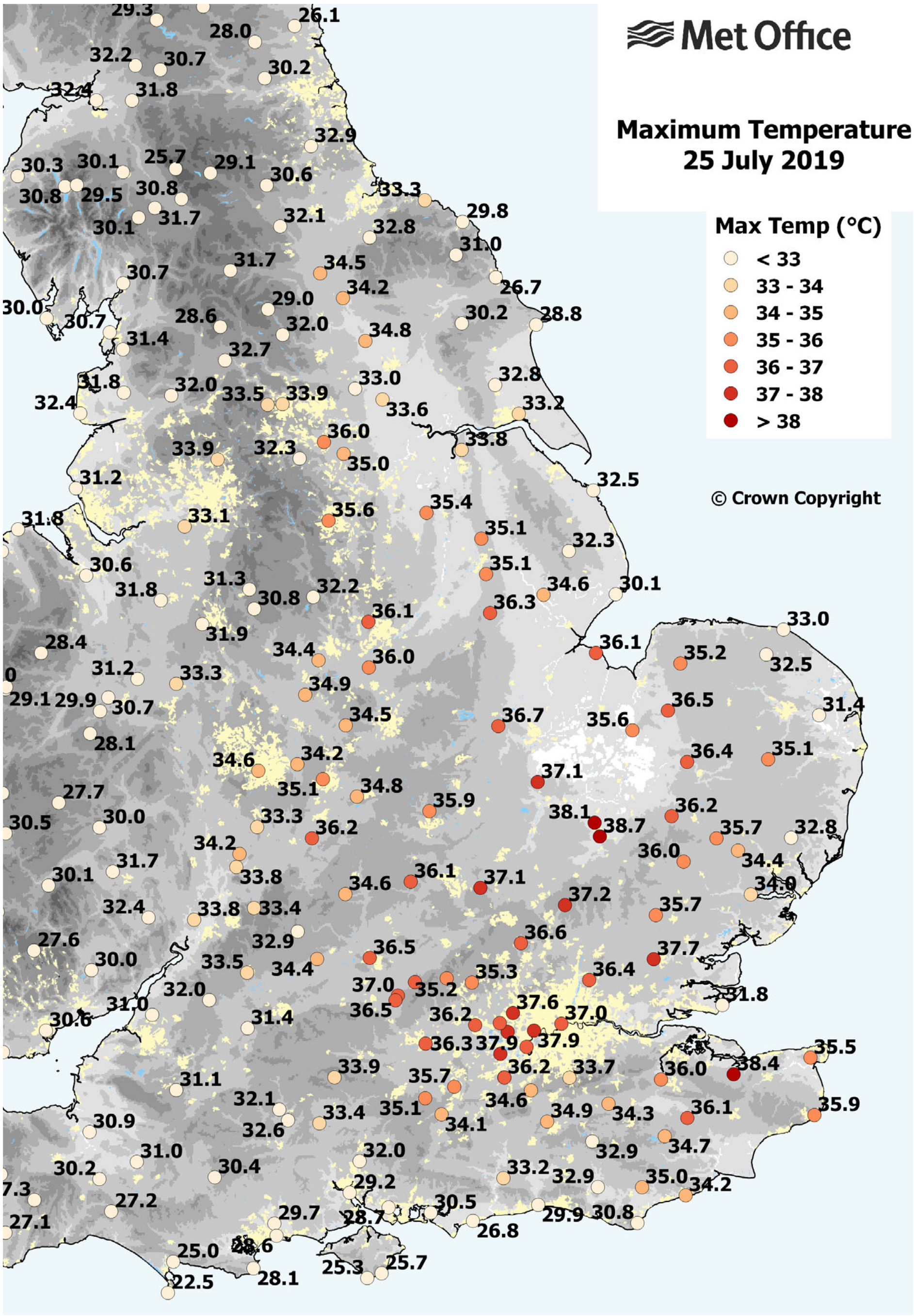


FIGURE 52 Daily maximum temperature station values (°C) on 25 July 2019

new all-time UK record, beating 38.5°C at Faversham, Kent on 10 August 2003. It also broke the UK July record of 36.7°C on 1 July 2015. Two other stations, including Faversham, also exceeded 38°C and a further 10 stations across the south-east, Midlands and East Anglia exceeded 37°C. The heatwave set a very large number of temperature records at individual stations, including those with very long-running series such as Durham (32.9°C, 138 years), Sheffield (35.6°C, 135 years), Bradford (33.9°C, 111 years), Rothamsted, Hertfordshire (36.6°C, 105 years), Cranwell, Lincolnshire (36.3°C, 105 years), and Woburn, Bedfordshire (37.1°C, 102 years).

Minimum temperatures overnight 25/26 July remained above 20°C across parts of Kent, East Anglia, Lincolnshire and Yorkshire and above 18°C in western Scotland. 20.9°C at Achnagart (Highland) set a new Scotland daily minimum temperature record (09–09 UTC) for any month—exceeding 20.5°C at Creebridge (Wigtownshire) on 2 August 1995.

The four hottest days in the UK's observational records—with at least 50 stations exceeding 34°C—are shown in Figure 53. On 25 July 2019 had the greatest spatial extent of anomalies more than 14°C above the 1981–2010 monthly long term average, across central

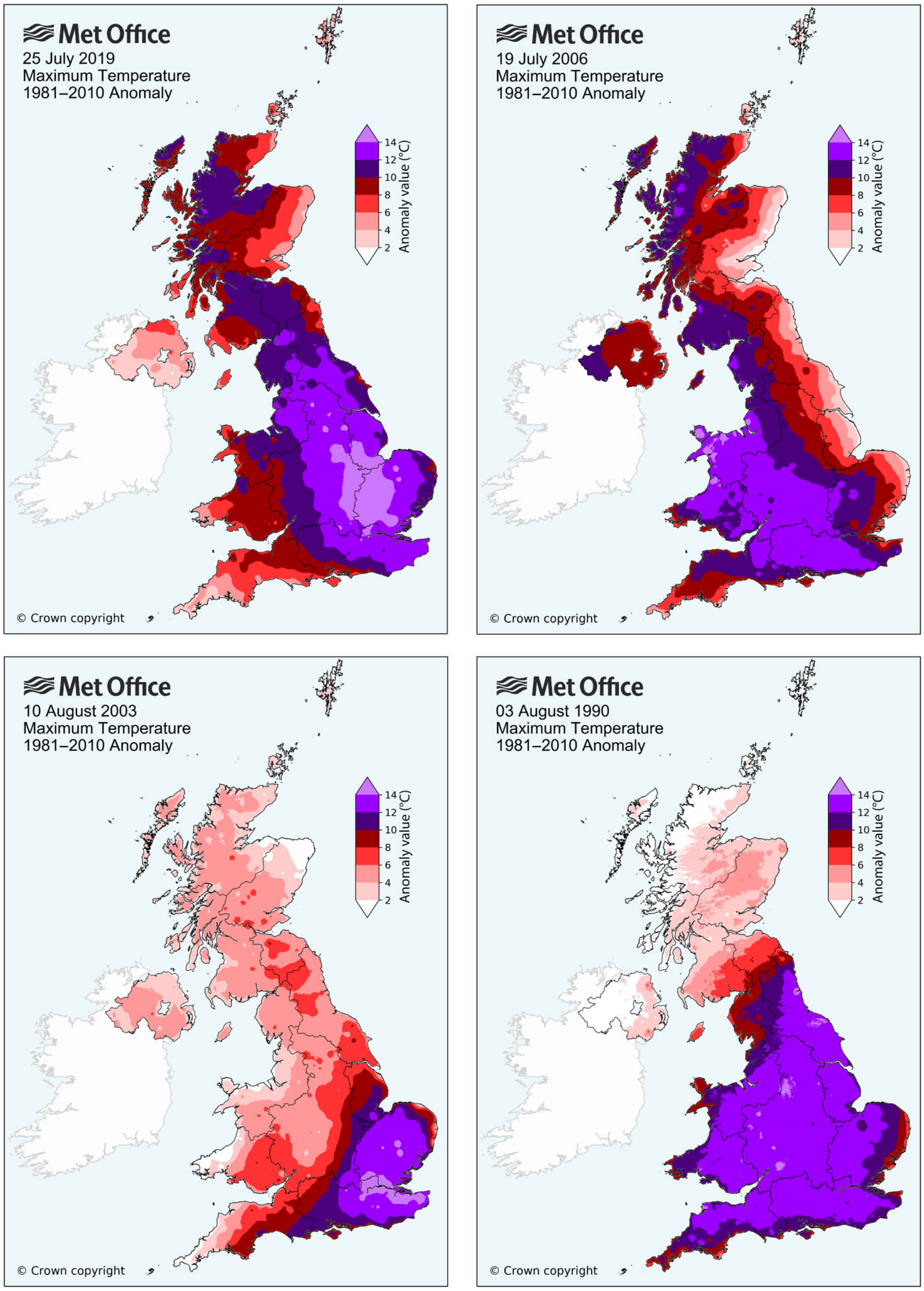


FIGURE 53 Daily maximum temperature anomalies (°C) relative to the 1981–2010 monthly average on 25 July 2019, 19 July 2006, 10 August 2003 and 3 August 1990

and eastern England, while on 10 August 2003 the highest anomalies were focussed more locally across London and the far south-east. On 3 August 1990 the heat extended further west to cover most of England and Wales, whereas on 19 July 2006 western areas were more affected.

Meteorological conditions—in particular the warmth higher in the atmosphere due to advection of air from the hot near-continent—made reaching 40°C somewhere in the UK a plausible outcome both at the end of June (when 46.0°C was recorded in the south of France) and during the July heatwave. However, in the '40°C near-miss' July 2019 case an upper-level trough promoting a deeper more unstable boundary layer resulted in the build up of cloud cover which held back temperatures where they were expected to peak to the west and north-west of London (D. Suri Met Office chief operational meteorologist, personal communication. Figure 51). In the current UK climate a temperature of 40 °C is a plausible but low probability extreme and is estimated to have a return time of 200–300 years –but by the end of the century under a mid-range greenhouse gas emissions scenario this could decrease to a 15 year return period (Christidis *et al.*, 2020).

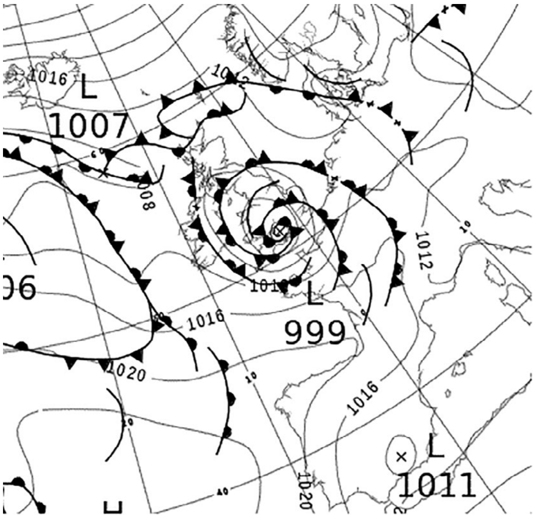


FIGURE 54 Analysis chart at 1200 UTC 30 July 2019

8.4 | Torrential downpours and flash-flooding, late July

An area of low pressure brought torrential downpours and flash-flooding to parts of northern England in late July. On 30 July, parts of Swaledale and Arkengarthdale in the Yorkshire Dales were worst affected. A bridge near Grinton collapsed, and a landslip closed the railway line between Carlisle and Skipton. Flash-flooding affected properties in Leyburn and Reeth, and floodwaters caused damage to farm walls and fences and deposited flood debris across farmland. The analysis chart (Figure 54) shows this area of low pressure centred over England, bringing some

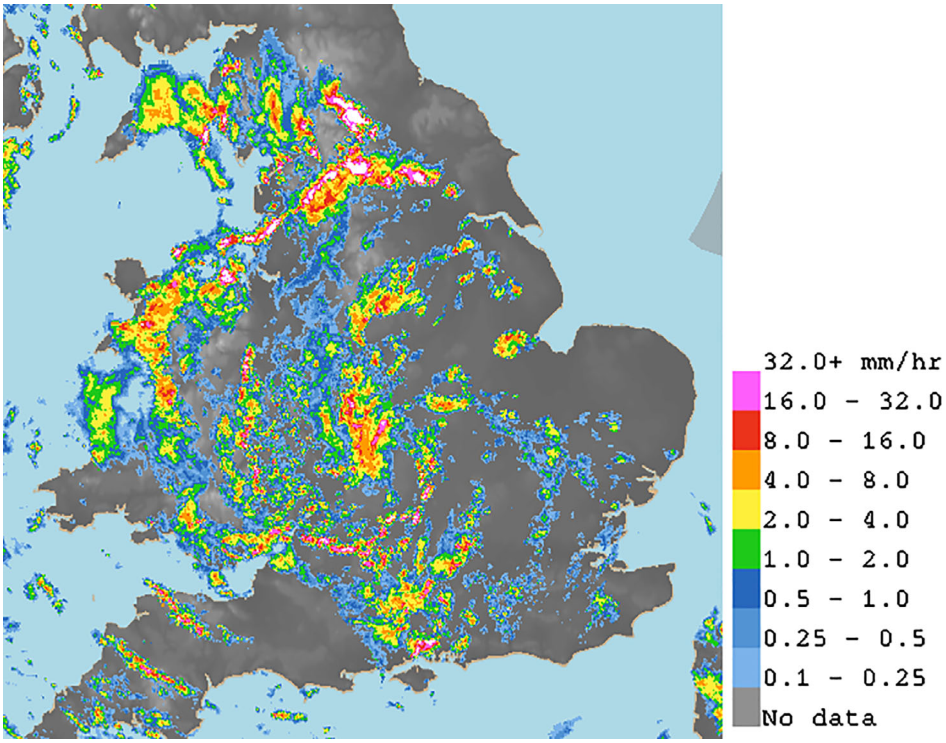


FIGURE 55 Rain-radar image at 1500 UTC 30 July 2019. White colours indicate rain-rates exceeding 32 mm/hr

TABLE 9 Highest 15-min, hourly, two-hourly and daily rainfall totals at four rain-gauges in the official registered network across the North Pennines

Station	Highest 15-min total (mm)	Highest hourly total (mm)	Hour ending (UTC)	Highest 2-hr total (mm)	Hour ending (UTC)	Daily total 30 July 2019 (mm, 0900 UTC 30th to 0900 UTC 31st)	July 1981–2010 long term average (mm)
Old Spital Farm (County Durham)	24.4	63.0	1600	72.2	1700	95.0	60.0
Sedbergh (Cumbria)	24.8	55.4	1200	63.6	1200	77.0	101.3
Arkle Town (North Yorkshire)	18.4	52.8	1500	85.6	1600	107.8	70.7
Malham Tarn (North Yorkshire)	18.2	43.6	1400	66.6	1500	91.1	105.0

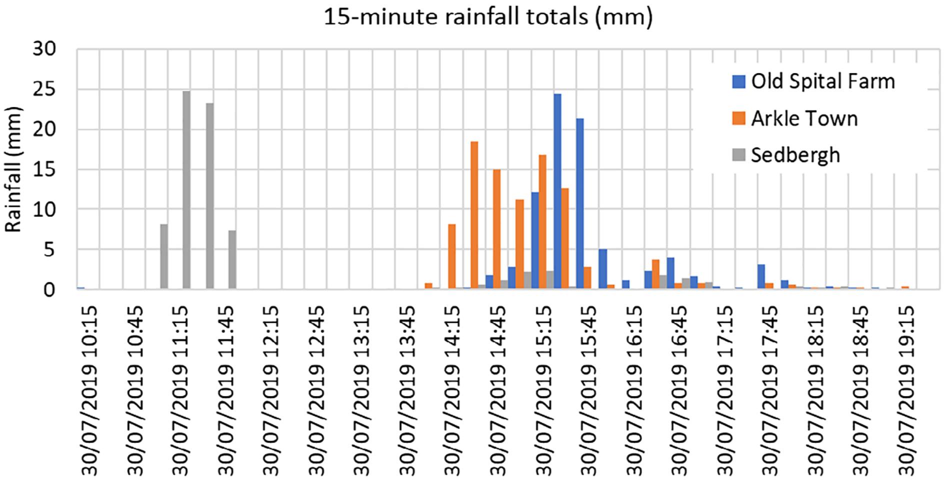


FIGURE 56 Fifteen-minute rainfall totals (mm) at Old Spital Farm, Arkle Town and Sedbergh on 30 July 2019

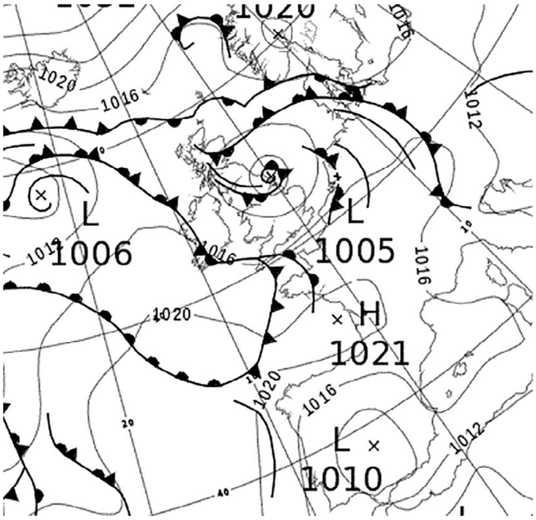


FIGURE 57 Analysis chart at 1200 UTC 31 July 2019

exceptionally intense downpours across England and Wales, focussed especially on the Pennines (Figure 55).

Table 9 lists the highest hourly, two-hourly and daily totals at four rain-gauges in the official registered network across the North Pennines. The highest hourly totals were 40–60+ mm, with 2-hr totals of 60–80+ mm and daily totals of 70–100+ mm, most of which would have fallen within a few hours. In some locations the whole-month July long-term average fell in 1–2 hr. Rain gauges at Sedbergh recorded 48.0 mm in 30 min, Arkle Town (Arkengarthdale, Yorkshire Dales) 58.0 mm of rain in 45 minutes, and Old Spital Farm (A66, County Durham) 82.2 mm in 90 minutes, with rain-rates sustained at 10–20 mm per 15-min intervals (Figure 56). The highly localized nature of the rainfall means that other locations may well have recorded totals exceeding those from the official network listed in the table below.

The area of low pressure moved slowly east on 31 July (Figure 57). Heavy rain in the Manchester area and through the Cheshire Gap overnight on the 30th/31st was followed by intense downpours on the afternoon of the 31st in a band extending across south Manchester, east Cheshire and into the western Peak District (Figure 58). This torrential rain fell on already saturated ground and resulted in significant flash-flooding across parts of south Manchester and east Cheshire. There was

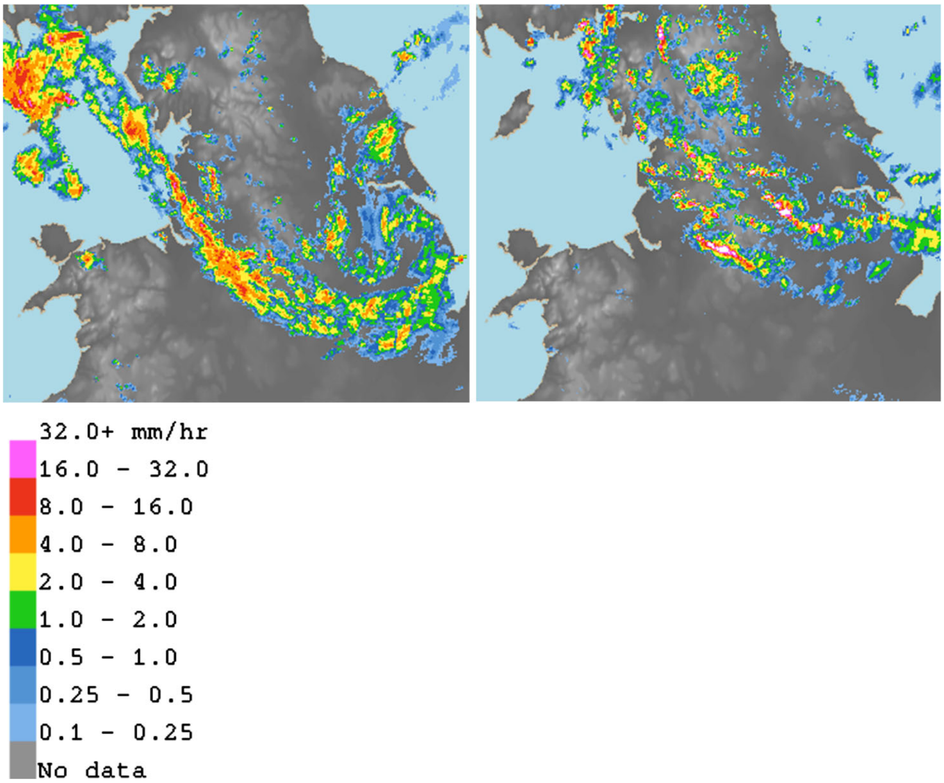


FIGURE 58 Rain-radar images (a) 0000 UTC and (b) 1500 UTC 31 July 2019

widespread flooding of properties and road closures across the region. Thousands of residents were evacuated from the centre of Whaley Bridge in Derbyshire due to damage to the spillway of Toddbrook Reservoir, threatening the risk of the dam breaking. Floodwater caused damage to roads and properties, train services were cancelled between Buxton and Manchester and several major roads were closed.

Figure 59 shows the 6-day rainfall totals from 26–31 July 2019 inclusive—actuals and as a percentage of the July long-term average. Over 75 mm was recorded widely across the Peak District, north-west England and parts of the Pennines, with 125–150 mm in some locations. Two rain-gauges in the western Peak District between Macclesfield and Buxton recorded 200 mm of rain in this 6-day period (an average of 33 mm per day). Much of the western Peak District received 150% of the July long-term average rainfall in only 6 days.

8.5 | Severe flooding across South Yorkshire, early November

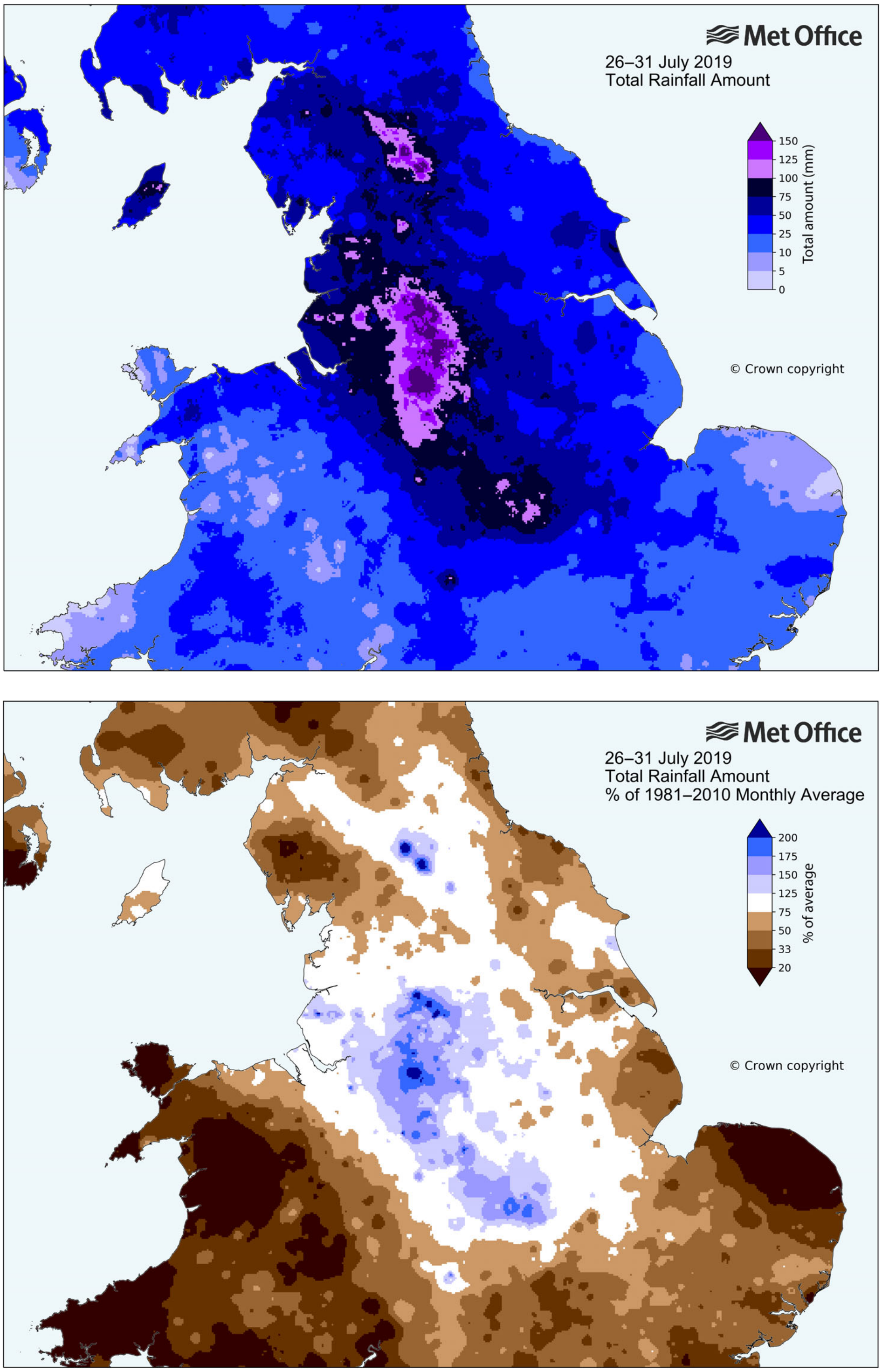
A slow-moving front brought persistent heavy rainfall across parts of Lincolnshire, Nottinghamshire, Derbyshire and South Yorkshire on 7 November 2019. 50–100 mm of rain fell in a swathe from the Humber to Sheffield, around the whole-month average rainfall or more in a period of 24 hr. This event followed heavy rain affecting a swathe from Wales, through Shropshire to South Yorkshire on 25 October and generally unsettled and wet weather from late September onwards.

The persistent heavy rain, falling on already saturated catchments, caused severe flooding from both the River Derwent in Derbyshire and the River Don in South Yorkshire. Tragically a woman lost her life when she was swept away by floodwater at Rowsley, Derbyshire. About 500 homes were flooded in the Doncaster area and hundreds of people evacuated in areas affected by flooding. Other parts of Derbyshire, Nottinghamshire and Lincolnshire were also badly affected by flooding from both river and surface water sources.

The analysis chart at 1200 UTC 7 November 2019 shows low pressure centred over the UK with an occluded front stretching across northern England (Figure 60). Persistent heavy rain fell across Lincolnshire and South Yorkshire with the front remaining largely stationary from around 0300 UTC on the 7th to 0300 UTC on the 8th in this location (Figure 61). At Sheffield and Gringley-on-the-Hill (located 40 km to the east in Nottinghamshire) 82.2 mm/63.2 mm fell over a 24-hr period between 0300 UTC on the 7th and 0300 UTC on the 8th November 2019. This was 104%/122% of the November 1981–2010 long-term average rainfall at these two respective locations (Figure 62).

Figure 63 shows rainfall accumulations for the two rain-days 6–7 November 2019—0900 UTC 6th to 0900 UTC 8th, both actual and as a percentage of the

FIGURE 59 Rainfall totals (mm) 26–31 July, 2019 (a) actuals and (b) as a percentage of the 1981–2010 July average



1981–2010 November long-term average. Rainfall totals were around the full-month average in the Sheffield area. To the east and north-east of Sheffield (climatologically a slightly drier area) they were typically 120–150% of the November long-term average.

The severe flooding was exacerbated by the persistently unsettled and generally wet nature of the weather from late September. Figure 64 shows daily rainfall totals through the autumn at three locations - Sheffield, Gringley and Kirk Bramwith (located near to the village of Fishlake which experienced fooding from the River Don). 10 mm or more fell on around 10 days, 20 mm on 5 days and up to 50 mm or more on both 25 October and 7 November—with these stations recording in autumn 2019 212%/223%/266% of the autumn 1981–2010 long term average, respectively.

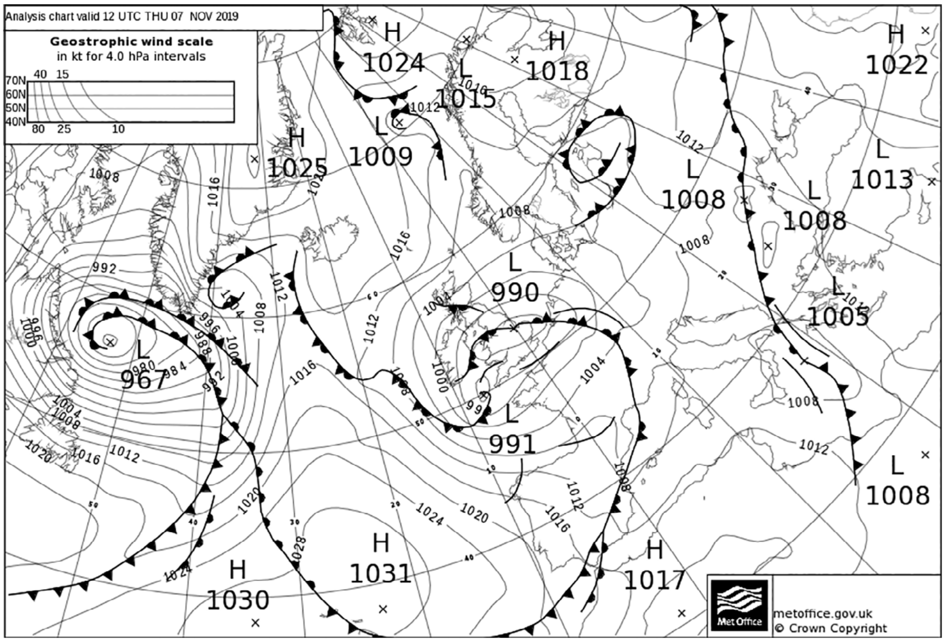


FIGURE 60 Analysis chart at 1200 UTC 7 November 2019

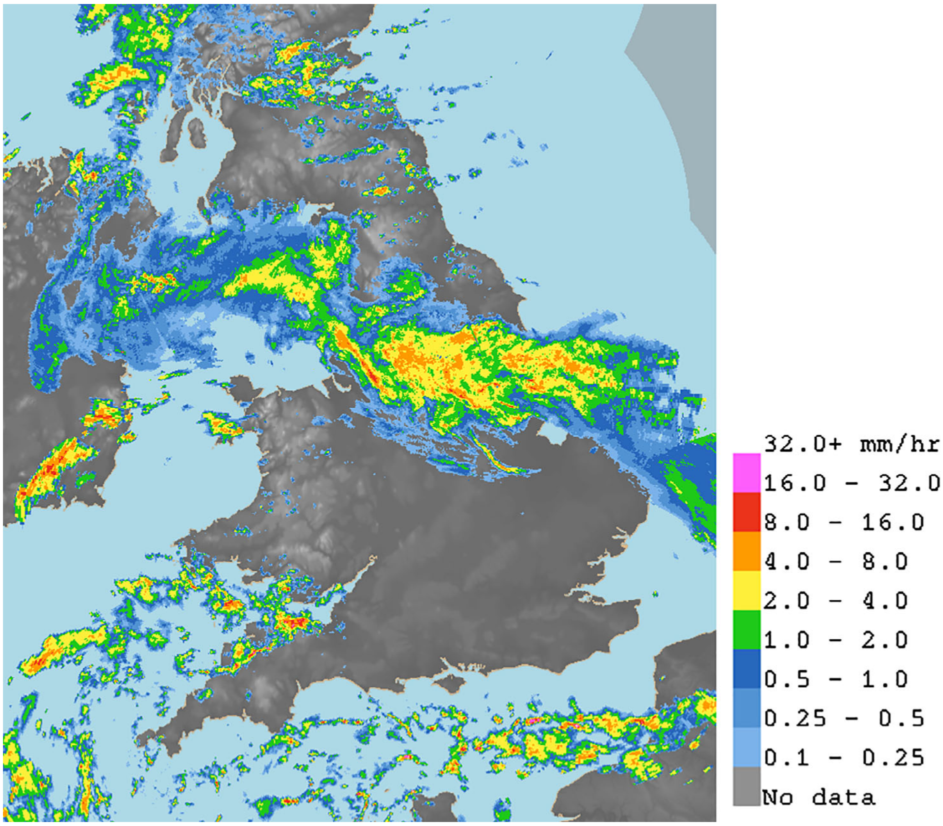


FIGURE 61 Rain-radar image at 1200 UTC 7 November 2019

The weather station at Sheffield provides a useful long-term context for this event, with records back to 1883, and in 2019 Sheffield recorded its wettest autumn on record (Figure 65).The daily total of 63.8 mm at Sheffield on 7 November 2019 was the seventh highest daily total on record at that station, however, all historical events exceeding this occurred in the summer months (June, July and August). Six of the ten highest daily totals at Sheffield have occurred since 2000.

Figure 66 compares autumn rainfall anomalies for 2019 against those in 2000. Autumn 2000 was the wettest autumn for the UK on record (series from 1862) and in the EWP series from 1766. In general anomalies were much higher across a much larger spatial extent across

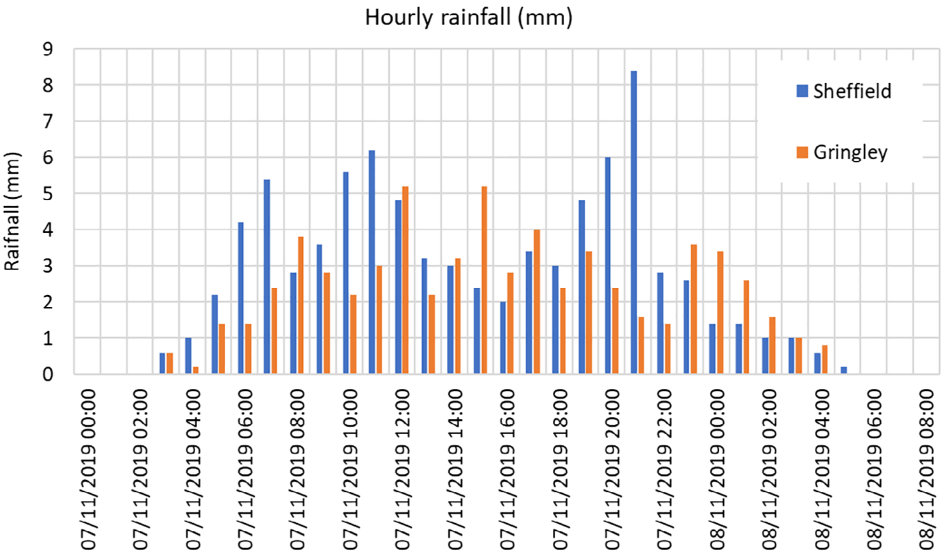


FIGURE 62 Hourly rainfall totals (mm) 7–8 November 2019 at Sheffield and Gringley-on-the-Hill, Nottinghamshire

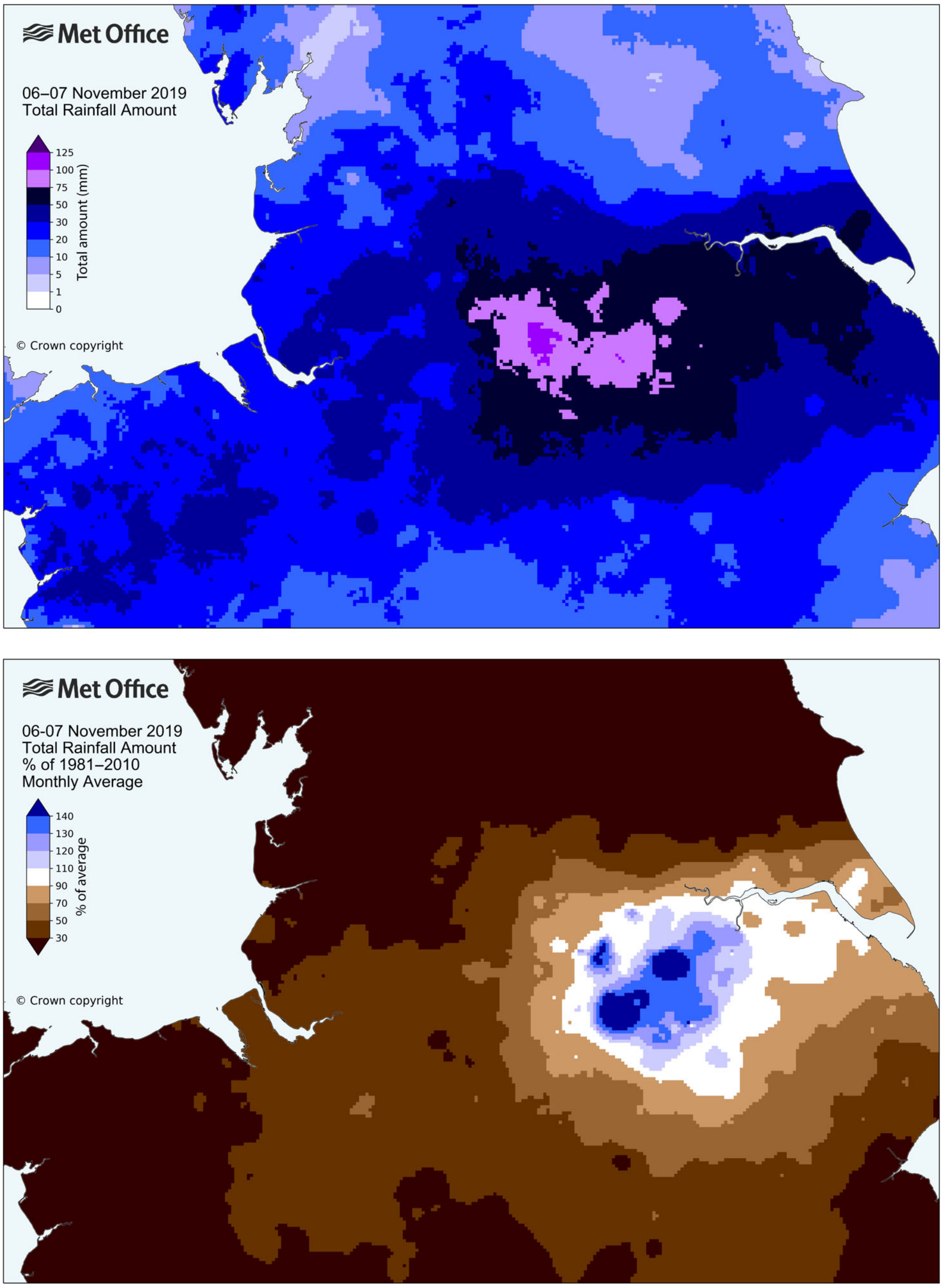


FIGURE 63 Rainfall totals (mm) 6–7 November, 2019 (a) actuals and (b) as a percentage of the 1981–2010 November average

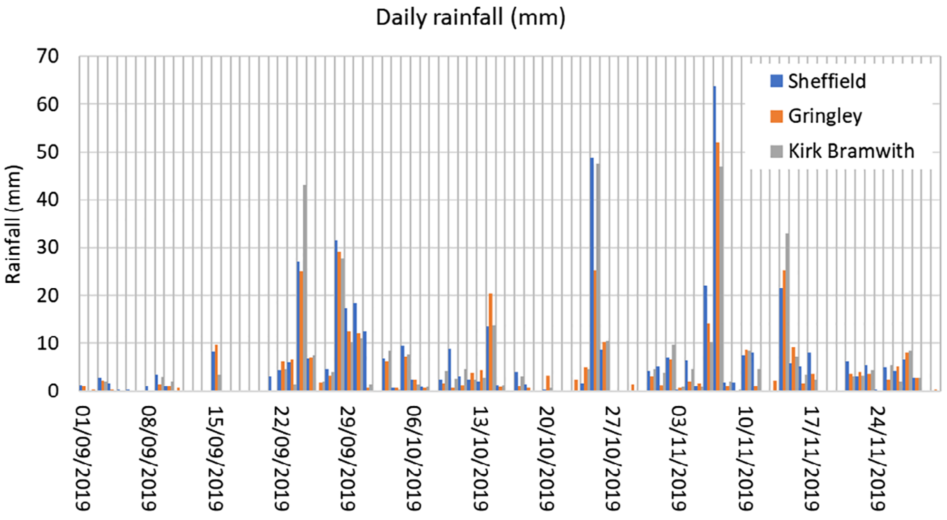


FIGURE 64 Daily rainfall totals (mm) at Sheffield, Gringley-on-the-Hill and Kirk Bramwith, located near the village of Fishlake in South Yorkshire during November 2019

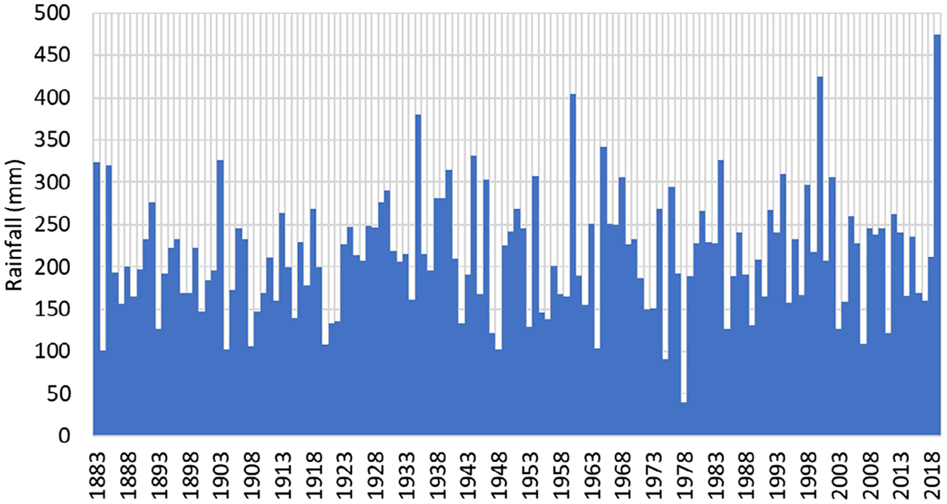


FIGURE 65 Autumn rainfall totals (mm) at Sheffield, 1883–2019 with the top three wettest years 2019, 2000 and 1960

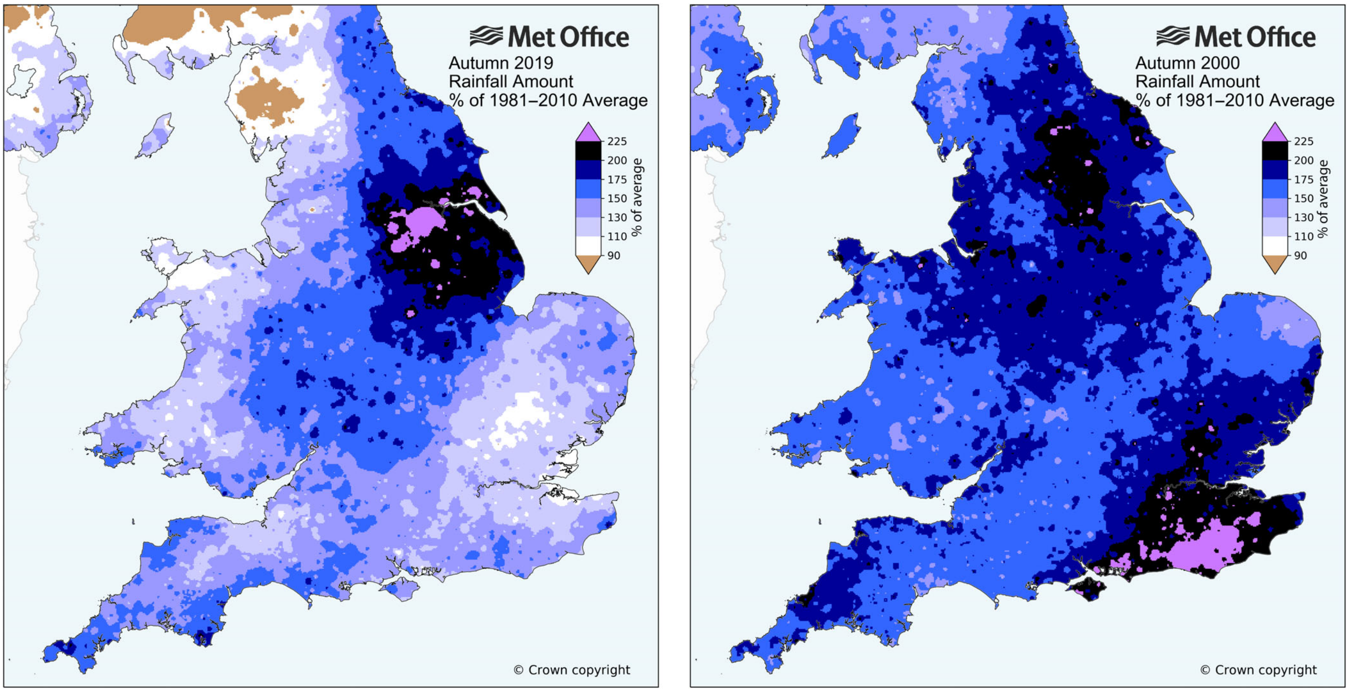
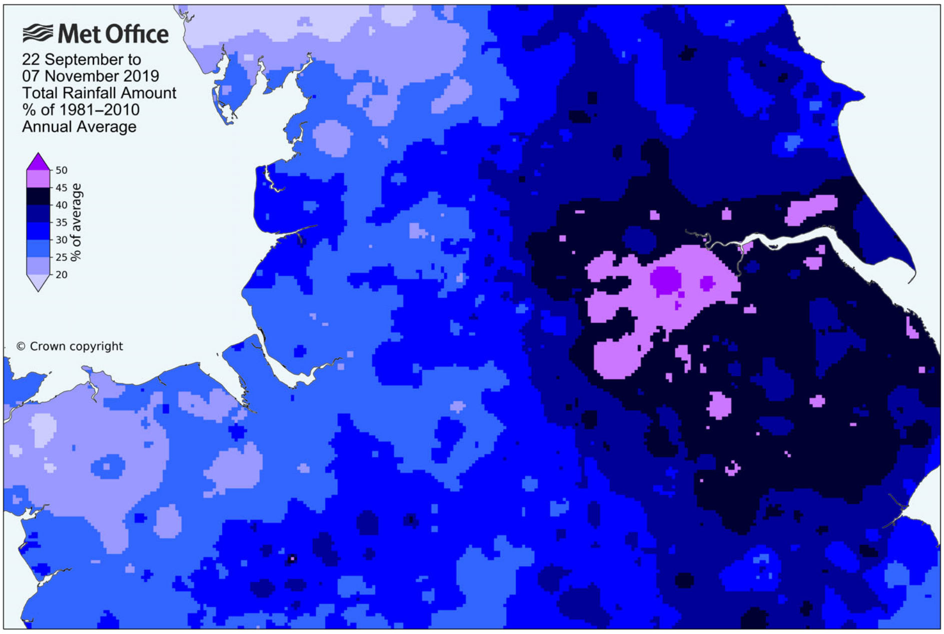


FIGURE 66 Autumn rainfall totals as a percentage of the 1981–2010 average for (a) 2019 and (b) 2000

FIGURE 67 Rainfall totals for the 47-day period 22 September to 7 November 2019 as a percentage of the 1981–2010 annual average



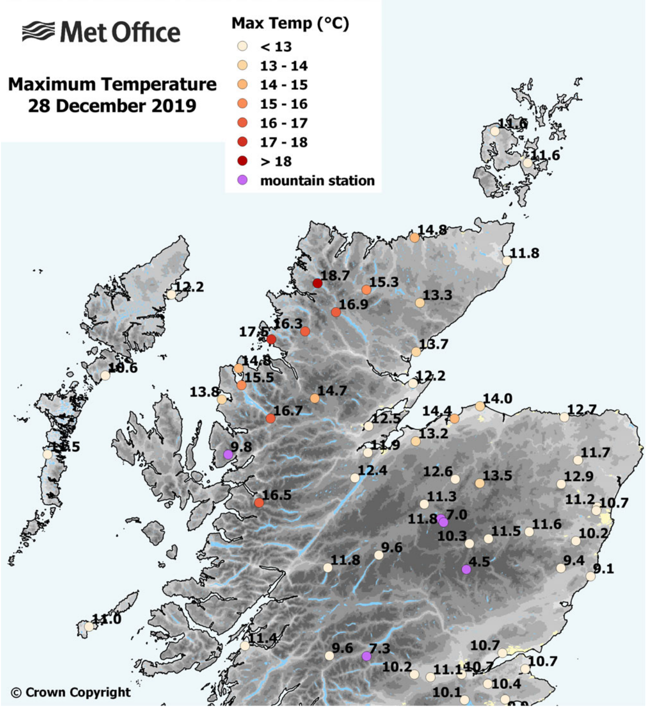


FIGURE 68 Daily maximum temperature station values (°C) on 28 December 2019. Mountain stations are above 500 masl

England and Wales in 2000 and flooding affected over 10,000 properties. The highest anomalies across the Pennines were generally slightly further north than in autumn 2019, with extreme flooding in York from the River Ouse (see for example Marsh and Dale, 2002).

Figure 67 shows station totals for the 47-day period 22 September to 7 November 2019 as a percentage of the annual average rainfall. Over this period 250–300 mm of rain fell across the area to the east of Sheffield, with 300–400 mm or more to the west of Sheffield. In these locations this represents typically between a third and a half of the annual average rain falling in a period of just over a month and a half.

8.6 | December UK temperature record

On 28 December the daily maximum temperature at Achfary (Sutherland) reached 18.7°C, the UK's highest December temperature on record, exceeding 18.3°C at Achnashellach, Highland on 2 December 1948. Temperatures locally across the far north-west of Scotland were 8–10°C or more above average for the time of year. Several other stations across the far north-west reached 16–17°C (Figure 68) and an unofficial weather station, Easter Badbea, located to the south-west of Ullapool recorded a maximum temperature of 19.2°C. An unusual feature of this temperature record was that it occurred in the middle of the night.

The record-breaking temperature was due to a Foehn effect in a very mild southerly airflow of Tropical Maritime air across the West Highlands, with pre-existing very warm air higher in the atmosphere mixing down to ground level (an ‘isentropic drawdown’). The time-series charts at Achfary AWS (an unofficial weather station located around 500 m from the Achfary climate station) and at Easter Badbea both show the dry bulb air temperature peaking at around 02 UTC, with a corresponding drop in dew-point temperature at the same time (Figure 69). The Foehn effect has been responsible for a

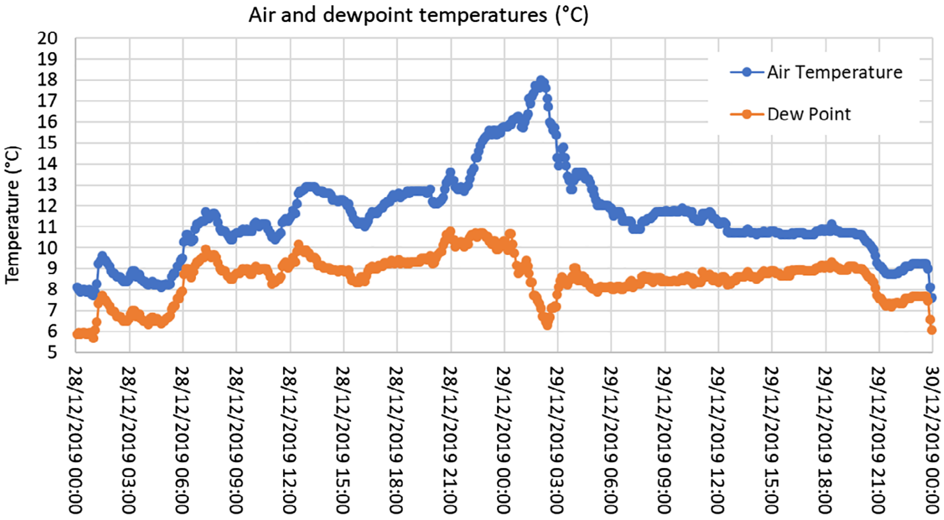


FIGURE 69 Air and dewpoint temperatures (°C) 28–29 December 2019 at Achfary AWS, Sutherland. The highest temperature occurred around 02 UTC on 29th, within the observing period for the 28th (09 UTC 28th to 09 UTC 29th)

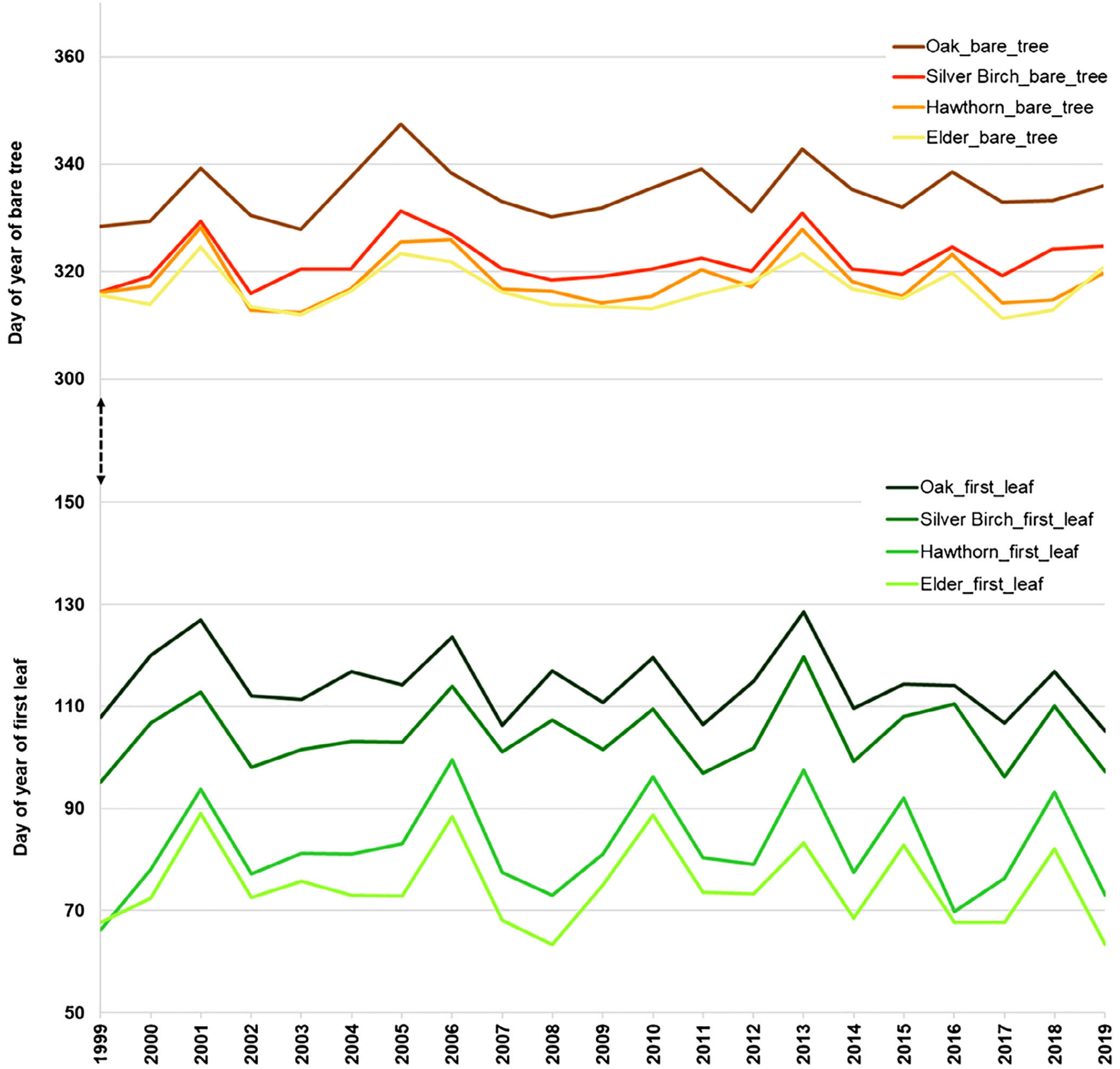


FIGURE 70 Mean day of year of first leaf and bare tree phenology indicators for four common shrub or tree species: Elder, Hawthorn, Silver Birch and Oak, derived from UK observations contributed to Nature's Calendar from 1999 to 2019

TABLE 10 Mean date of first leaf and bare tree phenology indicators for four common shrub or tree species: Elder, Hawthorn, Silver Birch and Oak, derived from UK observations contributed to Nature's Calendar from 1999 to 2019

	Elder	Hawthorn	Silver Birch	Oak
Mean first leaf date 1999–2018	Mar 16th	Mar 23rd	Apr 14th	Apr 24th
2019 mean first leaf date Relative to 1999–2018	−11.9	−9.7	−7.6	−9.7
Mean first leaf response to a 1°C increase in <month below>	−6.0	−6.2	−5.7	−5.7
Month(s)	Jan/Feb	Feb/Mar	Mar/Apr	Mar/Apr
Mean bare tree date 1999–2018	Nov 10th	Nov 12th	Nov 15th	Nov 28th
2019 mean bare tree date relative to 1999–2018	+4.3	+1.3	+2.7	+1.3
Mean bare tree response to a 1°C increase in <month below>	+1.8	+2.6	+2.2	+2.8
Month(s)	Oct	Oct	Oct	Oct

Note: Columns show the mean dates for the 1999–2018 period, the anomaly in days for 2019 relative to 1999–2018, the temperature response (days change per °C: –ve earlier, +ve later) and months of maximum temperature sensitivity.

number of historical national temperature records, particularly in winter, due to the interaction of the airflow and the local topography (a notable example being historical observations at Aber in North Wales, affected by the airflow across Snowdonia).

9 | PHENOLOGY

Changes in phenology (recurring events in nature and their relationships with climate) provide a wide range of information about the health and functioning of plants and ecosystems, and their responses to climate. Here, we present average UK changes in two phenological indicators—first leaf and bare tree dates. These provide an indication of changes in the timing of nature's response to spring and autumn, and therefore also the length of growing season.

The year 2019 was a year of notably early first leaf dates and slightly later bare tree dates across the UK, relative to the 1999–2018 baseline period, for four common shrub/tree species: Elder, Hawthorn, Silver Birch and Pedunculate Oak (Figure 70, Table 10). Elder and Hawthorn are typically the earliest to unfold their leaves (in mid-late March), followed, about 1 month later, by Silver Birch and Oak. In comparison, bare tree dates for these species are more condensed, typically occurring between mid and late November. In 2019, Elder showed the greatest shift in both first leaf (11.9 days earlier) and bare tree (4.3 days later), resulting in a 16.3-day extension of the leaf-on season, relative to the baseline. Hawthorn and Oak also showed a longer leaf-on season (11.0 days), with the same differences in first leaf date (9.7 days earlier) and bare tree date (1.3 days later), compared to the baseline. Silver Birch showed a slightly smaller lengthening of the season (10.3 days), with 7.6 days earlier first leaf date and 2.7 days later bare tree date.

High spring temperatures were the main driver of the particularly early first leaf dates in 2019. First leaf responses to temperature for the four species were around 6 days earlier for every 1°C increase in mean temperature for 2 months prior to the month of first leaf.

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APPENDIX: State of the UK Climate 2019—Appendices

Annex 1: Datasets

NAO index

Figures A1.1–A1.5

Tables A1.1–A1.6

The Winter North Atlantic Oscillation (WNAO) index is traditionally defined as the normalized pressure difference between Iceland and the Azores. 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 south-west Iceland and Gibraltar (Jones *et al*., 1997). These two sites are located close to the centres of action that comprise the WNAO. Data from these stations have been used to create homogeneous pressure series at the two locations which extend back to 1821. The WNAO index in this report is based on these data and presented back to 1850, with winter defined as December to February, to provide consistency with winter statistics presented elsewhere in this report.

For the UK, a positive WNAO index tends to be associated with higher temperatures and higher rainfall (R^2 values of .55 for winter mean temperature and 0.30 for winter rainfall based on years 1885–2019 and 1863–2019, respectively, see Annex 2). This means that just over half of the annual variability for UK winter mean temperature and almost a third for rainfall may be associated with the WNAO. Importantly, however, it also implies that the WNAO is unable to fully explain the variability of UK winters because the complexity of weather types and associated temperature and rainfall patterns through the season cannot be fully accounted for by this single index. 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 and 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 60N, 5E and 80N, 50W—corresponding to locations to the east of the Shetland Islands and in north-west Greenland, respectively These locations reflect the smaller spatial scale and a more northerly location of the summer Atlantic storm track (Folland *et al*., 2009). Unfortunately, due to the location of these points a station-based SNAO series cannot be used. Instead, the SNAO index has been calculated from the Met Office Hadley Centre's sea-level pressure dataset, HadSLP2 (Allan and Ansell, 2006) and extended to the present day using the NCEP reanalysis (Kalnay *et al*., 1996). The index is calculated as the difference in seasonal mean sea-level pressure between these grid-point pairs for each year from 1850 to 2019 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 .30 for summer mean temperature and 0.45 for summer rainfall based on years 1884–2019 and 1862–2019, respectively).

HadSLP2 is a global dataset of monthly mean sea-level pressure on a 5° latitude-longitude grid from 1850

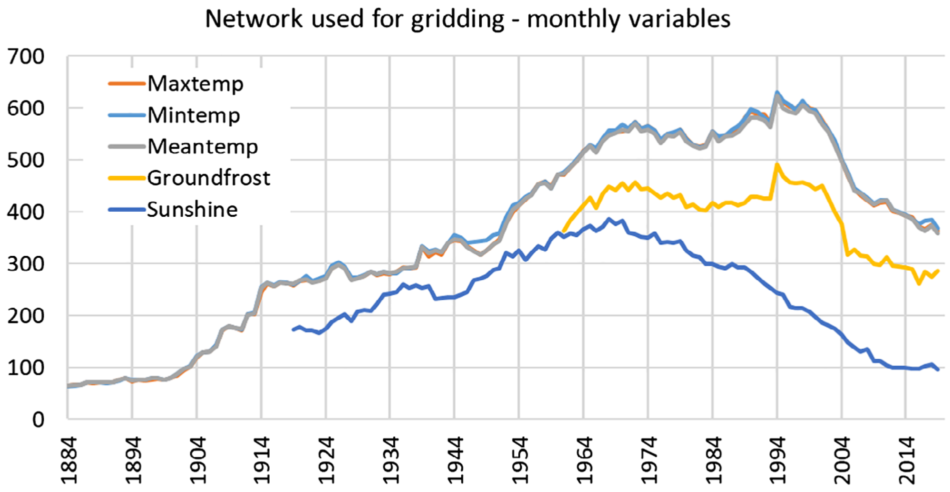

FIGURE A1.1 Number of stations used for gridding—monthly maxtemp, mintemp, meantemp (1884–2019), days of ground frost (1961–2019) and monthly sunshine (1919–2019)

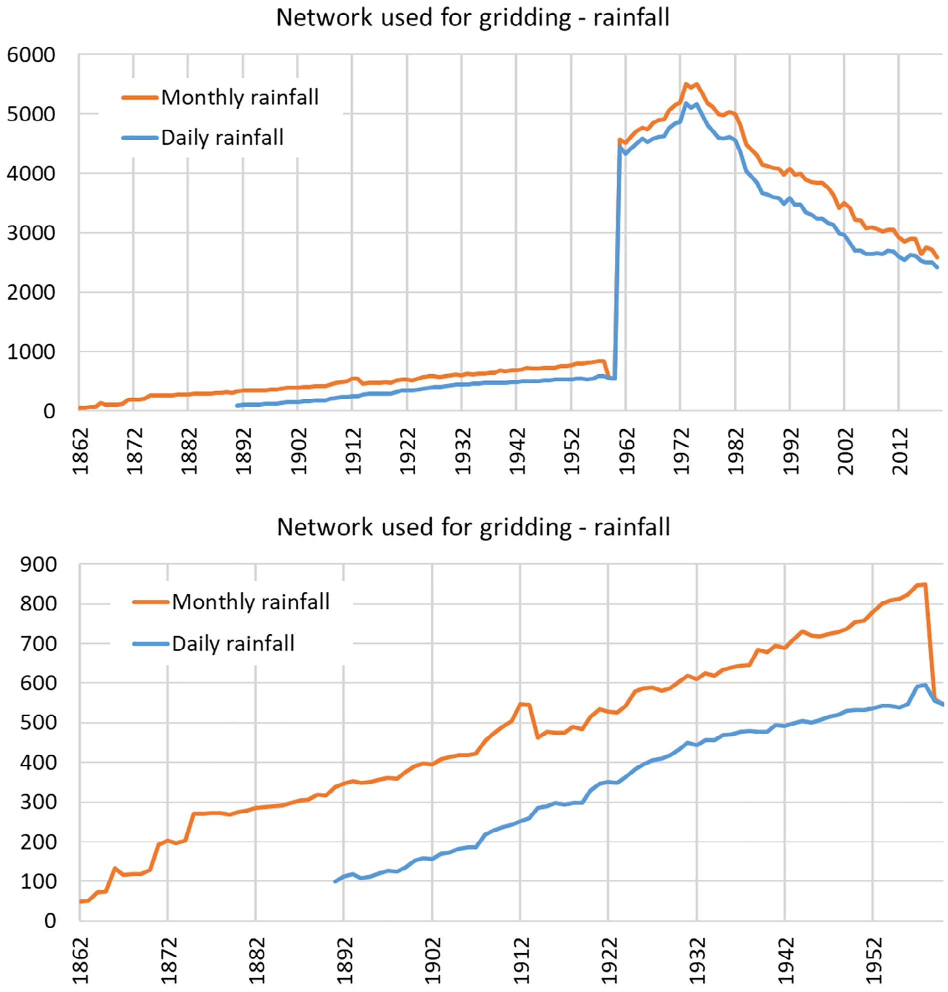

FIGURE A1.2 Number of stations used for monthly/daily rainfall (a) 1862/1891–2019 and (b) 1862/1891–1960, with the step change from <1,000 stations to >4,000 stations occurring in 1961

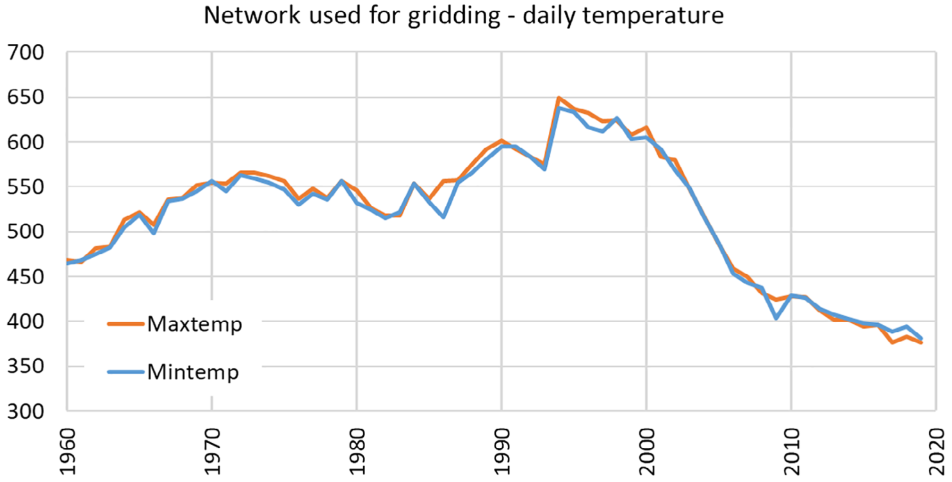

FIGURE A1.3 Number of stations used for daily temperature 1960–2019. The number of stations is very similar to monthly maxtemp and monthly mintemp as shown in Figure A1.1

to date. The dataset is derived from a combination of marine observations from ICOADS (International Comprehensive Ocean–Atmosphere Data Set) and land (terrestrial and island) observations from over 2000 stations around the globe. The dataset has a step change in variance in the mid-2000s, with an increased variance after this relating to when real-time updates from the NCEP reanalysis fields started.

Monthly, daily and annual grids

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. This report uses version 1.0.2.0 of the dataset.

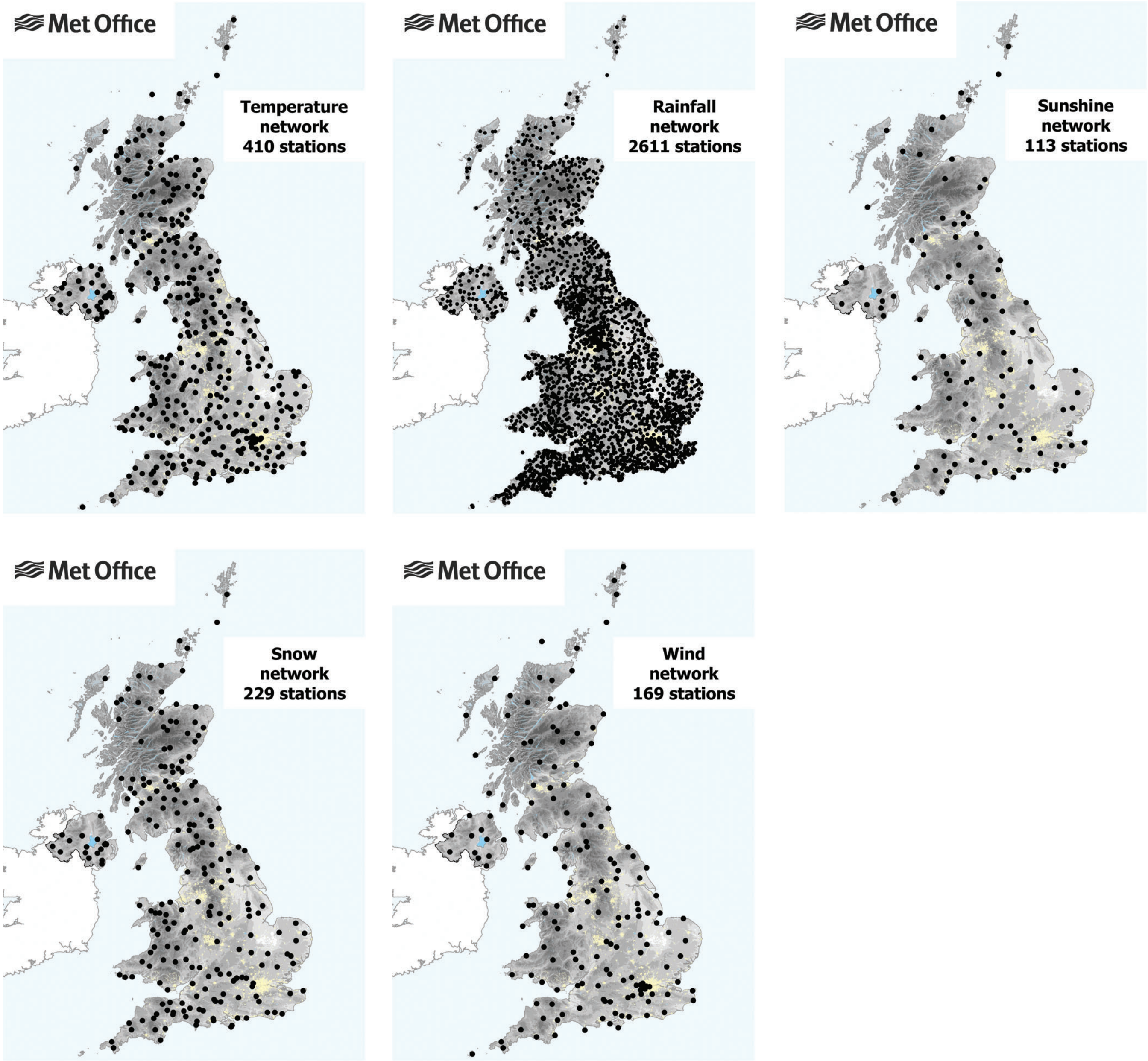

FIGURE A1.4 State of the UK observing network in 2019. The number of observations is indicative as these may vary on a daily basis due to data availability

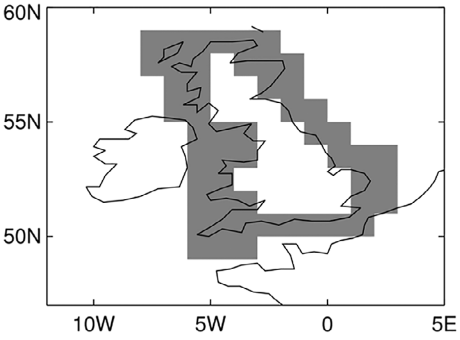

FIGURE A1.5 1° grid cells from HadISST1 used to calculate UK near-coast SST

The previous version 1.0.1.0 was used in the State of the UK Climate 2018 report (Kendon *et al.*, 2019) and released in November 2018 as part of the Met Office UK Climate Projections (UKCP).

All gridded data are at 1 km resolution. The method used for gridding follows that used for the earlier ‘legacy’ set of UK gridded datasets released as part of the Met Offfice UK Climate Projections (UKCP09) in 2009 (Perry and Hollis, 2005b; Perry *et al.*, 2009) which were at 5 km resolution, now superseded. The grids are based on the GB national grid, extended to cover Northern Ireland and the Isle of Man, but excluding the Channel Islands.

Table A1.1 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. The 1 km resolution results in an increased level of detail allowing the grids to better represent smaller-scale local features of the UK's climate—although inevitably this will always be constrained by the limitations of the underlying station network data and so micro-climate effects may not necessarily be improved. The higher resolution can also be used to better explore uncertainties in the gridding methods, and facilitates re-gridding to new high-resolution climate model resolutions.

The principal source of data is the Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Database containing UK station data, but this has been supplemented by further recently digitized historic data from multiple sources including British Rainfall and Met Office Monthly and Daily Weather Reports; in total several million additional daily and monthly observations of temperature, rainfall and sunshine from up to 190 stations. These additional historical data have allowed monthly temperature to extend back to 1884, monthly rainfall back to 1862, monthly sunshine back to 1919, and daily rainfall back to 1891. The extension of these gridded datasets back to the late 19th century provides an invaluable longer-term context for the interpretation of the time-series and variability of the UK's climate.

The HadUK-Grid data extraction and gridding process has been carried out in a single batch process. Generating the entire dataset in this way using a single process through a managed code base in a consistent manner eliminates the possibility of inhomogeneities being inadvertently introduced by changes in the processing chain over a period of several decades, potentially introducing non-climatic changes to the resulting dataset.

The daily maxtemp, mintemp and rainfall grids of the UK have also been generated using a similar method to that for the 5 km legacy grids (Perry *et al*., 2009). Daily temperature has been gridded back to 1960, with daily rainfall back to 1891 as described above. With daily data there is often a weaker link between the data and the geographical factors which shape the average over a longer time-scale. Metrics in this report based on the daily rainfall grids are only presented from 1961, even though these grids extend back to 1891. This is because of the step-change in station network density in 1961. The smaller number of stations before this date 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 mintemp and daily rainfall, respectively) rather than gridded from monthly station values directly. This approach has the advantage of ensuring that these monthly variables are consistent with the daily grids on which they are based (which would not be the case if they were gridded from station data). Because the gridding is at a daily timescale, we also anticipate that there will be a better overall representation of spatial variation in these monthly derived variables, although this is subject to ongoing research. Annual degree-day and rainfall intensity grids have also been derived from daily temperature and daily rainfall grids, respectively.

The network used for gridding for each variable changes each month. A key aim of the gridding process is to remove the impact of these changes in the distribution of stations on the climate monitoring statistics. This could be overcome by only using stations with a complete record, but the sparseness of such stations would introduce much greater uncertainty due to the spatial interpolation required. Instead, all stations believed to have a good record in any month are used, and every effort made to compensate for missing stations during the gridding process reducing uncertainty by maximizing the number of observations used.

Figures A1.1–A1.3 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. The number of stations recording monthly days of ground frost (i.e., with a grass minimum thermometer) is typically around 100 fewer than air temperature from the 1960s onwards. The number of monthly sunshine stations rises from around 150 to almost 400 from the 1920s to 1970, followed by a steady decline to around 100 stations in the 2010s (Figure A1.1). The number of stations for rainfall shows a fairly steady increase from fewer than 100 in the 1860s to over 800 in the late 1950s (Figure A1.2a), followed by a step-change to over 4,000 stations from 1961 and a peak of over 5,500 stations in the mid-1970s, with a subsequent steady decline to fewer than 3,000 in the 2010s (Figure A1.2b).

As would be expected the number of stations for daily temperature over the period 1960–2019 matches that for monthly temperature (Figure A1.3). However, the number of daily rainfall stations is significantly fewer than for monthly rainfall. This may be partly accounted for where some rainfall data has only been digitized at monthly timescales (e.g., from the British Rainfall publications), and in addition due to the presence of some monthly rain-gauges in the network, principally across upland areas of the UK (Figure A1.2).

Overall, Figures A1.1–A1.3 also emphasize the scope for further data recovery / digitization work, since the increase in station numbers in 1961 reflects an increase in digitized data since this date, but not an increase in the underlying observation network; many records held in paper archives are yet to be recovered. Major Citizen Science data recovery projects underway such as the University of Reading Rainfall Rescue Project have the potential to contribute large improvements in station network coverage in earlier years in the series. Data from an initial set of 95 stations have been used in HadUK-Grid version 1.0.2.0 to improve coverage in the period 1862–1909. However, this is ongoing work and further data from this project will feed into future versions of this report.

The approximate total number of station values used to generate the grids for each variable is given in Table A1.2. In total well over 100 million station values have been used to generate the HadUKGrid 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 (daily maximum temperature). So in practice the number of *station values* used to generate the grids will differ from the number of *station observations* extracted from the MIDAS database or the other recently digitized data sources.

FIGURE A1.4 shows the state of the UK's observing network in 2019. The networks are designed and maintained to achieve a good spatial coverage with stations representative of all areas of the UK. Due to the high spatial variation in rainfall, the network is much denser than for other variables, but even so highly localized events may still be missed. While the majority of the UK is reasonably well covered, some areas, notably western Scotland, are more data-sparse than others, but these also tend to correspond to areas with a smaller population. Coverage for some variables (notably sunshine) may considerably reduce if data for an individual station is missing, and where surrounding stations struggle to cover the gap—there is limited redundancy in the network. Overall however, even though the number of stations in the 2010s 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.

Long-term average grids

Areal averages for the WMO standard 30-year climatological reference periods 1961–1990 and 1981–2010 presented in this report have been calculated from long-term average monthly gridded datasets at 1 km resolution covering the UK. These gridded datasets were produced for HadUK-Grid following the same general method as the previous long-term average gridded datasets used previously (Perry and Hollis, 2005a) but modified as described in more detail by Hollis *et al.* (2019). The process for producing these grids is outlined as follows: For the majority of variables, long-term averages for each station are calculated from monthly station data. Gaps in individual months at stations are filled with estimates obtained via regression relationships with a number of well-correlated neighbours, and long-term averages are then calculated for each site. Gridded datasets of long-term averages are created by regression against latitude, longitude, elevation, terrain shape, proximity to coast and urban extent, followed by inverse-distance weighted interpolation of residuals from the regressions. The estimation of missing values allows a dense network of stations to be used, and this along with the range of independent variables used in the regression, allows detailed and accurate long-term average datasets to be produced. These are then used to constrain the gridded analyses for individual years, seasons, months and days via the geographical interpolation of deviations from, or ratios of, the long-term average.

However, this method does not work well for a number of variables, including days of air frost and ground frost, and an alternative approach is used. Here, the gridded long-term average datasets are obtained by averaging the monthly grids (Hollis *et al*., 2019).

Because the long-term average grids are obtained by gridding long-term average station data directly (‘average then grid’) rather than calculated from the monthly grids (‘grid then average’) the long-term averages are not exactly consistent with the monthly analyses. This is both because the order of the calculation differs, and because the station network will be very much denser for the long-term average grids than the monthly grids due to the infilling process used when calculating station long-term averages. Table A1.3 shows the approximate number of stations used to generate the HadUK-Grid long-term average grids for the period 1981–2010, compared to the average number of stations per monthly grid over the same period. For monthly maxtemp, rainfall and sunshine there are typically two to three times more stations used for the long-term average grids than for the monthly grids for these variables.

Table A1.4 compares 1981–2010 long-term average annual mean temperature and rainfall as derived from

TABLE A1.1 List of monthly and daily variables presented in this report, gridded over the UK at 1 km resolution. The table also includes monthly and annual grids derived from daily grids

Climate variable	Definition	First year available	Gridding time-scale
Max air temperature	Monthly average of daily max air temperatures °C	1884	Monthly
Min air temperature	Monthly average of daily min air temperatures °C	1884	Monthly
Mean air temperature	Monthly average of mean daily max and mean daily min air temperatures °C	1884	Monthly
Days of air frost	Count of days when the min air temperature is below 0°C	1960	Monthly[a]
Days of ground frost	Count of days when the grass min air temperature is below 0°C	1961	Monthly
Heating degree days	Day-by-day sum of number of degrees by which the mean temperature is less than 15.5°C	1960	Annual[b]
Cooling degree days	Day-by-day sum of number of degrees by which the mean temperature is more than 22°C	1960	Annual[b]
Growing degree days	Day-by-day sum of number of degrees by which the mean temperature is more than 5.5°C	1960	Annual[b]
Precipitation	Total monthly precipitation amount (mm)	1862	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	1919	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

[a] Monthly grids derived from daily grids.

[b] Annual grids derived from daily grids.

TABLE A1.2 Approximate total number of observations used for each variable

Climate variable	Number of years	Number of grids	Average number of stations values per grid	Total number of station values
Monthly maxtemp	136	1,632	360	590,000
Monthly rainfall	158	1896	1790	3,400,000
Monthly groundfrost	59	708	400	280,000
Monthly sunshine	101	1,212	250	303,000
Daily maxtemp	60	21,915	520	11,000,000
Daily rainfall	129	47,117	1880	89,000,000

1 km long-term average grids, and from the 360 individual monthly 1 km grids. For temperature, the difference of 0.02°C for the UK overall is much smaller than the difference of 0.6°C between 1961–1990 and 1981–2010 1 km long-term averages. For rainfall, the difference of 0.5% is also much smaller than the difference of 5% between the 1961–1990 and 1981–2010 1 km long-term averages. These ‘order of operation’ differences are generally small because the long-term average and individual monthly grids are at the same resolution (both 1 km), so, although the values are not exactly equal, the dataset is reasonably self-consistent.

Annual degree days

Degree-day datasets were generated from the daily temperature grids, as indicated in Table A1.1, using formulae given in Tables A1.5 and A1.6. 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 HDD) the defined threshold.

Consistency and quality control

Quality control of station observations held in the Met Office Integrated Data Archive System (MIDAS) database is the responsibility of the Met Office Observations Quality Management (OBQM) team. This team runs a suite of both automated and manual quality control checks on MIDAS, which is the source of the majority of the station data used in HadUK-Grid. The other digitized data sources have also had quality checks at time of digitization where possible. For example, tables of monthly rainfall published in British Rainfall also include annual totals, so the latter can be used as a closure check on the monthly totals. The previous 5 km UK gridded datasets have been manually quality controlled since 2001, and the HadUK-Grid processing chain includes a step to ensure these QC decisions were transferred by comparing the HadUK-Grid 1 km resolution grids and the associated 5 km resolution grids. For most variables an additional automated QC test has also been applied. 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, remains an active area of research and development and will feed

TABLE A1.3 Number of stations used to generate long-term average grids

Climate variable	Number of station values per monthly long-term average grid (1981–2010)	Average number of station values per monthly grid over period 1981–2010
Air temp	1,200	550
Rainfall	9,660	3,850
Sunshine	617	230

TABLE A1.5 Formulae used for calculating cooling or growing degree days above thresholds of 22 and 5.5°C

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

TABLE A1.6 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
$T_{\mathrm{max}} \leq T_{\mathrm{threshold}}$	$T_{\mathrm{threshold}} - T_{\mathrm{mean}}$
$T_{\mathrm{mean}} \leq T_{\mathrm{threshold}}$ & $T_{\mathrm{max}} > T_{\mathrm{threshold}}$	$0.5\,(T_{\mathrm{threshold}} - T_{\mathrm{min}}) - 0.25\,(T_{\mathrm{max}} - T_{\mathrm{threshold}})$
$T_{\mathrm{mean}} > T_{\mathrm{threshold}}$ & $T_{\mathrm{min}} < T_{\mathrm{threshold}}$	$0.25\,(T_{\mathrm{threshold}} - T_{\mathrm{min}})$

TABLE A1.4 Comparison of 1981–2010 long-term average annual mean temperature and rainfall as derived from 1 km long-term average grids and individual monthly grids. Differences are calculated from unrounded values

Area	Temperature—long- term average (degC)	Temperature—long-term average derived from monthly grids	Difference (degC)	Rainfall—long-term average (mm)	Rainfall—long-term average derived from monthly grids	Difference (%)
UK	8.85	8.86	−0.02	1,150	1,144	0.5
England	9.66	9.65	0.01	853	850	0.3
Wales	9.13	9.15	−0.02	1,459	1,443	1.1
Scotland	7.41	7.47	−0.06	1,562	1,552	0.6
Northern Ireland	8.92	8.92	0.00	1,133	1,130	0.3

into future versions. Further details are beyond the scope of this report.

The HadUK-Grid dataset uses open-source ancillary files for terrain elevation, proximity to coast and urban land use that are used within the interpolation scheme, which provides traceability. The dataset is also version controlled—including a version-controlled numbering system, so State of the UK Climate publications can all be linked to a specific version of the dataset. This report uses version 1.0.2.0 of the HadUK-Grid dataset. Details of the HadUK-Grid dataset are provided in Hollis *et al.* (2019).

Areal series

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

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

Central England temperature

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

Following each station change the data are adjusted to ensure consistency with the historical series by analysing periods of overlap between stations, and since 1960 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.

SST data

The Met Office Hadley Centre's sea ice and SST data set, HadISST1 is a global dataset of monthly SST and sea ice concentration on a 1° latitude-longitude grid from 1870 to date (Rayner *et al.*, 2003). The dataset is derived from a combination of fixed and drifting buoys, ship bucket and engine room intake thermometers and hull sensors; and satellite data. The UK near-coast SST series in this report comprises the average of all 1° latitude-longitude grid cells adjacent to the coast of Great Britain (approximately 50 grid cells). These grid cells were selected to ensure that all the main UK landmass fell within this area (Figure A1.5).

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 (Wigley *et al.*, 1984; Alexander and Jones, 2001; Simpson and Jones, 2012).

Rain gauge and snow depth data

Daily rainfall data presented in this report are 0900–0900 UTC totals from either daily or tipping-bucket rain-gauges registered with the Met Office. The rain-gauge network has diminished from over 4,000 rain-gauges across the UK in the 1960s to between 2,500 and 3,000 in the 2010s. The gauges are owned and maintained by several organizations: 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 all but the most localized convective events are captured at a daily time-scale.

Snow depth data are recorded at 0900 UTC. These are either spot observations from automatic snow depth sensors or manual observations of representative level depth in a location free from drifting or scour by wind; ideally the average of three measurements would be recorded. The network comprised over 400 stations from 1960 to 2000 but has subsequently reduced to around 200 stations in 2019.

Sunshine data

The UK's sunshine network in 2019 comprises two instrument types: approximately 40% Campbell-Stokes (CS) sunshine recorders which are read manually; the remainder Kipp & Zonen CSD-1 (KZ) automatic sunshine recorders. An upward adjustment of KZ totals is made to give a monthly ‘CS equivalent sunshine’. This ensures that the full sunshine network (automatic and manual) is used while maintaining consistency between the two instrument types. Legg (2014a) and references therein provide further details.

Sea level data

Sea-level changes around the British Isles are monitored by the UK national network of tide gauges; for 2019 this network comprises 44 stations. For more than 100 years tide gauges have provided measurements of sea-level change relative to the Earth's crust. However, tide gauges are attached to the land, which can move vertically thus creating an apparent sea level change. A UK sea level index for the period since 1901 computed from sea level data from five of these stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool) provides the current best estimate for UK sea level rise, excluding the effect of this vertical land movement. The records from each station are combined after removing the long-term trend from each to account for varying vertical land movement rates across the country. After aggregating the records, the calculated country-wide average rate of 1.4 mm/yr is reintroduced (Woodworth *et al.*, 2009; Bradley *et al.*, 2011).

As mentioned in Woodworth *et al.* (2009), the network of 44 stations falls under the responsibility of the Environment Agency (it is no longer operated by the Proudman Oceanographic Laboratory). Only five sites date back to the beginning of the 20th century: the others did not begin until the 1950s. In creating the long-term index, we follow Woodworth's approach, which only uses data from the long-term series. Woodworth *et al.* (2009), which is based on data from up to 2006, notes that throughout the course of the record, at least three of the five stations are present for all years apart from three, the last of which was 1915. Unfortunately, from 2007 onward, there have been more gaps in observations for the five stations. A UK national report in 2019 for the Global Sea Level Observing System (GLOSS) provides more information about issues with the network, available at https://www.jcomm.info/index.php?option=com_oe&task=viewDocumentRecord&docID=24144

Newlyn, Cornwall has a century of hourly (or, since 1993, 15-min) sea-level data from float and pressure tide gauges that have been maintained better than most around the UK. It also has a more open ocean location than stations around North or Irish Sea coasts (Araujo and Pugh, 2008).

Phenology data

Nature's Calendar, run by the Woodland Trust, has been collating information on the timing of the seasons for over 20 years. Furthermore, it has built up a considerable database of older data, derived from a number of sources. Current data, recorded by citizen scientists across the UK, identify dates on which particular phenological events are observed. Here we show UK mean dates for the first unfolded leaf (‘first leaf’) in spring and first bare tree (‘bare tree’) in autumn for four common shrub or tree species: Elder (*Sambucus nigra*); Hawthorn (*Crataegus monogyna*); Pedunculate Oak (*Quercus robur*); and Silver Birch (*Betula pendula*).

First leaf and bare tree dates for the baseline period, 1999–2018, derived from annual means, are compared with those for 2019. To assess the relationships with temperature, we have compared the 1999–2019 annual mean dates for first leafing to monthly CET for the month incorporating the mean date and the preceding 2 months. We report the response to a 1°C increase in the months that were significantly associated with first leafing date. We also compare 1999–2019 annual means of bare dates to October mean CET, since experience has shown that the influential window for autumn events is much shorter. CET provides a reasonable representation of the inter-annual temperature variations across the UK, for comparison with the UK-wide phenology indicators.

Annex 2: Time-series, trends and uncertainty

Time-series and trends shown in this report

The time-series in this report are plotted on either actual or anomaly scales. The plots with anomaly scales often show several different areas, seasons or variables which are offset for clarity and ease of comparison; the offsets do not reflect absolute differences between the time-series.

The time-series shown throughout are plotted showing the annual series and a smooth trend. This means that both annual variability and longer-term trends (removing this short-term variability) can be viewed simultaneously. Importantly, we note that 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. Most time-series plots also include the 1981–2010 and 1961–1990 long-term averages.

The smooth trend-lines are constructed using a weighted kernel filter of triangular shape, with 14 terms either side of each target point. The kernel defines how much weighting the terms either side of a point in the series have in estimating the smoothed average at that point; in this case the triangular shape using 14 data points either side means that data points further away have less influence. The effect is to smooth out the year-to-year variations and estimate any longer-term variations in the data. The kernel is reflected at the ends of the time series so the trend lines cover the full length of the series. Similar smoothing filters were used for earlier State of UK Climate reports (e.g., Kendon *et al*., 2019).

Climate records at individual stations may be influenced by a variety of non-climatic factors such as changes in station exposure, instrumentation and observing practices. Issues of changing instrumentation and observing practices will tend to be of greater importance early in the series, particularly before the 20th Century. In contrast, station exposure issues related to urbanization, which may for example, affect temperature-related variables, may be of greater importance in the late part of the series from the mid-20th Century. Identifying and correcting for such factors in climate monitoring is referred to as homogenisation. Some homogenisation has been undertaken for some series presented in this report, such as the CET record, and the adjustment of sunshine records described in Annex 1. For most variables however the individual station data in this report have not been explicitly homogenized to account for these non-climatic factors.

We note that the 1961–1990 and 1981–2010 averages presented are not exactly consistent with the average of the yearly data through the same period (see previous discussion on long-term averages), although in practice any differences are small. Annex 1 Table A1.4 provides further details. We use averages derived from 1961–1990 and 1981–2010 gridded data because they contain the most comprehensive set of stations, and thus represent our best estimate of these climatologies.

Uncertainty estimates

Table A2.1

Earlier studies have considered uncertainties in the gridded data and areal-averages based on the 5 km 'legacy' gridded dataset previously used for UK climate monitoring (Legg, 2011; Legg, 2014b). The HadUKGrid 1 km gridded dataset, while at a different resolution, uses the same method of interpolation, and a key source of uncertainty in both datasets is associated with spatial sampling—that is, the density of the observation network, which is the same in both cases. We therefore anticipate the uncertainty estimates for HadUK-Grid associated with spatial sampling to be similar to the 5 km gridded dataset. The uncertainty estimates in these 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). Legg (2014b) published uncertainty ranges for areal-averages of monthly mean temperature, rainfall and sunshine; these increase in the past as the network density reduces.

Table A2.1 lists 1σ uncertainty (standard error) ranges for annual mean temperature, rainfall and sunshine for different periods in the 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 is 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; and a relatively recent period in the the dataset indicating current uncertainty. More comprehensive tables covering the full date range can be found in Legg (2014b). We have applied a conservative reduction factor of √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).

TABLE A2.1 1σ uncertainty (standard error) ranges for annual T_{mean}, rainfall and sunshine

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

Uncertainties in the CET and EWP series have also been investigated elsewhere (Parker and Horton, 2005; Parker, 2010; Simpson and Jones, 2012).

Uncertainties in areal rainfall statistics may potentially be large for small (county-sized) areas early in the series due to the relatively small number of stations pre-1900. Rainfall will be affected to a much greater extent than temperature due to the much greater spatial variation, whereas temperature tends to be a much smoother varying field. This means that ranking of years (e.g., the wettest autumn in the series for county X) may change if more observations were added to the dataset in the future. Further work is required on the HadUK-Grid dataset to assess the uncertainties in areal-average statistics relative to station network density and area size.

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 and 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. However, this now tends to be usually less of a problem than during colder, snowier years of earlier decades.

Coefficient of determination

The coefficient of determination, R^2, is the square of the correlation coefficient, r, between an independent and a dependent variable based on linear least-squares regression. The R^2 value is a statistical measure of how closely the dependent variable can be predicted from the independent variable. An R^2 value of 1 would indicate a perfect correlation, in which the dependent variable can be predicted without error from the independent variable. An R^2 value of 0 would mean the dependent variable cannot be predicted from the independent variable. An R^2 value of .5 would mean that 50% of the variance in the dependent variable can be explained by variations in the independent variable. R^2 values exceeding 0.9 for time-series in this report would indicate that they are very highly correlated.

Rounding

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 1981–2010), this difference is calculated from the original unrounded values.

Annex 3: Useful resources

Met Office

Annual State of the UK Climate publications from 2014 http://www.metoffice.gov.uk/climate/uk/about/state-of-climate

UK climate information http://www.metoffice.gov.uk/climate

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 http://www.metoffice.gov.uk/hadobs/hadcet/

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

The HadISST1 dataset is maintained by the Met Office Hadley Centre and can be downloaded at http://www.metoffice.gov.uk/hadobs/hadisst/

The HadSLP2 dataset is maintained by the Met Office Hadley Centre and can be downloaded at https://www.metoffice.gov.uk/hadobs/hadslp2/

Met Office DataPoint (for application developers) https://www.metoffice.gov.uk/datapoint

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

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

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 http://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0

Bulletin of the American Meteorological Society (BAMS) State of the Climate Report https://www.ncdc.noaa.gov/bams

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

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

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

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

Marine Climate Change Impact report cards http://www.mccip.org.uk/impacts-report-cards/full-report-cards/

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

Natural Resources Wales Water Situation Reports for Wales https://naturalresources.wales/about-us/what-we-do/water/resources/water-situation-report-2019/?lang=en

Public Health England heatwave mortality monitoring reports https://www.gov.uk/government/publications/phe-heatwave-mortality-monitoring

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

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

University of Reading Rainfall Rescue Project https://www.zooniverse.org/projects/edh/rainfall-rescue