Two hundred years of thunderstorms in Oxford

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Two hundred years of thunderstorms in Oxford

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The long instrumental meteorological records from the Radcliffe Observatory site in Oxford (where records commenced in 1772) are well known, and have recently been documented to 2018 by Burt and Burt (2019). Less well-known, and still largely in manuscript or paper format, are the non-instrumental records also maintained by the Observatory which documented the occurrence of fog, snowfall, thunderstorms and the like. Records of thunderstorm occurrence at the Radcliffe Observatory, by date, are complete between 1828 and 1986, excluding the years 1936 to 1970 for which only monthly totals are available. Since 1986, a reliable private record of thunder frequency from Oxford, very close to the Radcliffe Observatory site, has been used to extend the record to 2019, forming a record of almost 200 years of thunderstorm frequency for the city – a record probably unique anywhere in the world. This newly digitised record, made available for the first time, is examined for long-term (decadal) trends in thunderstorm frequency, and by Lamb Weather Type. Comparisons are made with other long-period records from west London, around 75km southeast of Oxford. Reasons to account for the marked reduction in thunderstorm frequency in the last decade are suggested.

The observational record – details and sources

Sources

Full details of the Radcliffe Observatory site and instrumental records are given in Burt and Burt (2019). An almost unbroken daily temperature record has been maintained since November 1813, although the earliest surviving thunderstorm records are for 1828. The Radcliffe Observatory site is at 51.761°N, 1.264°W, at 63m above mean sea level; the location of the observatory site, known today as the Radcliffe Meteorological Station (RMS) and run by the School of Geography at the University of Oxford, is shown in Figure 1.

1828–1852

The format of the Radcliffe Observatory's meteorological register was expanded in January 1828 to permit more details of the day's weather to be included. For this project, dates with thunder were extracted manually by careful eye examination of the daily weather entries from high-resolution photographic copies of the monthly manuscript observation registers, the originals of which are held in the School of Geography at the University of Oxford. The period 1828–1840 was examined by myself, and 1841–1852 by Tim Burt; a random series of months within each period was checked by us both to minimise the risk of one of us missing an entry, although it is possible that some obscure or illegible entries may have been missed.

1853–1935

From 1840, the astronomical observations and tabulations from the Radcliffe Observatory were published in (initially) annual volumes entitled *Astronomical observations made at the Radcliffe Observatory in the year [x]*, volumes hereafter referred to as the *Radcliffe Results*. Some later years were amalgamated into multiyear volumes; from the 1900–1905 volume, the meteorological observations were published in their own binding until the 1931–1935 volume, the last in the series following the move of the (astronomical) observatory to South Africa and the transfer of responsibility for the meteorological records to the University. Meteorological summaries began to be included from the 1853 *Radcliffe Results* volume, and a more-or-less standard format quickly evolved, whereby from 1859 and in most years the dates of various phenomena including thunderstorms were

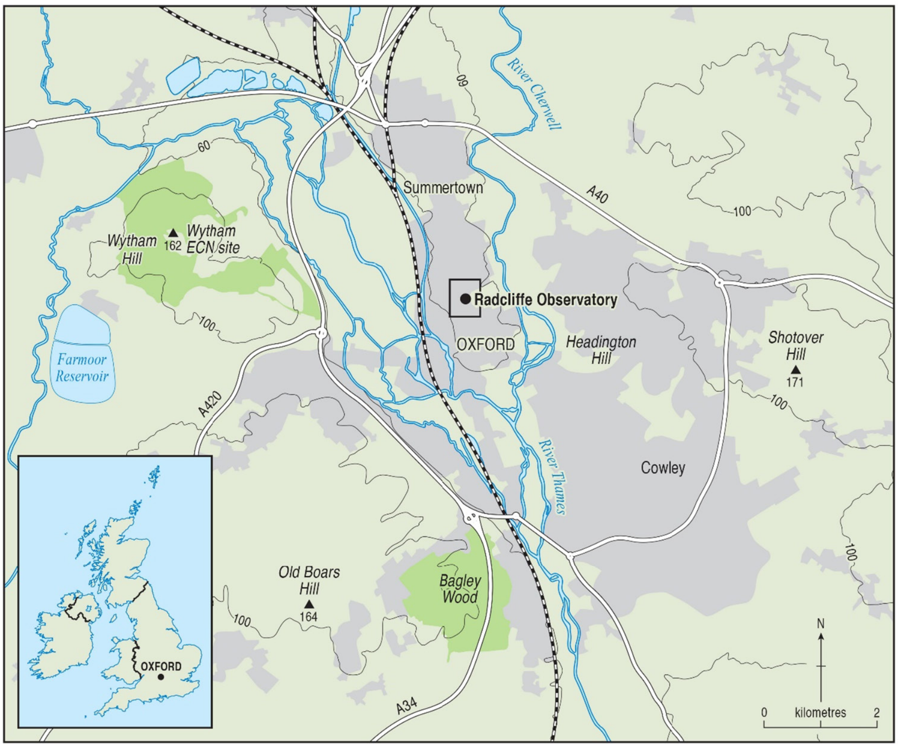

Figure 1. The Oxford area, showing the city, the River Thames and the 60 and 100m contours. The central square shows the Radcliffe Observatory quarter in North Oxford. (Map courtesy of Chris Orton, University of Durham.)

RMetS
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set out by month in a supplementary table entitled 'Summary [or 'Characteristics …'] of the weather and remarkable phenomena, for each month [year]'. An example, for the month of August 1878 (the most thundery month on the record), is included as Figure 2. In addition, the published monthly data tables often include notes of thunder, etc., although the annual 'Summary/Characteristics' table is generally the more complete. Some of the *Radcliffe Results* volumes have already been scanned and a number are available online; the relevant (meteorological) pages from the others were photographed from the partial set held within the School of Geography, the remaining volumes being consulted and photographed in the Bodleian Library to assemble the complete series as PDF files. (These are available on Figshare - https://www.doi.org/10.6084/m9.figshare.13333925.) These PDF files were converted to computer-readable text using Optical Character Recognition software, and dates of thunder events were then extracted by searching for the string 'thun' (the abbreviation allowing for hyphenation, abbreviations, etc.). Most entries also carried information on the timing and sometimes the severity of the storms, although these details were not extracted.

For much of the published record, thunderstorm records were separately categorised into 'thunderstorm' (thunder and lightning observed), 'thunder' (thunder heard, presumably without lightning seen) and 'lightning' (only). The first two were counted as a 'thunder day' record, only one per day if both were reported on the same date, while 'lightning only' events were not included in these analyses. The frequency of lightning at the Radcliffe Observatory was surprisingly high, sometimes twice or more the annual frequency of thunder heard; it should be remembered that this was an astronomical observatory with a staff of observers, working mainly at night, largely in the era before extensive urban street lighting.

Monthly and annual totals of 'days with thunder heard' for Oxford were published in the *Monthly Weather Report* (*MWR*) 1884–1993 (when the *MWR* ceased publication), and these together with other sites were analysed by Valdivieso *et al*. (2019). However, monthly values extracted from the *MWR* were normally lower than those taken from the *Radcliffe Results*. Examination of the discrepancies suggested that the 'thunder day' totals reported by the Observatory and subsequently published in the *MWR* were (often, but not always) 'thunderstorm days' alone, and days where thunder was heard but no lightning was observed were excluded, resulting in a lower total.

1936–1970

Monthly and annual totals of 'thunder days' for this period were extracted from manuscript tabulations held within the School of Geography. Unfortunately, dates of occurrence could not be traced within the School's archive for this period, although the original monthly manuscript climatological returns are believed to exist in the Met Office climatological archive[1].

[1]The author planned to visit the Met Office archives during spring 2020 to obtain daily thunder day dates for this period and thereby eliminate this gap, but was unable to do so once the facility closed to visitors in mid-March 2020 owing to the coronavirus lockdown. Completion of this paper was delayed for six months awaiting re-opening. Rather than delay publication indefinitely, this paper was resubmitted without the dates for 1936–1970 in late September 2020 as the archive remains closed for the foreseeable future. Monthly and annual totals are complete: the online dataset will be updated with the 1936–1970 dates once access to the Met Office archives is available once more.

AUGUST.

Temp. Highest in sunshine, ...$132°.2$
,, Lowest on grass,...................... $46°.5$
Rain fell on Aug. 2, 3, 4, 5, 6, 7, 10, 11, 13, 14, 15, 16, 22, 23, 25, 27, 28, 29, and 30.
Thunderstorms on the 3rd at 0^{h} to 1^{h}; 4th, 4^{h} 30^{m} to 6^{h}; 5th, 23^{h} 30^{m} to 0^{h}; 6th, 0^{h} to 0^{h} 30^{m}; 23rd, 6^{h} to 6^{h} 45^{m}; and 28th, 18^{h} 45^{m} to 19^{h} 15^{m}.
Thunder was heard on the 11th at 23^{h} 15^{m}; 12th, 0^{h} to 0^{h} 30^{m}; 23rd, 2^{h} 30^{m} to 4^{h} 30^{m}; 29th, 20^{h} 30^{m}; and 30th, 1^{h} 30^{m} to 1^{h} 45^{m}.
Lightning was seen on the 3rd at 11^{h}; 15th, 9^{h} to 10^{h} 30^{m}; and 23rd, 5^{h} 15^{m} to 5^{h} 30^{m}, and 7^{h} 30^{m} to 8^{h} 30^{m}.

Fog on the 25th at 16^{h} to 21^{h}.
Solar halos were seen on the 8th at 21^{h} 30^{m} to 22^{h}; 11th, 23^{h} to 23^{h} 50^{m}; and 16th, 20^{h}.
Lunar halos were seen on the 10th at 13^{h} 15^{m}; and 12th, 0^{h} 45^{m}.
Lunar irides were seen on the 10th at 13^{h} 15^{m}; 12th, 10^{h} 30^{m}; 14th, 9^{h} 30^{m}; and 15th, 10^{h} 20^{m}.
Dead calms on the 3rd at 10^{h} and 22^{h}; 6th, 10^{h}; 9th, 0^{h} to 0^{h} 45^{m}, and 2^{h}; 18th, 6^{h}; 20th, 21^{h} 15^{m}; 22nd, 20^{h}; 23rd, 2^{h} and 10^{h}; 24th, 0^{h} to 2^{h}, and 20^{h}; 25th, 20^{h} to 23^{h}; and 26th, 0^{h} 45^{m} to 2^{h}, and 10^{h}.
Storms of wind on the 27th, and 28th.

Figure 2. An example of the monthly 'Characteristics' data published in the Radcliffe Results volumes. This is for August 1878, the most thundery month on the long Oxford record, when 10 days with thunder were noted. Note the differences between 'thunderstorms' and 'thunder heard' and 'lightning' (only) – only the first two are counted as a 'day with thunder heard'.

1971–1986

Dates of 'thunder heard' were extracted from the Met Office Integrated Data Archive System (MIDAS) climate archives held within the Natural Environment Research Council's Data Repository for Atmospheric Science and Earth Observation (CEDA – http://archive.ceda.ac.uk/), and monthly and annual totals tabulated.

1987–2019

From late 1986, RMS authorities chose not to submit records of snow falling and thunder in their monthly observational returns to the Met Office, because it was felt that the vigilance required for a good record was becoming impossible to maintain. From January 1987 onwards, RMS records of thunder are mostly missing, and the Radcliffe Observatory records effectively cease at this point.

To complete the series to date, a high-quality personal record kept in central Oxford (mostly within 4km of the Radcliffe Observatory) since 1983 by Jonathan Webb, a director of the Tornado and Storm Research Organisation (TORRO), has been used. Accuracy and continuity of record was assessed by comparison with the record from the Met Office staffed airfield at Brize Norton, 21km to the west. Figure 3 shows the annual thunder day totals, and Table 1 the annual averages, from Brize Norton, from the commencement of records in 1968 through to 2019, compared with the record for the Radcliffe site for 1968–1986 and the Webb record for 'central Oxford' for 1987–2019. There is good temporal correlation between Oxford Radcliffe and Brize Norton annual thunder day totals 1968–1986 (correlation coefficient $R^2 = 0.54$) and Brize Norton and central Oxford 1987–2019 ($R^2 = 0.55$), although the more comprehensive Kolmogorov–Smirnov test (Massey, 1951) on the two distributions suggests a difference between the two distributions, probably owing to the 21km separation between the sites. However, the Webb record was chosen for 1987–2019 because it provided spatial continuity with the long Radcliffe record.

How consistent is the observational record?

A permanent or near-continuous weather watch together with a high level of observer vigilance is essential for accurate counts of thunder(storm) frequencies. Between 1828 and 1924, the Oxford record was from an astronomical observatory maintaining a 24h record, with three or four meteorological observations per day. From January 1925, the formal meteorological observation routine was reduced to once daily, at 0900 GMT, in preparation for the move of the (astronomical) observatory itself to South Africa, and

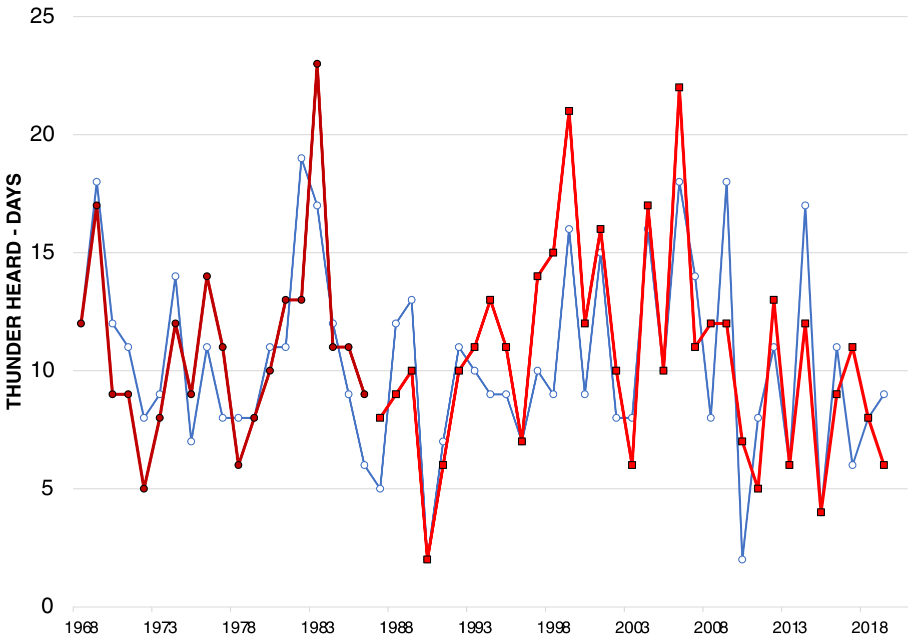

Figure 3. Annual thunder days at Brize Norton, Oxfordshire, 1968–2019 (blue line) compared with Oxford, Radcliffe Meteorological Station (dark red line, round points) 1968–1986 and Oxford City record 1987 to 2019 (red line, square points); see also Table 2.

Table 1

Oxford and Brize Norton thunder-day records and overlap periods.

Station and location	*Period of thunder record*	*All period average, days*	*Average 1968–1986, days*	*Average 1987–2019, days*
Oxford, Radcliffe Observatory 51.761°N, 1.264°W	1828–1986	12.0	11.1	–
Brize Norton 51.758°N, 1.576°W	1968–2019	10.3	11.1	9.9
Central Oxford 51.752°N, 1.258°W	1987–2019	10.5	–	10.5

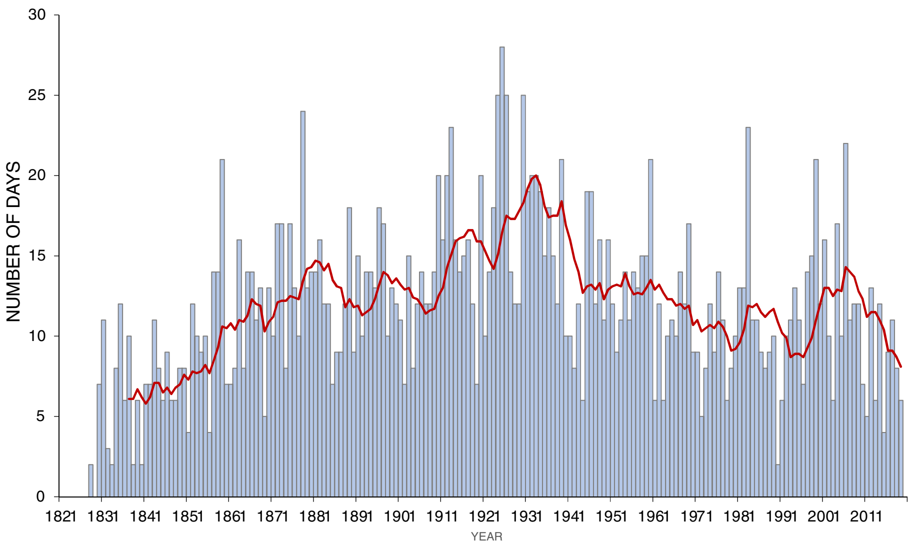

Figure 4. Annual totals of 'thunder heard', in days, in Oxford, 1828–2019, with 10-year running mean plotted at year ending: see text for sites and sources.

this routine has continued to the present day, notwithstanding the cessation of reporting of thunder and snowfall from 1987 onwards.

Records of thunder days are inconsistent in other ways. A day of thunder might include a single weak peal or a day of heavy and prolonged thunderstorms. Background noise (aircraft, traffic, etc.) can make weak thunder difficult or impossible to hear – or may lead to false counts. In addition, records relate to the civil day, midnight to midnight UTC, although thunderstorms occurring overnight are less likely to be noted by most observers (except perhaps by an astronomical observatory), particularly if they consist of only one or two claps of thunder. However, a storm spanning midnight – even if only two claps of thunder, one at 2359 and the other at 0001 UTC – will count as two 'thunder days'. The timing upon arrival in the south Midlands of summer storms imported on a 'Spanish plume' heatwave event will occasionally generate such 'double counts', although such events are a minority in the record.

Comparisons of the record using overlapping periods of record with other sites, both nearby (Brize Norton) and regional (west London, discussed subsequently) suggest that the majority of the dataset is remarkably consistent. The early part of the record, perhaps the first two decades, appear slightly 'light' when compared with thunder frequency in the London area, but there are few other records with which to compare, and this may simply reflect genuine geographical variation at that time, differing definitions as to what constituted 'a day of thunder', or a combination of reasons.

The observational record 1828–2019

Figure 4 (blue columns) shows the annual totals of 'days with thunder heard' in Oxford since 1828, together with a superimposed 10-year running mean (red curve), plotted at year ending. Table 2 gives monthly and annual averages by decade from 1830–1839 to 2010–2019, together with a selection of 30-year average periods including the current standard averaging period[2] (1981–2010) and the most recent 30-year period at the time of writing (1990–2019).

Averages and extremes

The average number of days with thunder heard in Oxford over the complete period of record (1828–2019) was 11.9 per annum, annual totals varying from zero in 1829 and 2 days in six other years (most recently 1990) to 28 days in 1925. In 1990, there was no thunder recorded until 16 October, and the annual total was the lowest since 1840. Extremes for the record as a whole are listed in Table 3. The three consecutive years 1924 to 1926 were extraordinarily thundery in Oxford (and elsewhere), each recording at least 25 days when thunder was heard. Two particularly thundery spells occurred in 1925 – 6–19 May (14 days, 7 with thunder) and 20–30 July (11 days, 6 with thunder),

[2]The figures quoted here differ slightly from those in *Oxford Weather and Climate since 1767* as additional records have come to light since publication; the data quoted in this paper should be regarded as a more complete set of averages.

Table 2

Monthly and annual averages of 'days with thunder heard' in Oxford, by decade 1831–1840 to 2001–2010 and 2010–2019, together with a selection of 30-year average periods including the current standard averaging period (1981–2010), the most recent 30-year period at the time of writing (1990–2019) and the entire dataset (192 years). Totals may differ slightly owing to rounding errors.

Decadal averages	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*Year*	*May–Aug*	*% annual*
1831–1840	0.1	0	0.2	0.3	0.8	1.4	1.5	1.4	0.3	0.1	0	0.1	6.2	5.1	82
1841–1850	0.2	0.1	0.1	0.9	1.2	1.0	1.2	1.7	1.0	0.1	0	0.1	7.6	5.1	67
1851–1860	0	0.1	0	0.5	1.1	2.9	3.2	1.5	0.6	0.2	0	0.4	10.5	8.7	83
1861–1870	0.3	0.1	0.2	0.6	1.6	1.8	2.0	1.8	1.9	0.5	0.1	0	10.9	7.2	66
1871–1880	0.2	0	0.1	0.9	1.8	3.3	3.2	3.2	1.1	0.3	0.2	0	14.3	11.5	80
1881–1890	0	0	0	1.2	1.9	3.1	2.6	1.8	0.6	0.4	0.1	0.1	11.8	9.4	80
1891–1900	0	0	0.3	0.7	1.4	3.1	2.8	3.0	1.7	0.3	0.1	0.2	13.6	10.3	76
1901–1910	0.1	0.3	0.2	1.1	1.8	2.6	2.6	2.2	1.1	0.5	0	0	12.5	9.2	74
1911–190	0.3	0	0.6	1.0	3.1	2.5	3.5	2.9	0.7	1.2	0	0.1	15.9	12.0	75
1921–1930	0.1	0.3	0.5	1.5	4.3	1.8	3.7	3.1	1.7	0.5	0.3	0.5	18.3	12.9	70
1931–1940	0.3	0.2	0.3	1.1	2.6	3.4	3.9	2.3	1.6	1.0	0.1	0.1	16.9	12.2	72
1941–1950	0	0.1	0	1.0	2.9	2.1	3.0	2.1	1.2	0.2	0.3	0	12.9	10.1	78
1951–1960	0	0	0.1	0.5	2.1	2.3	3.0	3.0	1.1	0.8	0.4	0.2	13.5	10.4	77
1961–1970	0.2	0.2	0.2	0.9	2.5	1.8	2.6	1.5	0.4	0.2	0.2	0	10.7	8.4	79
1971–1980	0.2	0.1	0.4	0.4	1.3	1.8	1.6	1.9	1.0	0.3	0.1	0.1	9.2	6.6	72
1981–1990	0.3	0	0.5	0.7	1.8	1.6	2.2	2.1	0.8	0.4	0	0.5	10.9	7.7	71
1991–2000	0.2	0.3	0.1	1.1	1.9	1.4	2.5	2.5	1.5	0.4	0	0.1	12.0	8.3	69
2001–2010	0.2	0.2	0.4	0.7	2.2	1.6	2.4	3.0	1.0	0.5	0.1	0	12.3	9.2	75
2010–2019	0	0	0.4	0.8	1.6	1.2	1.5	1.6	0.6	0.4	0	0	8.1	5.9	73
30 year averages	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*Year*	*May–Aug*	*% annual*
1831–1860	0.1	0.1	0.1	0.6	1.0	1.8	2.0	1.5	0.6	0.1	0	0.2	8.1	6.3	78
1861–1890	0.2	0.0	0.1	0.9	1.8	2.7	2.6	2.3	1.2	0.4	0.1	0.0	12.3	9.4	76
1901–1930	0.2	0.2	0.4	1.2	3.1	2.3	3.3	2.7	1.2	0.7	0.1	0.2	15.6	11.4	73
1931–1960	0.1	0.1	0.1	0.9	2.5	2.6	3.3	2.5	1.3	0.7	0.3	0.1	14.4	10.9	76
1961–1990	0.2	0.1	0.4	0.7	1.9	1.7	2.1	1.8	0.7	0.3	0.1	0.2	10.3	7.6	74
1971–2000	0.2	0.1	0.3	0.7	1.7	1.6	2.1	2.2	1.1	0.4	0.0	0.2	10.7	7.5	70
1981–2010	0.2	0.2	0.3	0.8	2.0	1.5	2.4	2.5	1.1	0.4	0.0	0.2	11.7	8.4	72
1990–2019	0.1	0.2	0.3	0.9	1.9	1.3	2.1	2.3	1.0	0.5	0.0	0.0	10.6	7.6	72
Entire record, 192 years															
1828–2019	0.1	0.1	0.2	0.8	2.0	2.1	2.6	2.2	1.0	0.4	0.1	0.1	11.9	8.9	75

although the longest spell of consecutive thundery days (period 1828 to 2019, excluding 1936–1970) occurred back in 1859, when thunder was noted on each of five consecutive days, 18–22 July. No thundery spell longer than three consecutive days has occurred since September 1976.

The majority of thundery activity in Oxford occurs during the summer half-year, the four months May to August accounting for around three-quarters of the annual number of days with thunder heard (with little variation across the near 200 years of record – Table 2). Thunderstorms are infrequent (averaging less than one per month using current averages) between September and April (Figure 5). Winter thunderstorms (particularly November to February) tend to be short-lived and often originate from relatively shallow cumulonimbus, typically associated with narrow frontal rainbands on pronounced cold fronts, while spring storms (March and April) are often associated with showery cyclonic systems. Summer storms tend to be larger in area and depth, and to last longer. During the most recent 30-year period (1990–2019), August was, on average, the most thundery month, averaging 2.3 days with thunder heard, but during the decade 1921–1930, May averaged 4.3 days with thunder heard (Table 2). Notable amongst monthly records are 10 days with thunder heard in August 1878, and 9 days in four months, most recently in August 2004 (Table 3). During the normally quieter months of the year, 6 days with thunder in April 1998 and 4 days in 10 with thunder in December 1989 are noteworthy.

Trends in thunderstorm occurrence

The main features of Figure 4 and Table 2 are an irregular rise in annual frequency to the 1920s, resulting in an annual average of 20.0 days with thunder heard for the 10 years ending 1933. Since the 1920s and 1930s, very thundery years have become much less common, although in recent years, 1983 (24 days) and 2006 (22 days)

Table 3

Extremes of thunder frequency in Oxford, 1828 to 2019.

Most thundery years	28 days, 1925 25 days, 1924, 1926 and 1930 24 days, 1878 and 1983 23 days, 1913
Least thundery years	Nil, 1829 2 days, 1828, 1833, 1838, 1840 and 1990 3 days, 1832 and 1862 4 days, 1851, 1856, 1866 and 2015
Most thundery months	
10 days with thunder heard	August 1878
9 days	July 1925, May 1926, May 1945, August 2004
8 days	June 1883, May 1924, May 1925, July 1947, July 1965, May 1969
The following are notable for particularly high thunder frequency during the normally quiet months:	
6 days	April 1998
5 days	October 1913, April 1925, April 1948
4 days	April 1913, April 1934, October 1960, December 1989
Longest consecutive runs of days with thunder *(1828 to 2019 excluding 1936–1970)*	
5 days	18–22 July 1859
4 days	3–6 August 1878, 14–17 July 1880, 29 May–1 June 1894, 11–14 June 1900, 7–10 June 1910[a], 7–10 August 1912, 14–17 August 1915, 15–18 August 1916, 14–17 June 1920, 18–21 August 1924, 29 August–1 September 1934 and 24–27 September 1976

[a]This notably thundery spell was documented by Webb (2011). LWTs for the four days 7–10 June 1910 were E, SE, CSE and NE, respectively. The spell included, on 9 June, a very violent thunderstorm with hail at Wheatley, just east of Oxford, in which 132mm of rain fell, most of that in an hour, probably the most severe thunderstorm in the Oxford area during the period of record considered here.

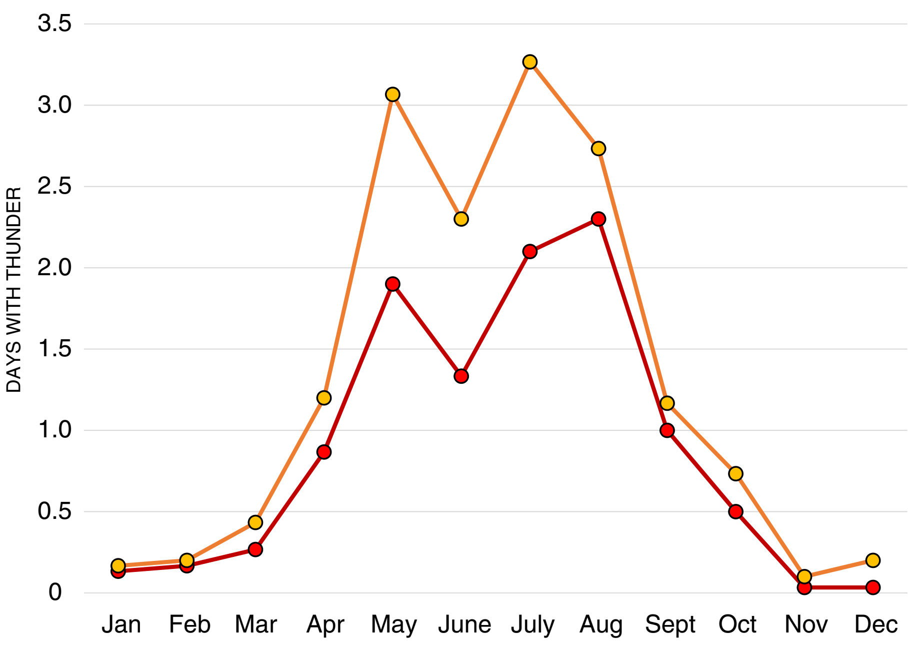

Figure 5. Monthly averages of days with thunder heard in Oxford. The red line shows the most recent 30-year period, 1990–2019 (annual average 10.6 days); the orange line is the average for the most thundery 30-year period 1901–1930 (annual average 15.6 days). See also Table 2.

oppose this trend. Instead, low annual totals have become much more frequent within the last two decades or so, with only 2 days with thunder in 1990 (the lowest annual total since 1840) and 4 days in 2015. The 10-year mean for the period 2010–2019 stands at just 8.1 days (Table 2), the lowest such value on Oxford's records since the 1860s. The possible reasons for this decline are discussed subsequently.

Local and regional comparisons

There are no other single-location records of thunderstorm frequency of similar length to Oxford in southern England, and comparisons must necessarily include overlapping records from several sites. A multi-site record for London extending back to 1713 was compiled by Mossman (1897), based mainly on the record from Greenwich (from 1814, Royal Observatory from 1841). An annual record of thunder days exists for Kew Observatory in west London, 73km southeast of the Radcliffe Observatory, from 1877 (Bishop 1947) until the Observatory's closure in December 1980; monthly totals for 1884–1980 were published in the *Monthly Weather Report* (*MWR*). Webb (2016) examined decadal trends of thunder frequency using composite records at eight UK sites during the twentieth century, including Kew. Kew Observatory was the Met Office's 'central observatory' for most of this period, with hourly observations made between 0600 and 2100 GMT daily (Galvin, 2003). To extend the 'west London' thunder record since Kew's closure, in this analysis observations from London's Heathrow Airport (10km west of Kew Observatory) and RAF Northolt (12km northwest of Kew Observatory) were used, and averages for overlapping periods calculated (Table 4). Note, however, that Northolt does not maintain 24×7 observational coverage, particularly at weekends, and the totals may therefore be slightly low.

The difference in mean annual days of thunder between Kew and Heathrow over the 32-year overlap period 1949–1980 (17.8 vs 14.4 days per annum) is surprisingly large for two permanently manned sites

Table 4

'West London' thunder-day records and overlap periods.

Station	Period of thunder record	All period average, days	Average 1949–1980, days	Average 1984–2005, days
Kew Observatory 51.468°N, 0.314°W	1877–1980	15.1	17.8	–
London Heathrow 51.479°N, 0.449°W	1949–2005	14.9	14.4	14.9
RAF Northolt 51.548°N, 0.415°W	1984–2019	12.3	–	14.4

Lamb Weather Types (LWT)

Hubert Lamb classified the daily synoptic situation over the British Isles from 1861 to February 1997, originally in *Geophysical Memoir 116* (Lamb, 1972). Lamb's original subjective classifications were later objectively reassessed using daily (1200 UTC) grid-point mean sea-level pressure data from reanalysis datasets extending back to 1871 (Jones *et al*., 2013). The Lamb Weather Types consist of cyclonic (C) and anticyclonic (A) features within the gridded area, together with directional variants – northeasterly (NE) and easterly (E) clockwise through to northerly (N), each with their cyclonic and anticyclonic variants, such that LWT SE represents a southeasterly flow, CSE a cyclonic southeasterly, ASE an anticyclonic southeasterly and so forth. An additional 'unclassifiable' (unc) category is also included for complex or fluid situations. Daily objective UK-centred LWTs are available, only a few days in arrears, courtesy of the Climatic Research Unit, University of East Anglia at https://crudata.uea.ac.uk/cru/data/lwt/.

just 10km apart. Differences were unexpectedly high in some years: in 1956, for example, Kew reported 24 days with thunder, Heathrow just 13. The reasons behind these differences remain unclear, whether it be due to a greater background noise level from traffic and aircraft movements at Heathrow, or simply greater vigilance at Kew, but the lack of homogeneity in the series should be noted.

Characteristics of thunderstorms in Oxford

Synoptic classification

The Lamb Weather Type (LWT; Jones *et al*., 2013: see Box) was used to identify the broad-scale synoptic weather pattern for each date on which thunder was heard on the composite Oxford record from 1871 (the first year of the reanalysis dataset upon which the objective LWTs are based), excluding only the years 1936–1970 for which thunder dates were not available. Frequency tables for all LWTs were tabulated for 'thunder days' and all remaining days ('non-thunder days') (Table 5). LWT profiles for 'thunder days' were compared with all 'non-thunder' days in the same analysis period, separately for 'winter' (November to February, just 3.5% of thunder days, Figure 6(a)) and 'summer' (May to August, 75% of thunder days, Figure 6(b)). By their very nature, LWTs provide only a broad-brush picture of the surface synoptic circulation across the British Isles, and two days with the same classification will inevitably show differences in detail at local or regional scales. Some latitude is therefore necessary in interpreting categorisation of local phenomena by synoptic scale, although for at least those LWTs with reasonable sample sizes, conclusions drawn appear consistent.

It comes as no surprise that Cyclonic (C) weather types dominate thunder days in both seasons, overwhelmingly so in winter – LWT C type accounting for 53% of all thunder days (30 of 57), compared to 13% of non-thunder days (Figure 6(a)). Cyclonic southwesterly CSW, cyclonic westerly CW and cyclonic northwesterly CNW types are similarly over-weighted compared to non-thunder days, although the sample of winter thunderstorms is so small (57 thunder days in total, four in December 1989 alone) that the analysis becomes sensitive to individual events. The broad picture for the winter months is of infrequent short-duration thunderstorms linked with the passage of active cyclonic centres and associated active cold fronts. In contrast, non-cyclonic thunder days occurring in southerly S, southwesterly SW and northwesterly NW LWTs are under-represented by one-third or more in comparison with non-thunder days.

For the summer months, Cyclonic (C) LWTs also accounted for the greatest single category of thunder days – 325 of the 1098 thunder days during the summer months May to August, just under 30% (Figure 6(b)), a little over twice the C frequency of non-thunder days. Perhaps surprisingly, the Anticyclonic (A) LWT saw the second-highest frequency of thunder days with individual weather types, with 99 (9%), suggestive of local convective outbreaks on the periphery of an anticyclone. Southeasterly weather types (SE and CSE) are also strongly linked to thundery conditions in Oxford, again suggesting association with Spanish plume events and/or declining hot spells. Of the cyclonic LWTs, cyclonic northerly CN, cyclonic northeasterly CNE and cyclonic easterly CE, as well as CSE, represent an increased likelihood of thunder: storms are relatively less likely in cyclonic southerly CS, cyclonic southwesterly CSW and cyclonic westerly CW situations. Provided the airflow is fairly slack, the relatively long land track of the surface winds in cyclonic CN, CNE or CE situations makes the Oxford area a favourite location for higher day temperatures, helping to increase the likelihood of thunder in favourable conditions. Situations where there is a warm east or northeasterly surface wind, coupled with a veer with height to a broadly southerly mid-level flow, are especially favourable for severe thunderstorms in the area; if the 500hPa flow is relatively light, storm initiation tends to occur over the downlands to the south. Such events in recent years include 24 May 1989, 17 May 1997, 19 May 1999, 3 August 2004 and 29 June 2005. The 1999 and 2004 events occurred in an LWT 'unclassified' situation: by their very nature, unclassified days are likely to be occasions of slack pressure (including classic col situations) and thus favourable days for local convergence zones to develop in the summer (see Figure 6(b)).

In non-cyclonic synoptic situations, LWTs easterly E, southeasterly SE and northerly N are relatively more likely to see thunderstorms in Oxford, and southerly S, southwesterly SW, westerly W and northwesterly NW less likely, particularly SW where that particular LWT accounts for 8.0% of non-thunder days but only 2.6% of thunder days. In such situations, with a surface wind between south and west, the highest temperatures tend to be well to the northeast of Oxford, towards The Wash or East Anglia, and cumulonimbus clouds are often in the developing stage over Oxfordshire with thunder breaking out only as they drift further northeast.

Relationship with summer maximum temperatures

There remains a strong belief that summer thunderstorms in the south and east of England are most often associated with hot weather, whether resulting from local surface instability during a heatwave or in a more widespread thundery breakdown following a hot spell. To examine the veracity of this belief, a further analysis examined maximum temperatures recorded on thun-

Table 5

Frequencies of Lamb Weather Types (LWTs) for days with and without thunder heard at Oxford, period 1871–2019 excluding 1936–1970, for all months and for the peak thundery months May to August only. Counts and percentage frequency are given within each LWT, together with the ratio of thunder to non-thunder days within each LWT.

All months	*unc*	*A*	*ANE*	*AE*	*ASE*	*AS*	*ASW*	*AW*	*ANW*	*AN*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*	*N*	*C*	*CNE*	*CE*	*CSE*	*CS*	*CSW*	*CW*	*CNW*	*CN*	*Total*
Counts																												
Non-thunder	385	8383	332	425	471	639	1106	1298	738	461	699	735	1206	2312	3916	3747	1959	1306	5414	247	235	369	810	995	901	627	439	40 155
Thunder	53	111	11	11	24	12	14	9	8	7	39	60	110	50	35	48	46	78	472	29	28	43	37	38	26	40	43	1482
Total	438	8494	343	436	495	651	1120	1307	746	468	738	795	1316	2362	3951	3795	2005	1384	5886	276	263	412	847	1033	927	667	482	41 637
% by LWT																												
Non-thunder	1.0	20.9	0.8	1.1	1.2	1.6	2.8	3.2	1.8	1.1	1.7	1.8	3.0	5.8	9.8	9.3	4.9	3.3	13.5	0.6	0.6	0.9	2.0	2.5	2.2	1.6	1.1	100.0
Thunder	3.6	7.5	0.7	0.7	1.6	0.8	0.9	0.6	0.5	0.5	2.6	4.0	7.4	3.4	2.4	3.2	3.1	5.3	31.8	2.0	1.9	2.9	2.5	2.6	1.8	2.7	2.9	100.0
Ratio thunder: non-thunder	3.73	0.36	0.90	0.70	1.38	0.51	0.34	0.19	0.29	0.41	1.51	2.21	2.47	0.59	0.24	0.35	0.64	1.62	2.36	3.18	3.23	3.16	1.24	1.03	0.78	1.73	2.65	
May to August only	*unc*	*A*	*ANE*	*AE*	*ASE*	*AS*	*ASW*	*AW*	*ANW*	*AN*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*	*N*	*C*	*CNE*	*CE*	*CSE*	*CS*	*CSW*	*CW*	*CNW*	*CN*	*Total*
Counts																												
Non-thunder	238	3096	112	157	139	200	302	377	256	176	224	245	365	598	1031	1023	631	405	1855	96	78	121	255	312	267	218	147	12 924
Thunder	45	99	7	11	21	10	10	6	6	6	27	46	87	38	28	27	32	56	325	19	23	36	22	25	17	34	35	1098
Total	283	3195	119	168	160	210	312	383	262	182	251	291	452	636	1059	1050	663	461	2180	115	101	157	277	337	284	252	182	14 022
% by LWT																												
Non-thunder	1.8	24.0	0.9	1.2	1.1	1.5	2.3	2.9	2.0	1.4	1.7	1.9	2.8	4.6	8.0	7.9	4.9	3.1	14.4	0.7	0.6	0.9	2.0	2.4	2.1	1.7	1.1	100.0
Thunder	4.1	9.0	0.6	1.0	1.9	0.9	0.9	0.5	0.5	0.5	2.5	4.2	7.9	3.5	2.6	2.5	2.9	5.1	29.6	1.7	2.1	3.3	2.0	2.3	1.5	3.1	3.2	100.0
Ratio thunder: non-thunder	2.23	0.38	0.74	0.82	1.78	0.59	0.39	0.19	0.28	0.40	1.42	2.21	2.81	0.75	0.32	0.31	0.60	1.63	2.06	2.33	3.47	3.50	1.02	0.94	0.75	1.84	2.80	

der and non-thunder days during the entire period for which thunder dates were available (157 years 1828–2019, excluding 1936 to 1970). It should be borne in mind, however, that the reported maximum temperature (referring to the 24-hour period commencing 0900 GMT/UTC for the majority of Oxford's record) may not coincide with the time when the thunderstorm occurred: for example, an overnight storm (between midnight and the morning observation) and the afternoon's maximum temperature would both be credited to the same date, although a significant change of air mass may have taken place between the two events.

For every month except August, median maximum temperatures on days with thunder are very slightly higher than on non-thundery days, but outside the winter months, the differences are slight (Table 6). The difference between the two is greatest during the months of December, January and February, when it exceeds 2°C, although it should be noted that sample sizes are very small outside of the summer peak period. Higher temperatures and reduced variation on days when winter thunderstorms were recorded tend to confirm the hypothesis above that winter thunderstorms in Oxford are most likely to occur in mild, unsettled cyclonic conditions, often associated with sharp cold frontal boundaries.

For the summer months May to August, representing around 75% of all thunderstorm days, the boxplots in Figure 7 show the median, interquartile range and extremes of daily maximum temperature for both thunder and non-thunder days. Although both the median (19.8°C non-thunder, 20.3°C thunder days) and the upper quartile (22.4°C vs 23.4°C, respectively) are slightly higher on thunder days, the two groups are statistically indistinguishable. Repeating the analysis using the highest maximum temperature within the previous three days produced a very similar result. The association with summer heatwaves is thus shown to be slight. There may be a greater degree

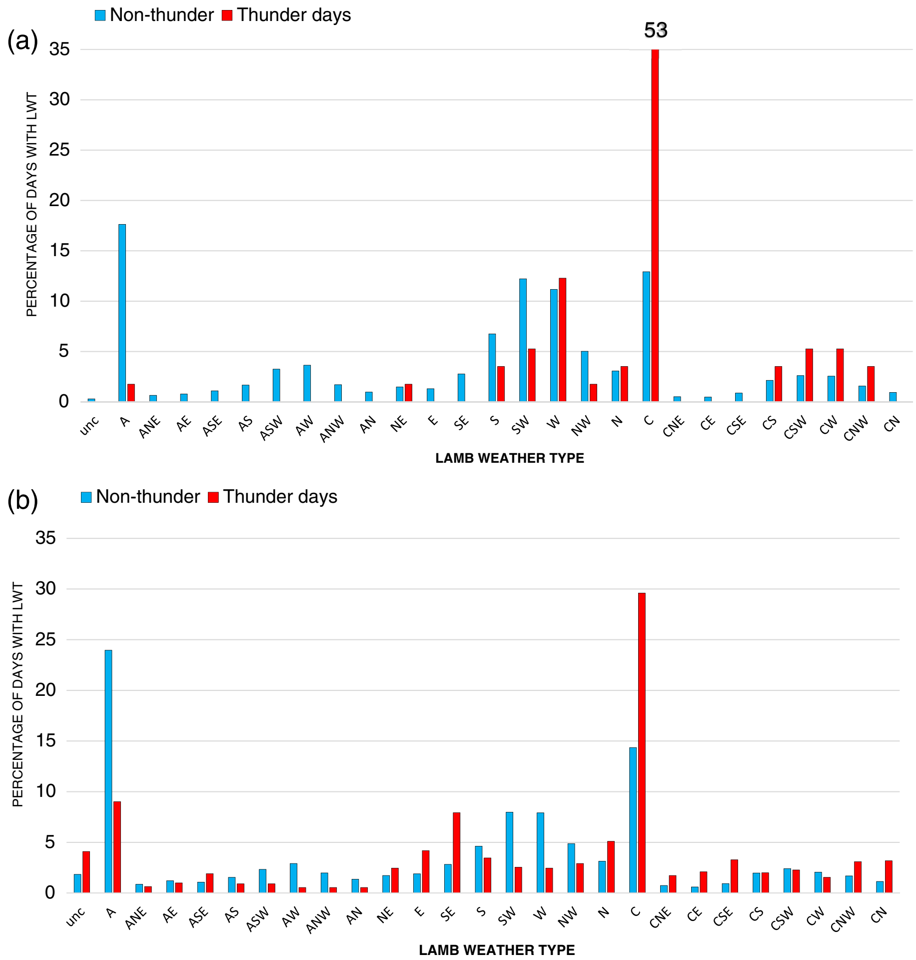

Figure 6. Distribution (percentage of dates) of Lamb Weather Types (LWT) for dates with and without thunder (red and blue columns, respectively) at Oxford, 1871–2019 excluding 1936–1970. Upper plot (a) is for November to February: lower plot (b) is for May to August. The scale is the same on both plots. For LWT details, see text.

Table 6

Comparison of mean maximum temperatures (°C) by month at Oxford on days with and without thunder heard, and the difference, including sample sizes. Period 1828–2019, excluding 1936–1970 – 157 years in total.

	Mean maximum temperature °C				*Number of days*		
Month	*All days*	*No thunder (noT)*	*Thunder (T)*	*T minus noT*	*No thunder*	*Thunder*	*Total*
January	6.6	6.5	9.0	2.4	4846	21	4867
February	7.4	7.4	10.4	3.0	4419	15	4434
March	9.9	9.9	10.5	0.6	4828	39	4867
April	13.1	13.1	13.9	0.8	4578	132	4710
May	16.7	16.7	18.3	1.6	4574	293	4867
June	19.9	20.0	20.6	0.6	4380	330	4710
July	21.8	21.7	22.4	0.7	4487	380	4867
August	21.2	21.2	21.2	0.0	4525	342	4867
September	18.4	18.4	18.7	0.3	4547	163	4710
October	14.0	14.1	14.9	0.8	4802	65	4867
November	9.6	9.6	11.6	1.9	4699	11	4710
December	7.3	7.2	10.7	3.4	4843	24	4867
					55 528	1815	57 343

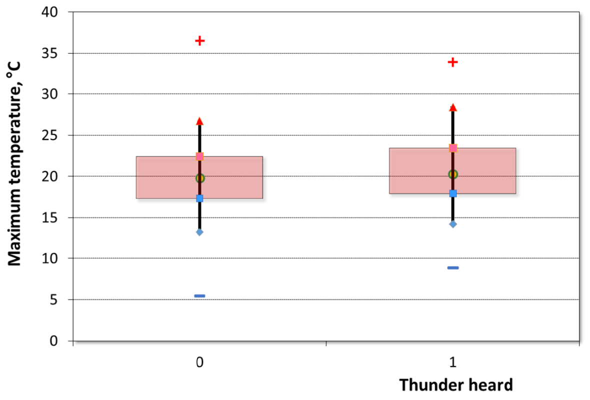

Figure 7. Box-and-whisker plots comparing the distribution of daily maximum temperatures on dates without and with thunder heard (left and right plots, respectively) at Oxford, May to August 1829–2019 excluding 1936–1970. The plotted variables are (from top) maximum value, 95th percentile, 75th percentile (upper box boundary), median (green circle), 25th percentile (lower box boundary), 5th percentile, minimum value.

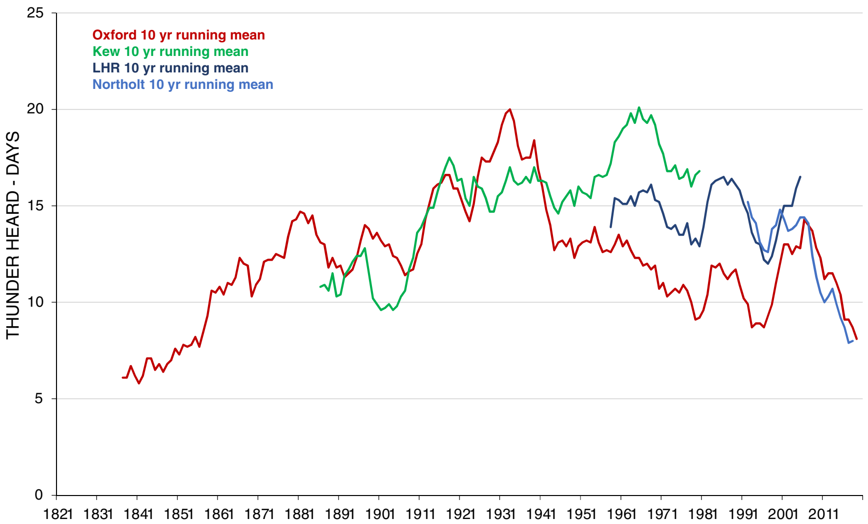

Figure 8. Ten-year running means of thunderstorm frequency (plotted at year ending) for Oxford (dark red line) 1828–2019, alongside similar averages for sites in west London – Kew Observatory (1877–1980, green line), Heathrow Airport (LHR, 1949–2005, dark blue line) and Northolt (1984–2019, light blue line).

of relationship between summer maximum temperatures and heavy or severe thunderstorms, but sample sizes are too small to allow reliable statistical analysis.

The recent decline in thunderstorm frequency

Figure 8 shows the 10-year running means (plotted at year ending) for Oxford from the commencement of the record in 1828, together with those for Kew Observatory (1877–1980), Heathrow (1949–2005) and Northolt (since 1984). Since at least the 1880s, the peaks and troughs (if not always the relative amplitudes) of decadal thunderstorm incidence in London and Oxford largely coincide, indicative of broader synoptic-scale influence rather than more local factors, although there is a suggestion that thunderstorm frequency in west London has not fallen as far since the peak seen in the Oxford record in the 1920s/1930s. The possible reasons for this are beyond the scope of this article, but stability changes in the boundary layer and/or urban heat island resulting from extensive urban growth in west London since that time may be involved. There is also an apparent periodicity in the peak years of around 20 years, traceable throughout the record.

Although the thunderstorm record from Oxford is unlikely to be statistically homogenous throughout the near-200 year series, for reasons already stated, Table 2 and Figures 4, 5 and 8 confirm that the most recent decade has seen a marked reduction in thunderstorm frequency. There is also evidence of an irregular but longer-term decline since the 1960s. Can the decline in frequency be explained, at least in part, by a decline in the frequency of synoptic situations conducive to summertime thundery outbreaks?

If changes in synoptic type over decadal scales are a factor in the observed decline, we might expect a decrease in conducive or 'positive' synoptic conditions and/or an increase in less conducive or 'negative' situations. Accordingly, Table 7 and Figure 9 examine the monthly mean frequency of each LWT (pro-rata for a 31 day month) for May to August over 1901–1930, the 30-year period with the greatest mean thunder frequency in Oxford, together with the equivalent data for the most recent 30-year period 1990–2019 (from Table 2).

Comparing the two periods graphically (Figure 9), it can be seen firstly that certain LWTs occurred considerably more frequently than normal during the most thundery months (blue columns – examples C, SE and CSE), and secondly that many of these LWTs occurred less frequently in the last 30 years (red columns) than during 1901–1930 (orange columns).

For a quantitative comparison, the ratios of LWT frequency between thunder days and non-thunder days during May to August (Table 5) were rearranged in Table 7, ranked by the ratio of each LWT, from 'most conducive' (greatest relative frequency of thunder days) to 'least conducive' (lowest relative frequency of thunder days). For example, the cyclonic southeasterly CSE LWT is 3.5 times more abundant for thunder days than non-thunder days, whereas the anticyclonic westerly AW type is less than one-fifth as common (ratio 0.19). The two 30-year periods were then compared and differences evaluated. Comparing 1990–2019 with 1901–1930, the sum of the difference in 'conducive' LWTs (ratio > 0, indicative of an increased frequency of thunder in those synoptic situations) is −0.91 days, and the equivalent for 'least conducive' LWTs (ratio < 0) is 0.85 days, suggesting a potential net reduction in conducive thundery synoptic situations between May to August of 1.76 days per 31 day month (−0.91 – 0.85), grossing up to 7.0 days across the four months (123 days). From Table 2, it can be seen that the average frequency of thunder between May and August in Oxford has fallen from 11.4 days in 1901–1930 to 7.6 days in the most recent 30-year period, a reduction of 3.8 days or 34%. Although almost certainly not the only reason for the decline, this analysis is of the right order and suggests that the recent reduction in thunderstorm frequency in Oxford, and by extension a wide area of southern England, can be partly attributed to reductions in the frequency of conducive synoptic environments.

Summary and conclusions

The long record of 'days with thunder heard' in Oxford, commencing in January 1828, is described. Thunder is heard, on average over the entire period of record, on 11.9 days per annum: typically three-quar-

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Table 7

Ranked relative frequency of Oxford thunder days to non-thunder days by Lamb Weather Type (LWT), for the peak thundery months May to August only, period 1871 to 2019 excluding 1936–1970. From Table 5, the synoptic types more or less conducive to thunder in Oxford are identified, and compared with LWT frequency over the (most thundery) 30-year period 1901–1930 and the (less thundery) most recent 30 years 1990–2019, with the differences between the two shown.

Lamb Weather Type	*Non-thunder days %*	*Thunder days %*	*Ratio thunder: non-thunder*		*LWT frequency 1901–1930, days*	*LWT frequency 1990–2019, days*	*Days change 1990–2019 versus 1901–1930*	
CSE	0.9	3.3	3.50	MORE CONDUCIVE TO THUNDER	0.34	0.27	−0.07	
CE	0.6	2.1	3.47		0.28	0.18	−0.10	
SE	2.8	7.9	2.81		1.06	0.91	−0.15	
CN	1.1	3.2	2.80		0.45	0.40	−0.05	
CNE	0.7	1.7	2.33		0.23	0.20	−0.03	
Unclassified	1.8	4.1	2.23		0.54	0.70	0.16	
E	1.9	4.2	2.21		0.70	0.63	−0.07	
C	14.4	29.6	2.06		5.01	4.70	−0.31	
CNW	1.7	3.1	1.84		0.65	0.61	−0.04	
ASE	1.1	1.9	1.78		0.26	0.40	0.14	
N	3.1	5.1	1.63		1.21	0.98	−0.23	
NE	1.7	2.5	1.42		0.63	0.50	−0.13	
CS	2.0	2.0	1.02		0.55	0.52	−0.03	
CSW	2.4	2.3	0.94	LESS CONDUCIVE TO THUNDER	0.71	0.72	0.01	
AE	1.2	1.0	0.82		0.33	0.34	0.01	
CW	2.1	1.5	0.75		0.60	0.76	0.16	
S	4.6	3.5	0.75		1.46	1.24	−0.22	
ANE	0.9	0.6	0.74		0.22	0.20	−0.02	
NW	4.9	2.9	0.60		1.45	1.76	0.31	
AS	1.5	0.9	0.59		0.40	0.50	0.10	
AN	1.4	0.5	0.40		0.45	0.37	−0.08	
ASW	2.3	0.9	0.39		0.60	0.63	0.03	
A	24.0	9.0	0.38		6.78	6.84	0.06	
SW	8.0	2.6	0.32		2.39	2.49	0.10	
W	7.9	2.5	0.31		2.30	2.64	0.34	
ANW	2.0	0.5	0.28		0.53	0.58	0.05	
AW	2.9	0.5	0.19		0.90	0.90	0.00	
Totals					31.0	31.0		
Total CONDUCIVE influence							−0.91	days per month
Total LESS CONDUCIVE influence							0.85	days per month

ters of these occur in the four months from May to August. The record is examined in terms of the links with particular synoptic types and the day's maximum temperature. Contrary perhaps to popular belief, there is little evidence of a clear relationship between thunder occurrence and high temperatures during the summer months: the incidence of certain weather types, particularly southeasterly variants often indicative of Spanish plume events, is of greater predictive value. By extension and comparison with long multi-site thunder records from London, this synoptic scale relationship is likely to hold over much of inland southern England. The frequency of thunder in Oxford has declined considerably in the last decade or so, such that the average for the most recent 10-year period 2010–2019 (8.1 days per annum) is the lowest such value in almost 150 years. Although probably not the sole cause of the observed reduction in frequency of thunderstorms in recent decades, a demonstrable decline in synoptic weather types conducive to thunderstorm development in southern England is of the right order to account for the reduction and involves plausible synoptic-scale mechanisms. However, there remains considerable variability between individual synoptic events and from year-to-year.

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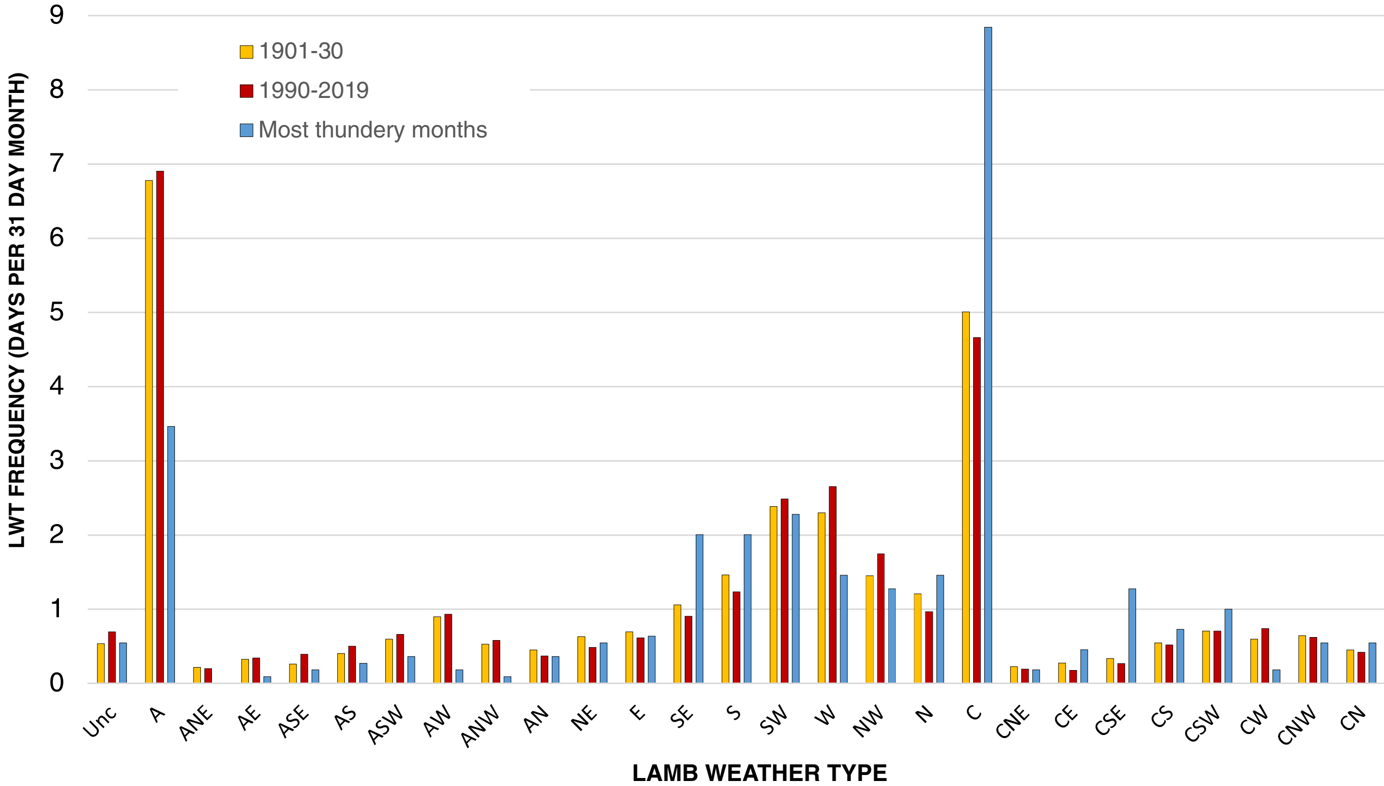

Figure 9. Comparison of LWT frequencies (days in a nominal 31 day month) for May to August 1901–1930 (orange columns) and 1990–2019 (red columns), together with those for the most thundery months on record in Oxford (8 days with thunder or more) listed in Table 3 (blue columns).

The Oxford Radcliffe Observatory thunder datasets

Two datasets have been placed on Figshare (https://www.doi.org/10.6084/m9.figshare.13347512.v1). **Dataset 1** contains the dates upon which thunder was heard in Oxford, January 1828 to December 2019, but note there are no records by date between 1936 and 1970 at present - these will be added post-publication once access to the Met Office archives has been restored.

Dataset 2 contains monthly and annual totals of the number of days with thunder heard in Oxford, January 1828 to December 2019. This includes monthly totals from 1936 to 1970, and the series is believed complete.

If using either dataset, please include a citation to this paper.

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