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Climatology, Storm Morphologies, and Environments of Tornadoes in the British Isles: 1980–2012

Kelsey J. Mulder and David M. Schultz

Centre for Atmospheric Science, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester, United Kingdom

ABSTRACT

A climatology is developed for tornadoes during 1980–2012 in the British Isles, defined in this article as England, Scotland, Wales, Northern Ireland, Republic of Ireland, Channel Islands, and the Isle of Man. The climatology includes parent storm type, interannual variability, annual and diurnal cycles, intensities, occurrence of outbreaks (defined as three or more tornadoes in the same day), geographic distribution, and environmental conditions derived from proximity soundings of tornadoes. Tornado reports are from the Tornado and Storm Research Organization (TORRO). Over the 33 years, there were a mean of 34.3 tornadoes and 19.5 tornado days (number of days in which at least one tornado occurred) annually. Tornadoes and tornado outbreaks were most commonly produced from linear storms, defined as radar signatures at least 75 km long and approximately 3 times as long as wide. Most (78%) tornadoes occurred in England. The probability of a tornado within 10 km of a point was highest in the south, southeast, and west of England. On average, there were 2.5 tornado outbreaks every year. Where intensity was known, 95% of tornadoes were classified as F0 or F1 with the remainder classified as F2. There were no tornadoes rated F3 or greater during this time period. Tornadoes occurred throughout the year with a maximum from May through October. Finally, tornadoes tended to occur in low-CAPE, high-shear environments. Tornadoes in the British Isles were difficult to predict using only sounding-derived parameters because there were no clear thresholds between null, tornadic, outbreak, and significant tornado cases.

1. Introduction

Although tornadoes in the British Isles have been labeled as "freak" occurrences by the media (Elsom 1985), the United Kingdom has been cited as having more tornadoes per area than any other country in the world (Reynolds 1999). In fact, over 30 tornadoes are known to have occurred in Britain before 1660 (Rowe 1999).

Deaths are not common in British Isles tornadoes (Elsom and Meaden 1984), but injuries and damage to property have been observed. For example, the F2 Birmingham tornado on 28 July 2005 resulted in 19 injuries and approximately £40 million ($68 million) in

damages (Russell 2010). Because tornadoes pose a threat to human health and property, the knowledge of when, why, where, and under which conditions tornadoes occur has great relevance.

Although tornadoes have been reported on every continent except Antarctica, the conditions under which tornadoes are produced may not be the same everywhere (Brooks 2009). This makes tornado climatologies conducted in countries outside of the United States, for example, important. Temporal analysis of tornadoes has been conducted before in the British Isles (Table 1). These climatologies reported average annual occurrence of tornadoes ranging from 10.3 tornadoes per year (Ireland, 1999–2001; Tyrrell 2003) to 47.2 tornadoes and waterspouts per year (United Kingdom, 1981–2010; Kirk 2014). This statistic varies depending on the study period and whether waterspouts were included. This article updates the knowledge of tornado occurrence in the British Isles by using a 33-yr study period excluding waterspouts.

Another common analysis of the studies summarized in Table 1 was seasonality. The results depended on the

TABLE 1. Selected results from previous tornado climatologies conducted in the British Isles.

Study	Location	Years	Avg annual No. of tornadoes	Avg annual No. of tornado days	Waterspouts included?	Tornado season	Season determined from tornado numbers or days?
Lacy (1968)	England, Scotland, and Wales	1963–66	19.5	9.0	No	Winter	Days
Elsom and Meaden (1984)	United Kingdom	1960–82	32.1	12.7	No	Summer and autumn	Days
Elsom (1985)	United Kingdom	1950–84	27.7	16.1	No	—	—
Meaden (1985a)	England, Scotland, and Wales	1970–79	≈ 32	18	Yes	Summer and autumn	Days
						Autumn and winter	Numbers
Reynolds (1999)	United Kingdom	1960–89	33.2	15.8	No	Autumn	Numbers
Tyrrell (2003)	Ireland	1950–2001	10.3 (1999–2001)	—	No	Summer and autumn	Numbers
Holden and Wright (2004)	United Kingdom	1995–99	24.4	—	No	Spring and summer	Numbers
Kirk (2007)	United Kingdom	1980–2004	45.7*	22.6*	Yes	Autumn	Numbers
Kirk (2014)	United Kingdom	1981–2010	47.2	24.3	Yes	Summer	Days
			36.5	18.9	No	Autumn	Numbers
This article	British Isles	1980–2012	34.3	19.5	No	Summer	Days
						Summer and autumn	Numbers

* Kirk (2007) originally reported a mean of 51.4 tornadoes and 24.2 tornado days per year. These numbers were revised to 45.7 tornadoes and 22.6 tornado days per year in Kirk (2014) after correcting database errors.

study period and whether tornado numbers or tornado days (number of days in which at least one tornado occurs) were used. The season with the most tornadoes has been cited as autumn (Reynolds 1999; Kirk 2007, 2014), summer and autumn (Tyrrell 2003), autumn and winter (Meaden 1985a), and spring and summer (Holden and Wright 2004). Using tornado days, tornado season has been cited as winter (Lacy 1968), summer and autumn (Elsom and Meaden 1984; Meaden 1985a), and summer (Kirk 2014). Using both tornado day and tornado number analysis, this article will address the discrepancy in seasonality.

An analysis of the types of storms and environmental parameters conducive to producing tornadoes has not been conducted by the studies in Table 1. The only research on environmental conditions associated with tornadic storms have been case studies (e.g., Bolton et al. 2003; Clark 2012) or were based on reanalysis data over short periods and large areas (e.g., Brooks et al. 2003b; Romero et al. 2007). This article addresses these gaps in the research by including storm type and proximity sounding analyses. Additionally, this article assesses the probability of tornadoes spatially in the British Isles, furthering the gridded tornado frequencies presented in Meaden (1985a).

Section 2 discusses the Tornado and Storm Research Organization (TORRO), the organization from which the tornado occurrence data come. Section 3 describes the data and methods used in this study. The type of parent storms producing tornadoes is analyzed in section 4. Spatial patterns in tornado occurrence are presented in section 5, including an analysis of probability of tornado occurrence and how those probabilities change throughout the year. Section 6 examines the interannual variability, annual cycle, diurnal cycle, and occurrence of outbreaks. Section 7 details the intensity of tornadoes. Section 8 describes the environmental conditions in which tornadoes occur using proximity soundings. The results are summarized in section 9.

2. TORRO

The data used in this climatology come from TORRO, a U.K.-based, nonprofit organization founded in 1974 (Elsom and Meaden 1984; Meaden 1985b; Elsom et al. 2001). TORRO collects severe weather reports from the media and over 350 observers in the United Kingdom, Republic of Ireland, and elsewhere around the world

(Elsom et al. 2001). The public can also submit reports through the TORRO website (http://www.torro.org.uk). Although TORRO collects reports worldwide, its contributors are concentrated in the British Isles, which is the subset of data used in this article. TORRO staff, ranging from amateur meteorologists to doctoral researchers, work on a volunteer basis. To help distribute work within the organization, TORRO is broken into three divisions: Tornado, Thunderstorm and Severe Weather, and Severe Weather Forecast.

Besides collecting severe weather reports, TORRO conducts site investigations to verify tornado reports and classify the damage using the tornado intensity scale (T scale). In 1972, Terence Meaden, the founder of TORRO, created the T scale, a tornado intensity classification scale, similar to the Fujita scale used in the United States (Elsom et al. 2001; Kirk 2014). The T scale has twice as many classifications as the Fujita scale, making it useful for European tornadoes, which tend to be less intense than American tornadoes (Meaden 1985b). To convert between the Fujita (F) and T scales, the equation $F \approx 0.5T$ and rounded down to the nearest integer can be used (Brooks and Doswell 2001; Meaden et al. 2007).

TORRO designates tornado reports as either probable, meaning a tornado likely occurred but no hard evidence has been cited, or definite, meaning a tornado has been confirmed. The distinction between probable and definite is determined on a case-by-case basis with the final word lying with the head of the Tornado Division of TORRO. The amount of information available on the report determines the designation of probable or definite. For example, a tornado would be classified as definite if a site survey was completed and damage was concluded to be attributable to a tornado. If there was no site survey, but a photo or video of the tornado was available, the report would also be considered definite. Reports coming from a knowledgeable, educated observer would likely become definite after more investigation. If only photos of damage were available, classification depends on the damage portrayed. For example, twisted trees or a narrow swath of damage would help designate a tornado as definite. In the absence of a site investigation or photographic or video evidence, an environmental situation conducive to tornadoes would designate the report as probable. This article uses both definite and probable reports, similar to Elsom and Meaden (1984) and Kirk (2014).

3. Data and methods

This climatology uses tornado reports collected by TORRO during 1980–2012 over England, Scotland, Wales, Northern Ireland (together considered the United Kingdom), the Republic of Ireland, the Channel Islands, and the Isle of Man (Fig. 1). For the purpose of this article, this area is considered the British Isles. As our period of analysis falls after the founding of TORRO, the data used herein are not based on historical reports, but instead from observer and media reports.

Waterspouts are excluded from this article because they are not as reliably reported as land-based tornadoes. Additionally, we want to document land-based tornadoes because these are more threatening to life and property. Cases that originated on land and moved over water or originated on water and moved over land were included in the analysis because they were over land for part of their duration. Some reports include multiple tornadoes in the same location, occurring as part of the same parent storm or boundary. These reports are considered one tornado case (Rauhala et al. 2012). To control for outbreaks (a day in which three or more tornadoes occur), tornado-day analysis was also conducted.

Some cases in the TORRO database are incomplete, containing uncertain location, time of occurrence, or intensity. Any uncertain information was left out of the analysis, although the case remained in the dataset to prevent the tornado dataset from becoming too limited. Therefore, there are different numbers of tornadoes included in different analyses. These numbers are reported along with the results.

An unusually large outbreak, which was omitted from some analyses, occurred on 23 November 1981 when 104 tornadoes were reported across the British Isles (hereafter called the 1981 Outbreak). The size of the outbreak was unusual for the British Isles (discussed in section 6d). One reason so many tornadoes were reported were the appeals made for further reports. According to Rowe (1985), reports of 35 tornadoes came from press cuttings, 30 came after meteorologist Michael Hunt called for reports on Anglia Television, and the remaining 39 came from TORRO's appeals in provincial newspapers. As a result of the appeals, it is possible that some tornado reports are not valid or are reporting the same tornado. It is also possible that there were indeed 104 tornadoes on that day, but a similar appeal process has not been followed for subsequent tornado cases. Therefore, in most analyses in the present paper, results are presented both including and excluding the 1981 Outbreak, in case this event was overreported.

There were 1241 tornado cases over 642 tornado days (including the 1981 Outbreak) over the 33 years. The data used herein differ slightly from Kirk (2014), who analyzed 1416 tornado cases on 729 tornado days. First, we included data from 1980, 2011, and 2012, and
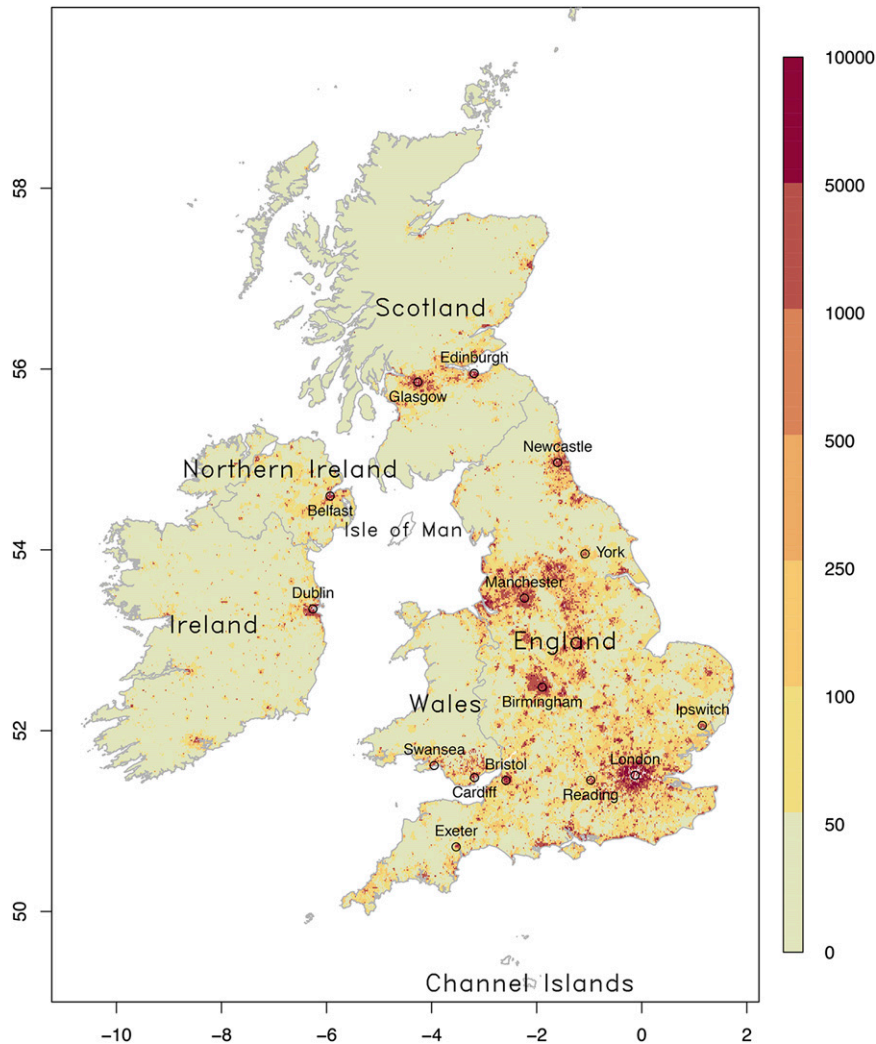
FIG. 1. Map of the British Isles and locations described in the text and 2000 population density in people per square kilometer.

included the Republic of Ireland. Second, we excluded tornadoes occurring only over water. Third, we excluded the 1981 Outbreak from some analyses. Fourth, we omitted uncertain data from analysis.

4. Parent storm analysis

To determine the type of storm from which tornadoes were produced, the Met Office 1-km grid spacing Nimrod radar 5-min composite rainfall rates were used. Radar data were only available starting in April 2004, so a subset of 254 tornadoes with known locations, dates, and times during April 2004–December 2012 (20% of all 1241 tornado cases) were included in this analysis.

Parent storms were categorized manually based on the classification scheme in Gallus et al. (2008) (Fig. 2).

All morphologies had at least 2.5 mm h^{-1} peak rainfall rate. Because of the small sample of tornadoes, broken lines, bow echoes, and all squall lines with or without stratiform rain were collectively classified as linear (Fig. 2). Linear morphologies were defined by being at least 3 times as long as wide and at least 75 km long, following Gallus et al. (2008). Other morphologies were isolated cell, nonlinear, cluster, and unassigned. Isolated cells were defined as cells with high rainfall rates completely separated from each other. Clusters, like isolated cells, had discrete regions of high rainfall rates but were connected by weak rainfall rates. Nonlinear morphologies differed from clusters due to their lack of discrete cells and large size (approximately 70 km wide). If the case did not fit into a category, belonged to multiple categories, or could not be classified because of poor
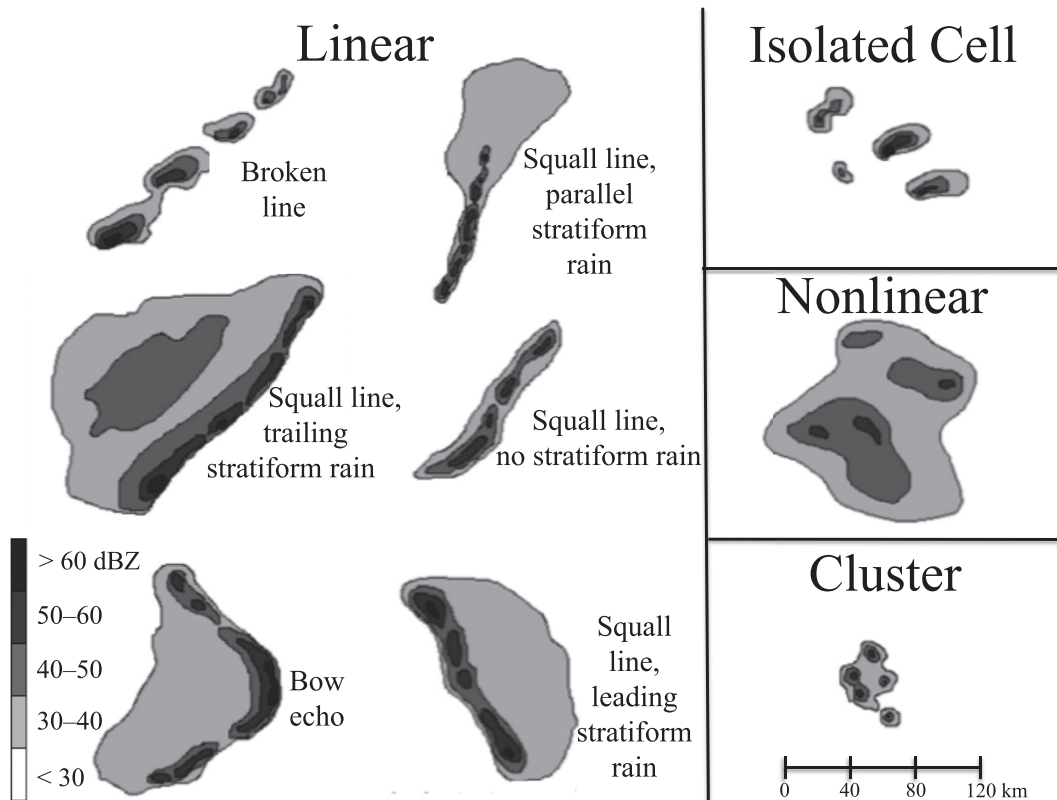
FIG. 2. Classification scheme for parent storm analysis, adapted from Gallus et al. (2008).

radar coverage, it was classified as unassigned (Doswell 1991).

The most common category of storm morphology, with 42% of all tornadoes in the British Isles, was the linear category (Fig. 3). In contrast, in the United States during 1998–2000, 18% of tornadoes were produced from linear systems, with 79% produced from isolated cells (Trapp et al. 2005). Other morphologies in the British Isles were isolated cells (28%), nonlinear systems (11%), and clusters of cells (9%). The remaining 10% were unassigned. In winter and autumn, the most common storm morphology was linear storms (52% and 62%, respectively; Fig. 4). In summer, 42% of tornadoes were produced by isolated storms, the most common storm morphology. In spring, the most common storm morphology was isolated cells (31%) followed by nonlinear storms (23%); linear storms were least common in spring compared to the other seasons (14%; Fig. 4).

5. Spatial distribution of tornadoes

To analyze the spatial distribution of tornadoes, gridded point observations of tornado touchdown locations ($n = 1091$) were smoothed temporally and spatially using Gaussian smoothers. The method is the same as Brooks et al. (2003a) and is summarized below. Touchdown locations were used because only 20% of cases had track information. Additionally, because 83% of track lengths were less than or equal to 5 km, incorporating track length would produce similar results. Tornadoes from the 1981 Outbreak were omitted from the spatial analysis because they distorted the spatial distribution of tornadoes on and near that day.
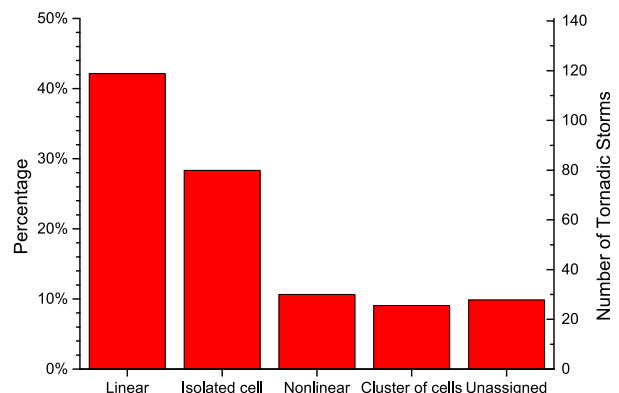

FIG. 3. Histogram of parent storm type for tornadic storms in the British Isles, based on the classification scheme in Fig. 2. Left side y axis in percentage of total 254 tornadic storms; right-side y axis in number of tornadic storms.
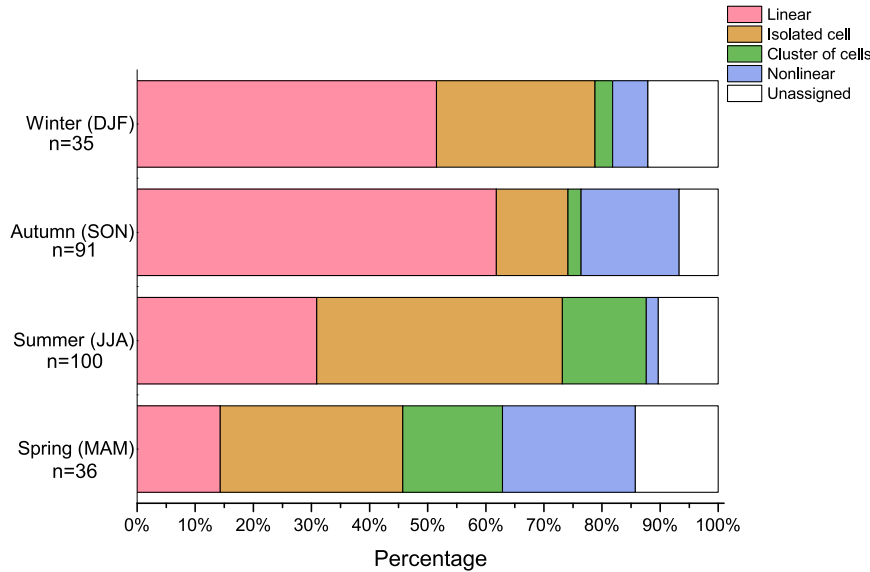
FIG. 4. Percentage of tornadic storms classified as each parent storm type in the British Isles by season based on the classification scheme in Fig. 2.

First, tornado point observations were transferred to a grid box with Lambert conformal conic map projection (standard parallels of 43° and 62°N). Grid spacing was 0.125°, or approximately 10-km by 10-km grid size. Second, the mean unsmoothed frequency of tornado occurrence on the day of interest m, was calculated for each grid box every day of the year by

$$m = \frac{M}{N}, \qquad (1)$$

where M is the number of years in the period with at least one tornado in the grid box and N is the number of years in the dataset ($N = 9$ for 29 February, $N = 33$ for all other days). Third, the data were temporally smoothed using

$$f_n = \sum_{k=1}^{366} \frac{m}{\sqrt{2\pi}\sigma_t} \exp\left[-\frac{1}{2}\left(\frac{n-k}{\sigma_t}\right)^2\right], \qquad (2)$$

where f_n is the mean time-smoothed frequency of tornadoes on the day of interest n, k is the day of the year, and σ_t is the temporal smoothing parameter. Fourth, f_n is smoothed spatially to find $p_{x,y,n}$, the probability of a tornado occurring within the grid box (x, y) on day n by

$$p_{x,y,n} = \sum_{j=1}^{J} \sum_{k=1}^{I} \frac{f_n}{2\pi\sigma_x^2} \exp\left[-\frac{1}{2}\left(\frac{d_{i,j}}{\sigma_x}\right)^2\right], \qquad (3)$$

where I is the number of grid boxes in the x direction, J is the number of grid boxes in the y direction, $d_{i,j}$ is the Euclidean distance between the location of interest

(x, y) and the data location (i, j), and σ_x is the spatial smoothing parameter. A 15-day temporal smoothing parameter was used, the same as used in Brooks et al. (2003a). Brooks et al. (2003a) used a 120-km spatial smoothing parameter for their 80-km by 80-km grid size. Because of our smaller grid size, a 50-km spatial smoothing parameter was chosen. The results were plotted as smoothed contours to help detect important spatial patterns.

Maximum annual cumulative probability of a tornado in a 10-km grid box was maximum in England (Fig. 5), where 78% of cases occurred. Local probability maxima were typically near cities. More specifically, probabilities of tornadoes within 10 km of a point were locally higher southwest of London between London and Reading (up to 6.0%), northeast of London to Ipswich (up to 4.0%), from Bristol north to Manchester (up to 5.0%), and along the south coast of Wales near Swansea (up to 3.0%). Scotland, Northern Ireland, the Republic of Ireland, and the Channel Islands had local maxima up to 2.0% chance of a tornado occurring within 10 km of a point.

The area of highest tornado probability varied by location throughout the year (Fig. 6). February through April, tornado probabilities were small (up to 0.02%) and localized across England. In May through September, the probability of tornadoes filled in across England and locally increased to up to 0.03%. In October through December, the maximum tornado probability moved to southern England before low probabilities become scattered across England again in January.
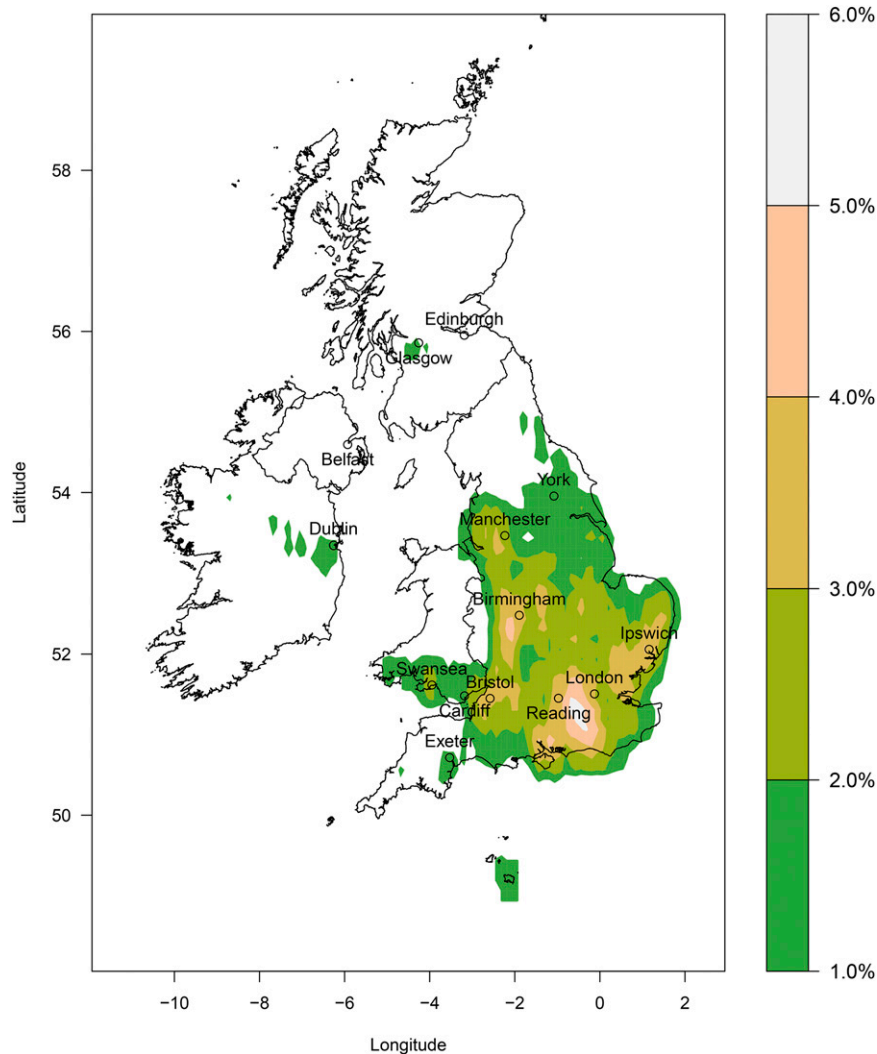
FIG. 5. Cumulative percent probability of a tornado occurring in a 10-km grid box across the British Isles per year, using a 15-day temporal and 50-km spatial smoothing parameter.

The migration of maximum tornado probability, up to 0.04%, in the British Isles south toward coastal areas and relatively warm seawater is similar to the migration of maximum tornado probability from the Great Plains to the southeastern United States (referred to as "Dixie Alley") during November through February (Brooks et al. 2003a; Gagan et al. 2010; Dixon et al. 2011; Smith et al. 2012). Perhaps the spatial change in tornado probabilities in the British Isles is due to local, seasonal conditions favorable to deep, moist convection. For example, Holley et al. (2014) found that highest convective available potential energy (CAPE) values in September through January (over the study period 2002–12) were along the south coast of England.

The overall spatial patterns of tornado probabilities could be affected by secular differences. This is especially apparent in Fig. 5, where higher probabilities mirrored the population density in the United Kingdom (Fig. 1) and in Fig. 6 where areas of higher probability lingered near cities throughout the year. Tornado probabilities were near zero in central and eastern Wales, most of Scotland, the Republic of Ireland, and Northern Ireland throughout the year (Fig. 6). These patterns were likely present because of the few people present to witness and therefore report a tornado. An additional challenge in the British Isles is that tornado occurrence data are not actively collected through the Met Office or Irish Meteorological Service. Although tornado occurrence data are collected for tornado warning verification in the United States, tornado warnings are not issued in the United Kingdom (Rauhala and Schultz 2009) or the Republic of Ireland (http://www.met.
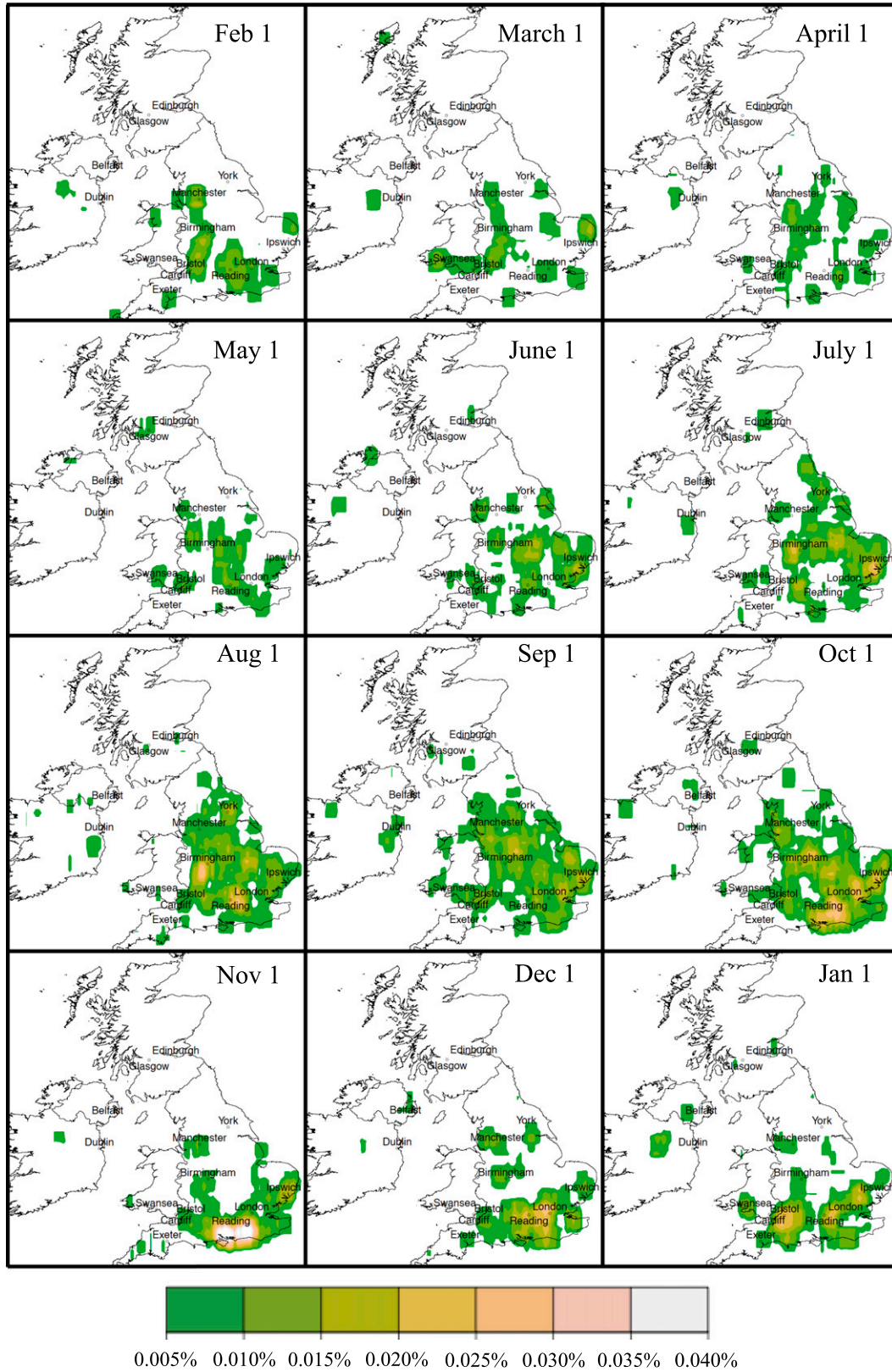
FIG. 6. Change in tornado percent probabilities on the first day of every month using a 15-day temporal and 50-km spatial smoothing parameter.
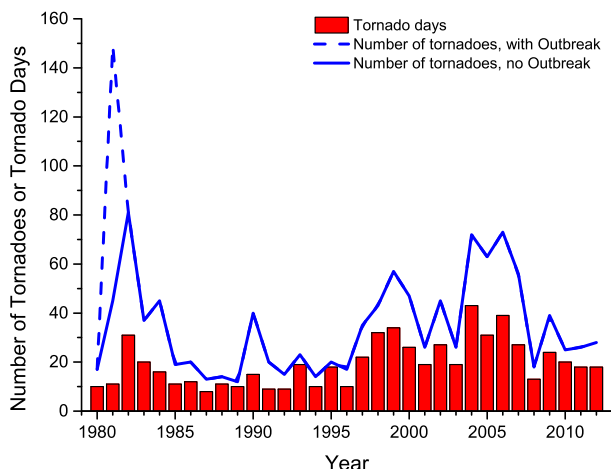
FIG. 7. Histogram of number of tornadoes and tornado days per year during 1980–2012. Number of tornadoes including the 1981 Outbreak are shown as a dashed line (*n* = 1235). Number of tornadoes not including the 1981 Outbreak are shown as a solid line (*n* = 1131). Tornado days are shown as columns (*n* = 642).
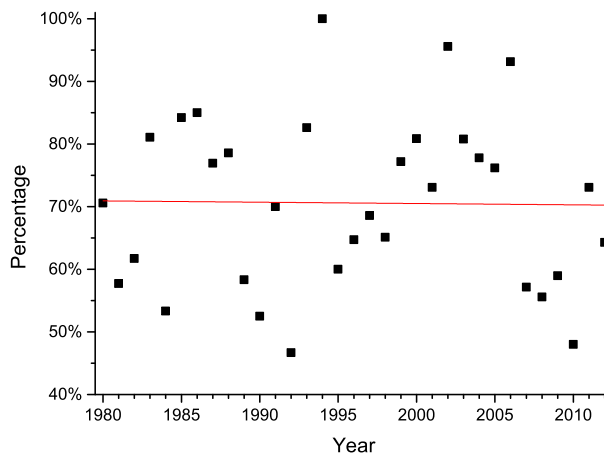

FIG. 8. Scatterplot of the percentage of all tornado cases that are definite (as opposed to probable) by year, 1980–2012. The best-fit line is also shown.

ie/nationalwarnings/warnings-explained.asp). Instead, wind and rain (and thunderstorm, in the Republic of Ireland) warnings are issued because these hazards pose a greater risk, partially because of their more common occurrence and larger area affected. Additionally, hazards from wind and rain occur simultaneously with tornado threats.

6. Temporal analysis

The following sections discuss when tornadoes and outbreaks occur in the British Isles.

a. Annual variation

The number of tornadoes by year, including the 1981 Outbreak, ranged from 12 in 1989 to 149 in 1981 with a mean of 37.4 and a median of 26 tornadoes per year. Not including the 1981 Outbreak, the maximum annual tornado occurrence was 81 in 1982 with a mean of 34.3 and a median of 26 tornadoes per year. A mean of 19.5 and median of 18 tornado days occurred annually with a minimum of 8 in 1987 and a maximum of 43 in 2004. The mean tornado numbers and days per year were lower than that of Kirk (2007) because waterspouts were not included in this article. The mean tornado numbers and days differed from that of Kirk (2014) because this article included different years (Table 1) and handled the data differently.

There was evidence of a stepwise increase in tornado cases between 1980–96 and 1997–2012 (Fig. 7). The mean number of tornadoes per year, not including the 1981 Outbreak, increased from a mean of 26.6 and a median of 20.0 in 1980–96 to a mean of 42.4 and a median of 41.0 in 1997–2012. The means did not differ

significantly when including the outbreak (*p* = 0.31), but significantly differed when the outbreak was omitted (*p* < 0.01). Mean annual tornado days differed significantly (*p* = 0.02) between 1980 and 1996 with a mean of 13.5 and a median of 11.0 and 1997–2012 with a mean of 25.8 and a median of 25. The increase in tornado cases could be explained by increased awareness and interest in tornadoes due to the popular film *Twister* released in July 1996 in the United Kingdom.

There did not appear to be a difference in the percentage of definite (versus probable) tornadoes during 1980–2012 (Fig. 8), indicating that social media and the prevalence of phones with cameras, which have gained popularity in the past five years, have not necessarily led to an observed increase in reporting or verification of tornadoes. In fact, there was a significant decrease in the mean percentage of definite tornadoes in the last five years studied (*p* = 0.02).

All previous U.K. tornado climatologies including 20 years or more of data, not including waterspouts, cite a mean of between 27 and 37 tornadoes per year (Table 1). These means are comparable to the means found herein, providing evidence that the dataset has stabilized since the 1997 step function increase.

England averaged 2.2 tornadoes per year per $10\,000\,km^2$, more than the 1.3 per year per $10\,000\,km^2$ in the United States (including Alaska and Hawaii, 1991–2010; NCDC 2014). Because the frequency of occurrence of tornadoes in the United States is higher east of the Rocky Mountains, the country as a whole averaged fewer tornadoes per area compared to England. For comparison, Oklahoma, in "Tornado Alley," had an average of 3.5 tornadoes per year per $10\,000\,km^2$. Including the rest of the British Isles, there were 1.2
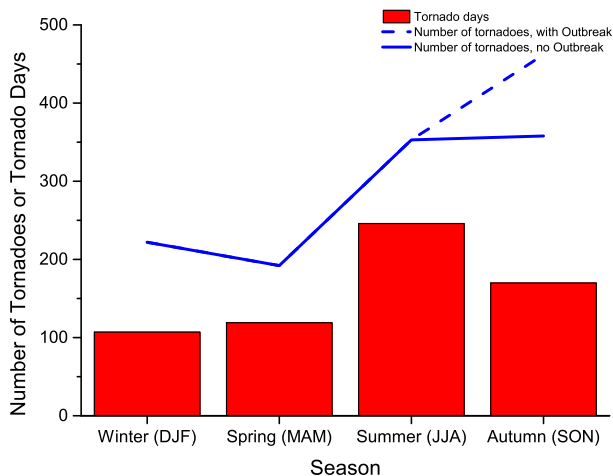
FIG. 9. Histogram of the number of tornadoes and tornado days by season. Number of tornadoes is shown both including the 1981 Outbreak (dashed line, $n = 1229$) and not including the 1981 Outbreak (solid line, $n = 1125$). Tornado days are shown as columns ($n = 642$).
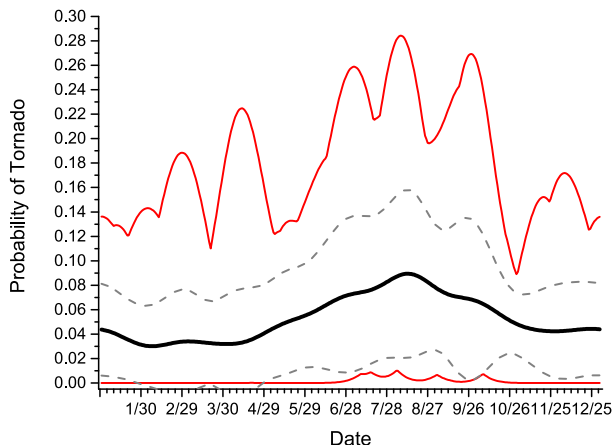

FIG. 10. Probability of a tornado day occurring anywhere in the British Isles by temporally smoothing tornado occurrence data using a 15-day moving window. Probabilities are expressed as a decimal between 0 and 1. The bold black line is the mean, dashed lines are the mean plus and minus one standard deviation, and the red solid lines are maximum and minimum values.

tornadoes per year per $10\,000\,km^2$, comparable to the value for the entire United States.

b. Monthly distribution

Tornado season in the British Isles depends upon the inclusion of the 1981 Outbreak and the use of tornado numbers or tornado days. With the outbreak, the season with the highest number of tornadoes (37.6%) was autumn (Fig. 9), consistent with Reynolds (1999), Kirk (2007), and Kirk (2014) (Table 1). Removing the outbreak, there were nearly equal tornado numbers in the summer and autumn (31.4% and 31.8%, respectively), consistent with Tyrrell (2003) (Table 1). Conversely, the season with the highest proportion of tornado days (38.3%) was summer (Fig. 9), consistent with Kirk (2014) (Table 1).

Smoothing all tornado occurrence data with known dates ($n = 1183$) temporally following Eq. (2) yielded the probability of a tornado day occurring anywhere in the British Isles any day of the year, represented as a decimal between 0 and 1 (Fig. 10). The probability of a tornado day doubled from 0.04 in January to 0.08 in August, which makes May through October appear to constitute a "tornado season." For comparison, the decimal probability of tornadoes in the United States increased from almost 0.2 to approximately 0.9 from 1 January to mid-June (Fig. 11). The nearly fivefold increase in tornado probabilities indicates a more distinct tornado season in the United States compared to the twofold increase in the British Isles. Additionally, the probability of tornado days in the British Isles from September to December was nearly constant (Fig. 10).

Although there is a slight seasonality to tornado days, tornadoes occur year-round in the British Isles.

c. Diurnal distribution

Of the 669 tornadoes in the British Isles for which the time of occurrence was known, including the 1981 Outbreak, 77.6% occurred during the daytime between 0800 and 2000 UTC (Fig. 12). There was a maximum in tornado occurrence in the late morning and afternoon with 57.5% of tornadoes touching down between 1100
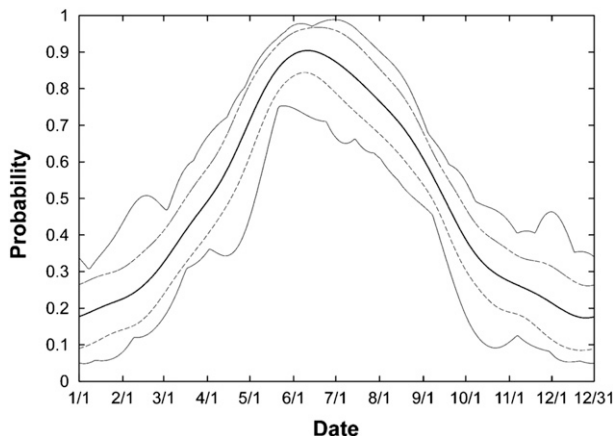

FIG. 11. Probability of a tornado day anywhere in the United States, smoothing tornado touchdown data during 1980–99 using a 15-day moving window. Probabilities are expressed as a decimal between 0 and 1. Similar to Fig. 10, the bold black line is the mean, dashed lines are the mean plus and minus one standard deviation, and the thin solid lines are maximum and minimum values [from Brooks et al. (2003a)].
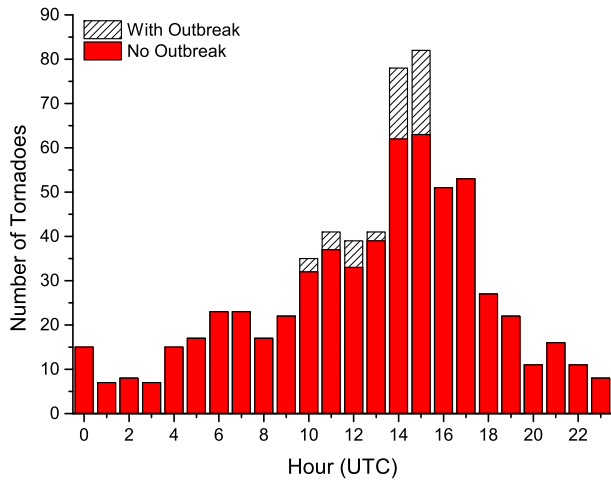
FIG. 12. Histogram of diurnal distribution of tornado cases including the 1981 Outbreak (hashed columns, $n = 669$) and not including the 1981 Outbreak (solid columns, $n = 619$).

and 1759 UTC, the same percentage as Kirk (2014). Excluding the 1981 Outbreak, 54.6% of tornadoes occurred between 1100 and 1759 UTC, resembling the distribution including the outbreak.

By season, an afternoon peak in tornado activity occurred in spring, summer, and autumn (Figs. 13a, 13b, and 13c, respectively). In the winter, tornadoes occurred consistently through the day and night, except for a dip before midnight and at 0100 UTC (Fig. 13d). The British Isles are between 49° and 60° latitude so there are less than 8 h of daylight in the winter. Because tornadoes were reported throughout the night, especially in winter, there likely was not a reporting bias toward daytime tornadoes.

d. Tornado outbreaks

There was a mean of 2.5 and a median of 2 tornado outbreaks (3 or more tornadoes in a day) per year with 12.8% of tornado days being outbreak days (Fig. 14). Omitting the 1981 Outbreak, all tornado outbreaks consisted of fewer than 30 tornadoes and 90.2% of outbreaks had fewer than 10 tornadoes. The probability of exceedance of a 29-tornado outbreak was 0.3%, meaning a 104-tornado outbreak would be unlikely and rare, although still possible.

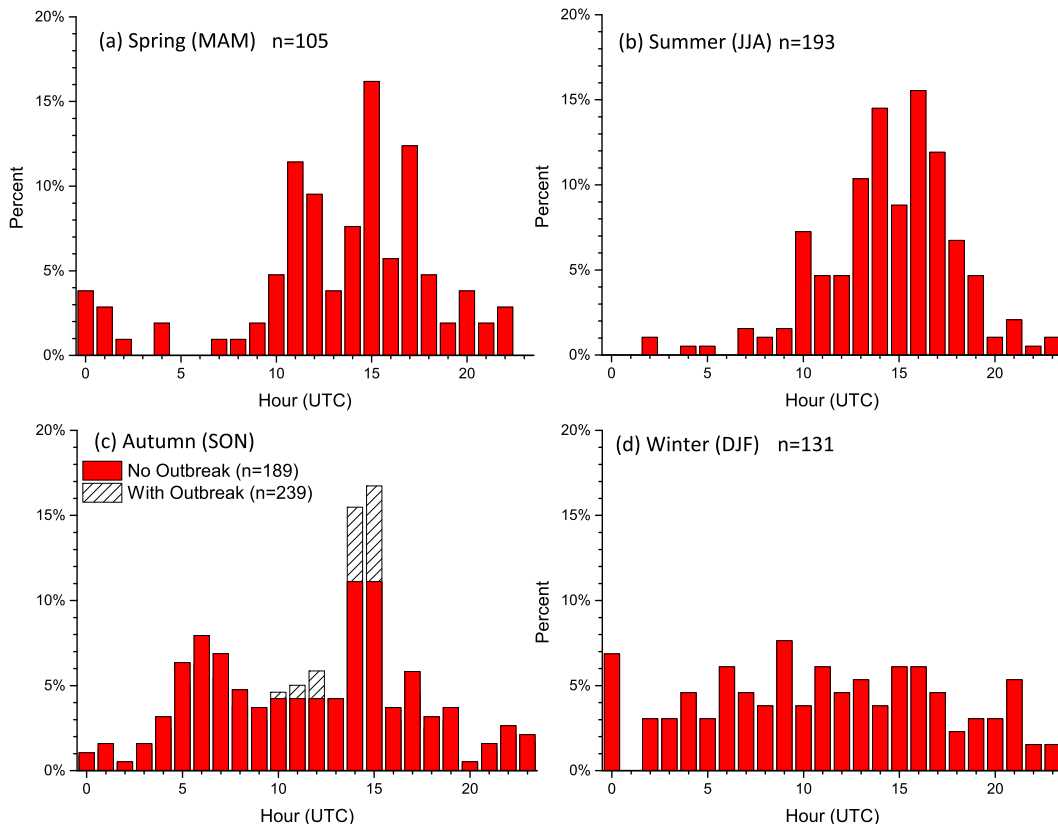Tornado outbreaks, 51% of which were produced by linear storms, occurred year-round with a maximum of

FIG. 13. Histogram of diurnal distribution of tornado cases in (a) spring, (b) summer, (c) autumn, and (d) winter. In autumn, the distribution is shown both including the 1981 Outbreak (hashed columns) and without the 1981 Outbreak (solid columns).
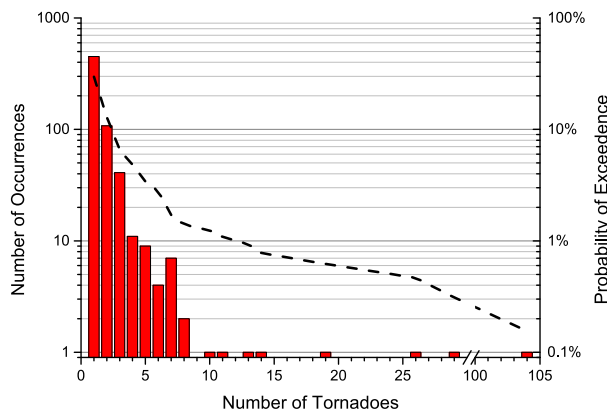
FIG. 14. Number of tornadoes occurring on each of the 642 tornado days, defined as 0000–2359 UTC during 1980–2012. Number of occurrences is on the left-side y axis. The probability of exceedance, presented as percent probability, is shown as the dashed black line corresponding to the right-side y axis.
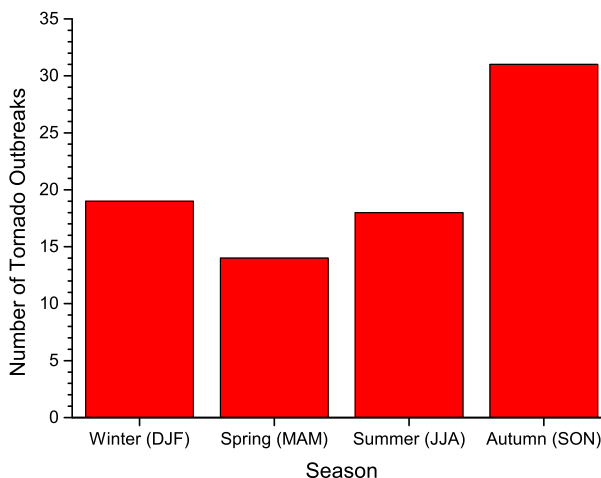

FIG. 15. Histogram of number of tornado outbreaks, defined as three or more tornadoes in one day, by season in which they occurred. There are a total of $n = 82$ outbreaks, including the 1981 Outbreak.

13 outbreaks in November and a minimum of 3 in May. Seasonally, outbreaks most commonly occurred in autumn than the rest of the year, when the number of outbreaks was nearly constant (Fig. 15).

7. Intensity

Tornadoes ranged from T0 to T5 (F0–F2) in intensity, a maximum intensity less than the United States (Fig. 16). Of the 608 tornadoes with known intensities, 95% ($n = 577$) were between T0 and T3 intensity (F0–F1), comparable to the 90% of tornadoes between T1 and T3 intensity that Kirk (2014) found. Only 5% of tornadoes ($n = 29$) during the study period were significant [T4–T5 or F2 intensity, after Hales (1988)].

Figure 16 is a log–linear graph showing the number of tornadoes of each T-scale rating by decade. Each decade was normalized to 100 T2 tornadoes to more easily compare the slopes of tornado intensity. The slope was nearly log–linear in the United States (Fig. 16), which Brooks and Doswell (2001) hypothesized to signify a nearly complete tornado dataset. In the British Isles, there were too few weak tornado cases for the slope to be log–linear. The T0 and T1 (F0) tornado cases increased from 31% in the 1980s to 43% in the 1990s to 56% in the 2000s. The increase of weak tornado cases signified less underreporting of weak tornadoes; however, the British Isles tornado dataset still appears less complete than that of the United States, assuming that log–linear implies completeness of the dataset.

Brooks and Doswell (2001) also discussed the differences in slopes of log–linear intensity graphs for different regions in the United States and different countries worldwide (their Figs. 3 and 4, respectively). They

speculated that differences in slopes relate to the type of storms from which tornadoes are produced: steep slopes representing regions dominated by nonsupercell tornadoes and less steep slopes representing regions dominated by supercell tornadoes. The slope of the British Isles log–linear intensity graph in each decade was steeper than that of the United States (Fig. 16), suggesting that the British Isles was dominated by nonsupercell tornadoes.
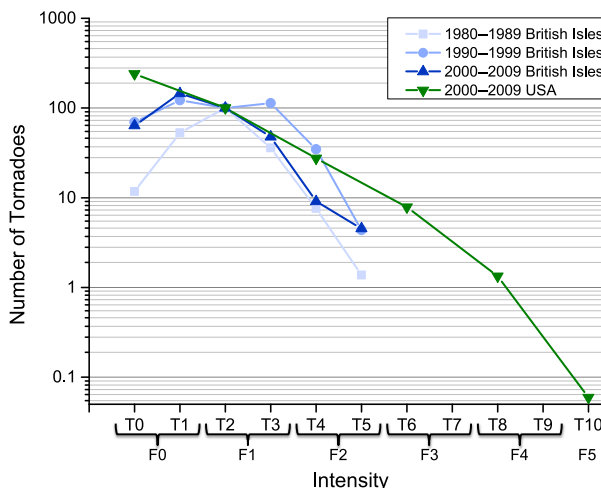

FIG. 16. Tornado cases by the tornado intensity (T) scale for the British Isles and the United States by decade. Conversion to the Fujita (F) scale is also shown. U.S. F-scale ratings were converted to the T scale by $T \approx 2F$. Tornadoes with intensity information were used for the British Isles ($n = 569$, including the 1981 Outbreak) and United States ($n = 14\,116$). Tornado numbers were scaled to 100 T2 tornadoes to easily compare slopes.

One reason the British Isles had weaker tornadoes than the United States is because British Isles tornadoes most commonly came from linear storms, which tend to be weaker than tornadoes from isolated cells, especially supercells (Trapp et al. 2005; Grams et al. 2012). Indeed, of the 228 cases included in the parent storm analysis where intensity information was known, 5% of tornadoes from isolated cells were significant, whereas only 2% of tornadoes from linear storms were significant. However, we cannot verify whether the parent storms in section 4 were supercells because Doppler velocity data were unavailable. Another reason for weaker tornadoes in the British Isles is the weaker instability compared to environmental soundings of tornadoes in the United States, discussed further in section 8.

8. Environmental parameters derived from proximity soundings

To determine environments conducive to tornadoes in the British Isles, sounding-derived parameters were calculated for tornadic and nontornadic (null) convective storms using upper-air observations provided by the University of Wyoming. We adopted the same proximity criteria as in Brooks (2009): soundings within 3 h and 180 km of the case. Because the date, time, and location of the tornado were required, tornado cases without those data were omitted, leaving 659 tornadoes, 53% of all tornado cases, for the proximity analysis. After applying the proximity criteria and removing duplicate soundings, 438 tornado-case soundings remained.

All hourly surface SYNOPs in the British Isles during 1980–2012 reporting current thunderstorm or hail, which ensured the timing and location of the event was known, were chosen as potential null cases ($n = 938$). After applying the same proximity criteria as tornado cases to station locations and removing duplicate soundings, 773 null case soundings remained.

Because we wanted to study the air mass producing the null or tornadic convective thunderstorm, soundings showing an airmass change (e.g., postfrontal soundings in the case of storms occurring in the prefrontal environment) were omitted. To help identify postfrontal soundings, Met Office surface analyses were cross checked for front locations, when available. Additionally, if observations that affected calculations of parameters (discussed shortly) were missing, the sounding was also omitted. After removing soundings not representing the null or tornadic environment or incomplete soundings, 393 null and 188 tornadic soundings remained. Of the tornadic soundings, 46 represented outbreak days and 7 represented significant tornado environments.

Parameters calculated in the radiosonde analysis were low-level (0–1 km) and deep-layer (0–6 km) bulk shear (i.e., the vector difference in wind between levels), convective available potential energy (CAPE) with virtual temperature correction (Doswell and Rasmussen 1994), convective inhibition with virtual temperature correction (CIN), height of the lifting condensation level (LCL), and height of the level of free convection (LFC). CAPE, CIN, LCL height, and LFC height were calculated from a mean temperature and dewpoint temperature from the bottom 500 m of the sounding (http://weather.uwyo.edu/upperair/indices.html). Parameters were analyzed separately for null, tornado, outbreak, and significant tornado soundings to compare environments.

There was no significant difference in low-level shear between null, tornado, outbreak, and significant tornado cases ($p > 0.05$, Fig. 17a). Similarly, Clark (2013) found that differences in 0–1-km and 0–3-km shear between tornadic and nontornadic cold season convective lines in the United Kingdom were not significant. Although Craven and Brooks (2004) suggested $10 \, \text{m s}^{-1}$ of low-level shear as a threshold for significant tornadoes in the United States, only 3 of the 7 (43%) significant tornadoes in the British Isles occurred in environments exceeding that threshold. An alternative threshold cannot be given because the differences between these groups were not statistically significant ($p > 0.05$).

Mean deep-layer bulk shear was $20.5 \, \text{m s}^{-1}$ for tornado cases and $23.3 \, \text{m s}^{-1}$ for null cases (Fig. 17b). The mean deep-layer shear in tornado cases was significantly less than that for null cases ($p = 0.01$). Although significant tornadoes appeared to have higher deep-layer shear than null, tornado, and outbreak cases, these relationships were not statistically significant ($p > 0.05$) due to the small sample size of significant tornadoes. All but one deep-layer shear value for significant tornadoes was higher than $20 \, \text{m s}^{-1}$, the threshold Craven and Brooks (2004) cited for significant tornadoes. Although 42% of all tornado soundings had a deep-layer shear greater than $20 \, \text{m s}^{-1}$, 7.8% of all tornado soundings with greater than $20 \, \text{m s}^{-1}$ deep-layer shear were associated with significant tornadoes. In contrast, 0.9% of all tornado events with less than $20 \, \text{m s}^{-1}$ deep-layer shear were associated with significant tornadoes, suggesting that significant tornadoes rarely occur in the British Isles with less than $20 \, \text{m s}^{-1}$ deep-layer shear.

Mean CAPE in tornado and outbreak cases was significantly higher than in null cases ($p < 0.01$, $p = 0.02$, respectively, Fig. 17c). However, zero CAPE did not preclude tornado cases. Significant tornadoes all had nonzero CAPE with a mean of $81.6 \, \text{J kg}^{-1}$ and a median of $39.7 \, \text{J kg}^{-1}$, larger than a mean of $99.7 \, \text{J kg}^{-1}$ and a median of $18 \, \text{J kg}^{-1}$ for all tornado cases. However,
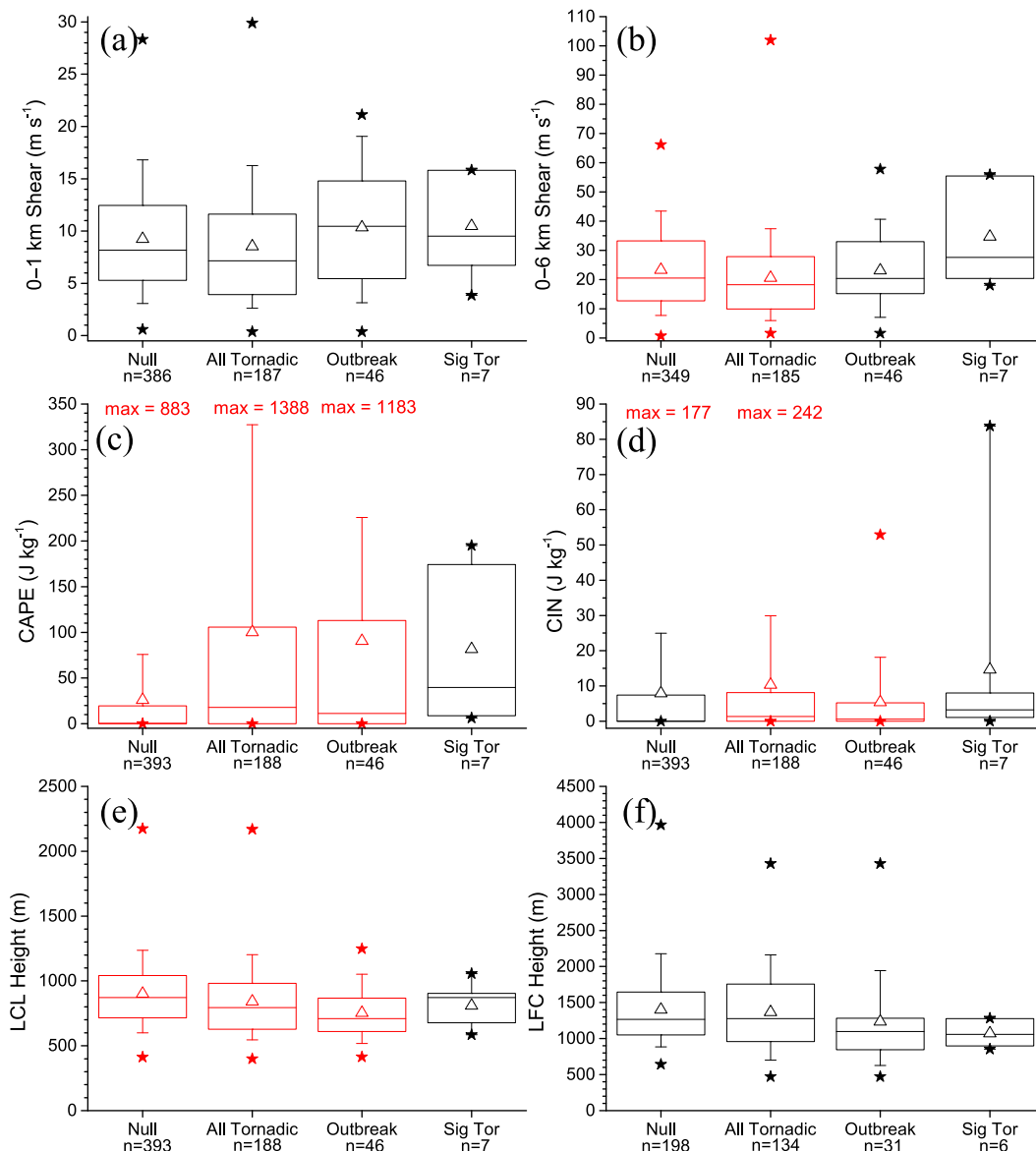
FIG. 17. Selected parameters from proximity radiosondes representing convective storms without a tornado (null), tornadic storms (all tornadic), tornadic storms that occurred on an outbreak day (outbreak), and tornadic storms that produced a T4+ or F2 tornado (sig tor). The top and bottom of the boxes represent the 75th and 25th percentile, respectively. The bar in the middle of the box is the 50th percentile. The triangle is the mean. The whiskers above and below the box represent the 90th and 10th percentile, respectively. Stars represent the maximum and minimum values in the dataset. Red coloring represents statistically significant differences in means ($p < 0.05$). Black coloring represents differences in means that are not significant ($p > 0.05$). More details on results of statistical tests appear in the text. The parameters shown are (a) low-level (0–1 km) bulk shear, (b) deep-layer (0–6 km) bulk shear, (c) mixed-layer CAPE with the virtual temperature correction, (d) CIN with the virtual temperature correction, (e) LCL height, and (f) LFC height.

because of the small sample size, CAPE in significant tornado cases did not differ statistically significantly from that for all tornado cases ($p > 0.05$). In the continental United States, significant tornado mean-layer CAPE values were higher than in the British Isles and can exceed 4000 J kg^{-1} with a median just over

1000 J kg^{-1} (Grams et al. 2012, cases from 2000 to 2008) compared to a median of 39.7 J kg^{-1} for significant tornadoes in the British Isles.

Null, tornado, and outbreak cases did not appear to have separate parameter space when combining CAPE and deep-layer shear (Fig. 18). Although high
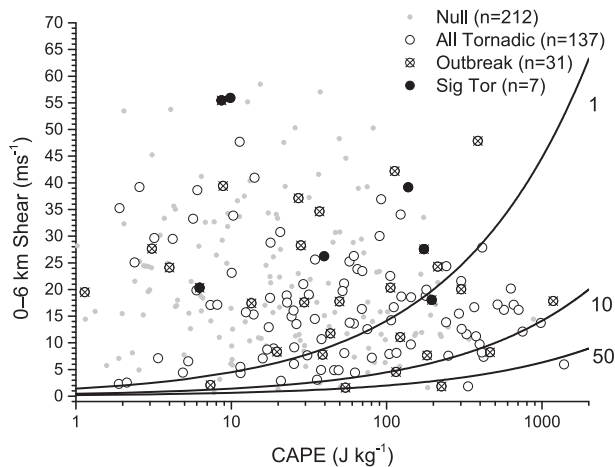
FIG. 18. Mixed-layer CAPE with the virtual temperature correction plotted against deep-layer (0–6 km) bulk shear for null, all tornado, outbreak, and significant tornado cases. Only nonzero CAPE cases are shown. Lines of constant bulk Richardson numbers of 1, 10, and 50 are shown as black lines.

deep-layer shear and nonzero CAPE appeared to discern significant tornadoes, there were too few cases to make a definitive classification. Additionally, there did not appear to be a threshold of bulk Richardson number (BRN, defined as a unitless ratio of CAPE to deep-layer shear; Glickman 2000) between null, tornado, outbreak, and significant tornado cases with 99% of null and 82% of tornado cases with a BRN less than 10. Weisman and Klemp (1982) found that supercells are favored with BRN between 10 and 50 and multicellular storms for BRN greater than 45. BRN values less than 10 were found to have too strong of shear for storm development (Weisman and Klemp 1982). Because the majority of tornadic storms in the British Isles occur with BRN less than 10, perhaps these thresholds are not relevant. Additionally, the low-CAPE, high-shear tornado environment could explain the lower intensity of tornadoes compared to the United States.

There was no significant difference in mean CIN between the null and tornado cases ($p = 0.25$, Fig. 17d). Conversely, tornadic supercells east of the Rocky Mountains in the United States had less CIN than nontornadic cases (Davies 2004). CIN values in British Isles tornado cases, with a mean of $10 \, \mathrm{J \, kg^{-1}}$, were smaller than those in the United States, with a mean of $30 \, \mathrm{J \, kg^{-1}}$ (Grams et al. 2012). Tornado outbreaks in the British Isles had less mean CIN than in all tornado cases ($p = 0.02$). However, because the difference in means was small, CIN is not a useful forecasting parameter for tornado outbreaks.

The mean LCL heights in tornado and outbreak cases were lower than in null cases ($p = 0.01$ and $p = 0.01$,

respectively, Fig. 17e). Additionally, outbreak mean LCL heights were lower than that for all tornado cases ($p < 0.01$). However, there were no significant differences between mean significant tornado LCL heights and all tornado cases ($p > 0.05$). In contrast, in the contiguous United States, significant tornadoes tended to have lower LCLs than all other cases with 75% of significant tornado cases occurring with LCL heights less than 1200 m AGL (during 1997–99; Craven and Brooks 2004). In 90% of tornado and 88% of null cases in the British Isles, LCL heights were less than 1200 m, making the 1200 m AGL threshold for significant tornadoes suggested by Craven and Brooks (2004) of little forecasting use in the British Isles. We do not suggest an alternative threshold for LCL height to distinguish between null and tornado cases because the difference in means was small, even though it was statistically significant.

The mean LFC height did not differ significantly between null and tornado cases ($p > 0.05$, Fig. 17f). Although outbreak and significant tornado cases appeared to have lower LFC heights than all tornado cases, these were also not statistically significant ($p > 0.05$). Similar to LCL heights, LFC heights tended to be lower in the British Isles than in the United States, where the median LFC height for supercells with F0–F1 tornadoes was 1871 m and nontornadic supercells had a median LFC height of 2338 m (Davies 2004). In the British Isles, 84% of null and 82% of tornado cases were below 1871 m.

Because of the lack of clear thresholds, forecasting tornadoes in the British Isles based solely on sounding-based parameters is more difficult than doing so in the United States. The exception is that significant tornadoes are unlikely in deep-layer shear of less than $20 \, \mathrm{m \, s^{-1}}$.

9. Summary

This paper analyzed 1241 tornadoes during 1980–2012 in the British Isles to determine when, where, from what parent storm, and in what environment tornadoes form, finding the following:

- There were a mean of 34.3 and a median of 26 tornadoes, a mean of 19.5 and a median of 18 tornado days, and a mean of 2.5 and a median of 2 outbreaks per year over the 33 years.
- Tornadoes were most common in summer and autumn, whereas tornado days were most common in summer. However, tornadoes occurred throughout the year, so the British Isles tornado season was not as well defined as the United States.
- Tornado outbreaks were most common in autumn.
- The most common storm morphology producing tornadoes in the British Isles was linear storms

(42%), contrary to the United States, where only 18% of tornadoes were produced from linear storms (Trapp et al. 2005).

- Tornado outbreaks were produced by linear storms 51% of the time. Outbreaks consisted of relatively few tornadoes with 90.2% consisting of 3–10 tornadoes.

- Tornadoes in the British Isles were weaker than those in the United States, likely because linear storms tend to produce weaker tornadoes than supercells (Trapp et al. 2005; Grams et al. 2012) and because of the weaker instability in the British Isles compared to that in the United States.

- Tornadoes in the British Isles are more difficult to forecast using sounding-based parameters than they are in the United States because of the lack of clear thresholds between null and tornadic events. The exception is in forecasting significant tornadoes, which are unlikely to occur in deep-layer shear less than $20\,\mathrm{m\,s^{-1}}$.

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