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UK tornado climatology and the development of simple prediction tools

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SUMMARY

The principle features of tornado climatology in the UK are presented based on the 5-year period from January 1995. Just over one third of reported tornadoes occurred in the south-east region of England, and most tornado activity took place during the spring and summer while the least activity occurred during autumn. This was different to the seasonal distribution for the period from 1960 to 1989 when autumn had the greatest number of tornadoes. The reported tornado distribution was shown to be significantly affected by topography and the density of potential observers. Of the ground-based meteorological variables tested, air temperature was most closely related to tornado occurrence with a peak at 13 °C. An equation incorporating air temperature, dew-point temperature, wind speed and pressure was shown to predict a tornado day with an accuracy of 86.2%. The probability that a tornado would occur on a predicted day was 81.2%. The model was used to predict actual tornado occurrences across England, Wales and Scotland during the 5-year study period, and it was estimated that just over five-times as many tornadoes occurred than were reported. The model results suggest that the bias induced by population density was not greater than the combined influence of topography and spatial setting. This is important in the UK, because most tornadoes are reported in lowland areas which are heavily populated and it has been difficult until now to determine the extent to which tornado reports are biased by the density of potential observers.

KEYWORDS: Binary logistic regression Climate modelling Population bias Tornado distribution Tornado frequency

1. INTRODUCTION

Tornadoes are by no means unusual climatic phenomena in the British Isles and have been reported since 1091. There were a mean of 33 recorded events per year and 15 ‘tornado days’ per year between 1960 and 1989 (Reynolds 1999; Elsom *et al.* 2001). Thus there are more reported tornadoes per unit area in Britain than in the USA although British tornadoes tend to have a lower intensity and duration (Meaden 1985). Meteorologists have studied tornadoes over the past 50 years in an attempt to improve our understanding of their character, behaviour and potential threat to the built environment and human life (Snow and Wyatt 1998). Continued research in this field is, therefore, crucial if effective monitoring and forecasting techniques are to develop. To improve such methods it is essential to be able to recognize favourable climatic conditions under which tornado events are likely to be spawned. Tornadoes are often associated with extreme atmospheric vertical instability. This often occurs when cold drier air overrides warmer moist air such as with squall-line thunderstorms (Church *et al.* 1993). Davies-Jones (1985) demonstrated theoretically that the interaction between streamwise vorticity and a strong updraught leads to rotation, and this has been supported by observational studies (e.g. Rasmussen and Blanchard 1998). Air temperature, atmospheric pressure, dew-point temperature and local wind speed are all recognized meteorological variables suggested as influential on tornado genesis and development. Moisture is invariably a key factor in identifying regions with potential for strong deep convection, and surface dew-point temperature is widely considered a better indicator than relative humidity (e.g. Markowski 2002; Brookes *et al.* 2003).

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However, the role of these variables has not previously been examined in association with UK tornadoes.

Although tornadoes may occur in any season in Britain, Reynolds (1999) suggested that activity was most frequent in autumn, based on data for 1960–89 inclusive. During the British autumn, north-easterly cold air flows over relatively warm seas. Occasional surges of very warm, moist air also flow from more southerly latitudes, and cold polar air starts to reappear at higher levels in the atmosphere (Reynolds 1999). These climatic conditions, as well as a strengthening jet stream in autumn (Reynolds 1999), produce atmospheric instability, a fundamental necessity for tornado development. Such a setting has been associated with the UK's largest tornado outbreak on 23 November 1981, when 105 tornado sightings were reported; a record multiple tornado outbreak which occurred during the 6-hour passage of a very active cold front (Rowe and Meaden 1985).

Other factors may play a role in the frequency distribution of tornado reports in the UK. These include topography and population density. British tornadoes have been generally associated with relatively flat terrain and rolling hills (Reynolds 1999). This type of landscape allows smooth airflows which many believe encourage tornado development. Reynolds (1999) assigned, in part, the highest reported tornado frequencies during the period 1960–89 to this type of terrain, in East Anglia, south-east England, central-southern England and south-west England. In contrast, the turbulent airflows more likely in steeper landscapes could prevent circulation in the clouds aloft from reaching ground level, thus reducing the potential for tornado development. However, while there has been much discussion concerning the role of surface topography on tornado occurrence the question of this relationship still remains open. Of course, flat terrain improves visibility of tornadoes by increasing the area over which they are visible.

Some, perhaps many, tornadoes may go unseen or unreported in the UK (Elsom, *et al.* 2001). There is, therefore, a problem in that the spatial distribution of tornado reports may be biased by the spatial unevenness of population density. King (1997) found no relationship between population density and tornado totals in south-central Canada. Brookes and Doswell (2001) assumed that 65 to 80% of actual tornadoes are reported in the UK but that only 15% of French tornadoes are currently being reported. UK tornadic events tend to be localized and short-lived, reducing the likelihood of their observation by radar or detection by ground-station (Elsom and Meaden 1984). Typically only the most devastating British tornadoes are reported correctly. In areas of higher population, tornado sightings are likely to be more common than in rural areas. In the UK this may add bias to the distribution, because the most heavily populated areas tend to be those with gentle topography and are therefore more likely to generate tornadoes. Spatial analysis of events during the 1960–89 period, shows that the majority of the counties with highest tornado frequencies were in East Anglia, Lincolnshire, Essex and south-eastern regions of England (Reynolds 1999), all of which have average county population densities exceeding 240 persons km^{-2} (Champion *et al.* 1996). In contrast, many counties in Northern Ireland and Scotland had no reported tornadoes during the 1960–89 period (Reynolds 1999); these are regions averaging less than 120 persons km^{-2} (Champion, *et al.* 1996).

Some tornadoes may occur during darkness preventing them from being witnessed (Elsom and Meaden 1984; Pike 1998). In the most recent UK tornado climatology, Reynolds (1999) documents 42% of the total tornado sightings, based on 1960–89 data, occurring between 1200 and 1659 UTC. This reflects the period of the day when the air temperature reaches its maximum. Less than 3% of tornadic activity was reported between 1800 and 0559 UTC. The extent to which this is biased by observational difficulties is unknown. Tornadoes can be witnessed and recognized but not reported, or in other instances tornadoes can be seen but go unrecognized. A clearly defined vortex can frequently be obscured by debris, buildings or precipitation (Elsom and Meaden 1984), reducing the chance of it being reported. Other whirlwind types such as waterspouts, funnel clouds and wind-devils can also be misclassified as tornadoes; a rotating vortex of strong winds is only termed a tornado when it is in contact with the ground. Because of the wide range of reporting problems Elsom and Meaden (1982) speculated that the true frequency of tornadoes in the UK may be ten-times the number being reported. With better knowledge of true tornado frequency, climatologies will be improved, which in turn will facilitate future accurate forecasting of tornadoes in the UK.

This paper examines the spatial and temporal distribution of tornado observations in the UK for the period from 1995 to 1999 inclusive. It also examines whether tornado reports are significantly influenced by population density, and aims to estimate the extent of this influence. The paper will show how a simple model based on ground meteorological observations can be used to predict tornado days. These results will then be scaled up for the whole of the UK in order to estimate the real frequency of UK tornadoes, thus enabling a comparison with the number reported by observers.

2. Methodology

Observation reports were provided by the UK Tornado and Storm Research Organization for the period 1995–99. A total of 122 observations were listed on the database for this period and the date and location of each sighting was recorded. Tornado locations were analysed with reference to population density, altitude and slope index. To develop the slope index, 5 km^2 grid cells across the UK were analysed. For those cells containing a tornado (‘tornado cells’) the mean elevation was recorded as well as those of the eight surrounding grid cells. The mean slope angle was then calculated for each tornado cell (based on the angle between the tornado cell and the surrounding eight cells; all values were given as positive integers whether they were upslope or downslope). This was repeated for many cells which did not contain a sighting. These ‘no-tornado cells’ were selected systematically across the UK (every third cell) so that one third of all cells were analysed.

In order to ensure that tornado reports could be adequately related to population densities so that, for example, the effect of urban conurbations within an otherwise sparsely populated county could be examined, data for regional, county and urban administrative areas were taken from the 2001 UK census.

Surface air temperature, pressure, dew-point temperature and wind speed values were obtained for each site of a tornado report, by taking relevant values from the meteorological station closest to the reported tornado location. Observations were discarded if the station was situated more than thirty kilometres from the sighting, or if the specific climatic data was not all available. This resulted in eight of the original 122 tornadoes being eliminated from the dataset for this particular analysis. For every reported tornado sighting, the same climatic data was obtained for ten other randomly selected non-tornado days during the same year, for use in data analysis. This resulted in a total of 114 datasets for tornado days and 1140 datasets for non-tornado days.

Binary logistic regression examines the relationship between two categorical response variables and one or more predictors (Press and Wilson 1978). This technique produces a model in which parameter values are estimated in an attempt to optimize the model. In particular, logistic regression obtains maximum-likelihood estimates of the parameters using an iterative re-weighted least-squares algorithm (McCullagh and

Nelder 1992). A major aim of this paper is to detect the climatic conditions present on a tornado day and then use these parameter values to predict an ‘expected-tornado’ day. A binary variable has only two possible values (e.g. *tornado day* or *non-tornado day*) and one or more predictors (e.g. from wind speed, dew-point temperature, air temperature and pressure). Through this technique it is, therefore, possible to assess how well the meteorological values can be used to predict a tornado day. Alternatively discriminant analysis could be performed, but an advantage of using binary logistic regression for tornado analysis is that it is likely to give fewer classification errors (Press and Wilson 1978).

The tornado day category was assigned a binary value of ‘1’ and the non-tornado day category was assigned ‘0’. To ensure rigorous data analysis, the total dataset of 1254 meteorological values was split into a ‘training’ dataset and a ‘test’ dataset. 75 tornado day and 750 non-tornado day datasets were classed as the training set, and the remaining 39 tornado day and 390 non-tornado day datasets were categorized as the test set. All equation manipulation in order to obtain the most accurate prediction was performed on the training set. The test data provide independent values that can be used to test the equation and determine whether the predictions are reasonable. In an attempt to maximize the percentage of correctly predicted tornado days, the regression link function ‘logit’ was changed to ‘normit’ (the inverse of the cumulative standard normal distribution function) (McCullagh and Nelder 1992). This method slightly improved the percentage of correct predictions.

Before test data were run through the model it was necessary to determine the probability that a predicted tornado day would belong to the tornado group. To do this, the median values of data for tornado days and non-tornado days were found, and the difference between the upper and lower quartiles of each were calculated and divided by two. These values were then used to calculate how far data values, between 1 and 0, deviated from the median. In doing so, tornado day probability could be determined; this was given by those days where values greater than 0.5 were calculated. Below this a non-tornado day is more likely. Test data were then independently put through the resultant predictive equation, and the effectiveness on this dataset was analysed.

For the 5-year study period 130 meteorological stations were chosen for sampling. They were chosen in order to give an approximately full coverage of England, Wales and Scotland, so that each station was assumed valid for a 30 km radius. The sparse station coverage in some rural areas meant that this was difficult to achieve, but approximately 80% coverage was possible. The model was then run for these stations and the number of predicted tornado days was counted. This allowed an estimate of the number of tornadoes to be made for comparison with those actually reported across the UK during the study period.

3. Results

The following section presents the spatial and temporal frequency distributions of tornadoes in the UK for the period 1995–99. It then addresses the ‘simple’ meteorological aspect of tornado events, by showing how reported frequency relates to different climatic factors, and then how these were used to produce tornado day predictions.

(*a*) *Spatial distribution*

Figure 1 shows that reported tornado occurrence in the UK for the period 1995 to 1999 was concentrated in England (91%), with much lower numbers in Wales (5.7%) and Scotland (3.3%). At the regional-scale, the southern regions of England appear

Figure 1. Location of reported tornadoes for the UK 1995–99. There were no reports available for Northern Ireland.

TABLE 1. TORNADO OCCURRENCES ACROSS THE UK 1995–99

Region	% Tornado occurrences	Tornado occurrences per 10 000 km^2
South-east England	31	18.4
Central England	29	7.4
North England	16	5.3
South-west England	15	7.6
Wales	6	3.4
Scotland	3	0.5

to have had the greatest tornado occurrence during this period. Table 1 confirms that the south-east region of England occasioned just under one-third of all tornado reports during 1995–99, with Scotland having just 3%. The tornado frequency per unit area for each region is also shown in Table 1. This allows direct comparison of tornado occurrence between the six regions. Even after unit-area weighting, the south-east of England remains the region with the greatest tornado density.

A t-test comparing population density for English, Scottish and Welsh counties and urban areas with and without tornado reports shows a significant difference at $p = 0.004$. Low tornado incidence is associated with lower mean population densities; only 3% of total tornado occurrences were in Scotland where population density is largely under 200 people km^{-2}. Three of the four Scottish tornado sightings, however, occurred in the strip of higher population density stretching from Glasgow to the east coast near Edinburgh (Fig. 1). This 'population bias' may explain the higher tornado occurrence near large cities shown on Fig. 1, such as Glasgow, Newcastle and Birmingham, where all recorded sightings were located in areas where population density was greater than 500 people km^{-2}. This may also be the case in coastal towns, such as those on the southern coast of England, including Brighton, Newhaven and Portsmouth, where areas with population densities exceeding 1000 people km^{-2} recorded almost 40% of the south-east region's total tornado occurrences. This does not apply everywhere in the UK. Almost a third of total tornado activity (28.7%) occurred in areas where population density was less than 300 people km^{-2}, with nine events reported where population density was less than 200 people km^{-2}.

There appears to be a general association of tornado occurrence not only with regions where population density is higher but also where relief is lower and gentler such as in central and southern England. A more sparse distribution of tornadoes is associated with higher altitudes and more rugged terrain such as the Pennines in northern England, the Cambrian Mountains in Wales and the Grampian range of Scotland. Slope index analysis reveals that mean slope angles based on 5 km^2 grid cells in which tornadoes occur is significantly less than those for non-tornado cells ($p = 0.02$). Clearly there is a scaling problem here in that for cells of, say, 100 m^2 topographic roughness would be highlighted in a different way than for 5 km^2 cells. Nevertheless, this provides an indication of the role of topography. In terms of the mean altitude of every grid cell with and without a tornado there is again a significant difference at $p = 0.04$, with tornadoes mostly occurring at altitudes below 170 m (only eight tornadoes reported during the study period occurred at higher altitudes). However, the roles of population density and topography are very likely to be autocorrelated in that lower population densities occur in areas of high topographic roughness or altitude. Thus a meteorological approach is preferable to adopting a spatial approach based on statistical analysis of tornado reports.

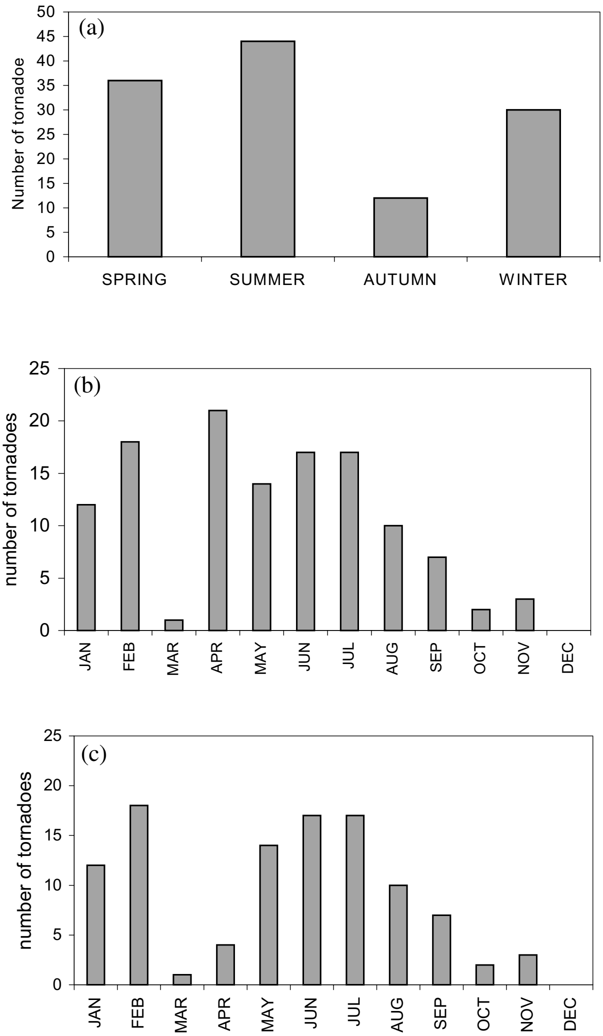

Figure 2. Monthly and seasonal tornado reports for the UK 1995–99: (a) total number of tornadoes per 3-month season; (b) total number of tornadoes by month; (c) total number of tornadoes but with the multiple outbreak of April 1998 removed.

(*b*) *Temporal distribution*

Tornadoes may occur in any season (Fig. 2), with most frequent activity during the study period being in summer (36%). Unlike the period 1960 to 1989 analysed by Reynolds (1999), where autumn had the greatest number of tornadoes, we found that the autumn quarter of the year had the lowest number of tornadoes during our 5-year period . Monthly tornado totals are shown in Fig. 2(b). While 24.6% of tornado activity occurs during winter (December, January and February), no events were recorded during December. Only one tornado occurred in March during the study period. The high figure for April can be partly accounted for by a multiple outbreak in 1998 when 17 tornadoes occurred during just 6 days, between 3 and 9 April. To detect any alteration to the seasonal totals due solely to this outbreak, these 17 tornadoes were eliminated from the monthly totals shown in Fig. 2(c). The trend then seems to become much

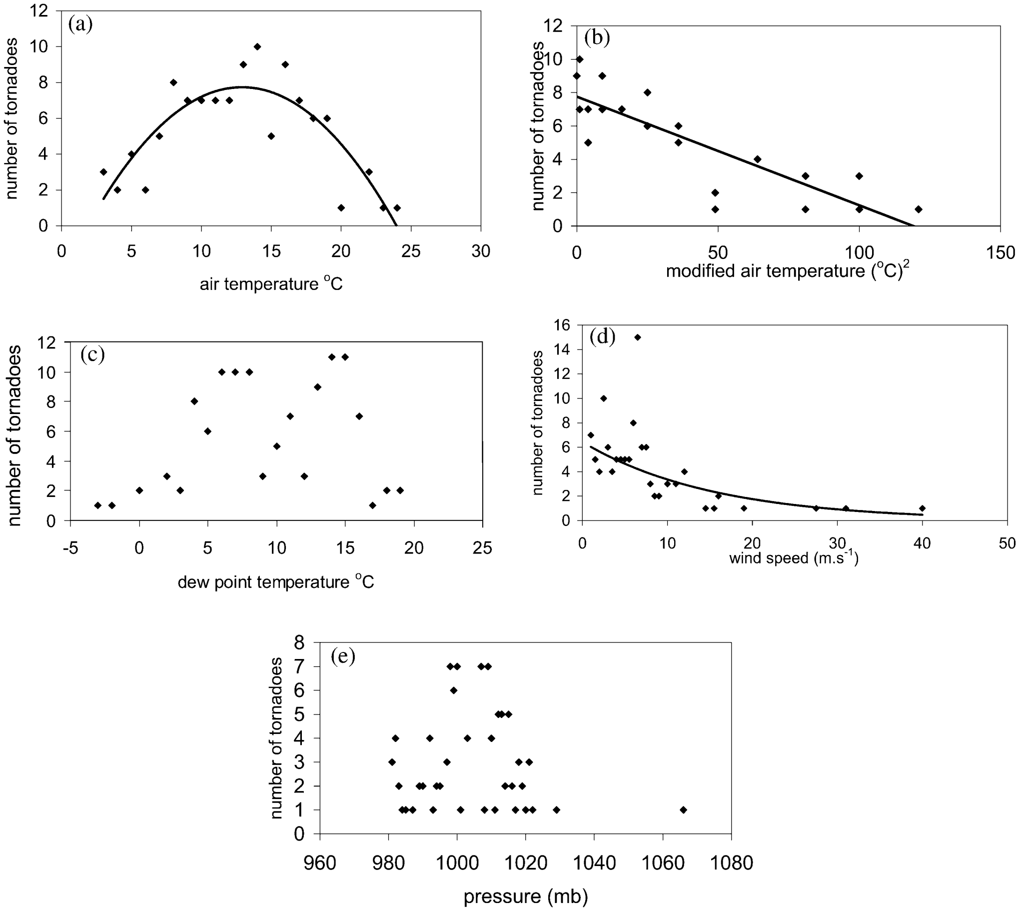

Figure 3. Relationship between the number of tornadoes reported in the UK 1995–99 and meteorological variables near the surface: (a) air temperature; (b) modified air temperature (see text); (c) dew-point temperature; (d) wind speed; (e) pressure.

more seasonal with a March to December cycle. However, the January and February tornadoes stand out as outliers to this seasonal trend. This suggests that temperature and seasonality might be significant controls on UK tornadoes, but that other factors dominate the control on January and February outbreaks (Paice 1998).

(*c*) *Local meteorological relationships*

Wind speed, air temperature, dew-point and pressure have all been highlighted as important climatic parameters for tornado development. Figure 3 shows plots of the relationship between each of these parameters and the number of tornadoes produced. Figure 3(a) shows that a high proportion of tornadoes occur when ground-level air temperature is from 10 to 15 °C with the modal number at 13 °C. To facilitate statistical analysis of these data, air temperature values were modified in order to produce a linear relationship (Fig. 3(b)). The modification took the form $(air\ temperature - 13)^2$. A two-sample T-test showed that modified air temperature on tornado days was significantly greater than that on non-tornado days. Linear regression resulted in an R^2 value of 0.72 with $p < 0.001$.

TABLE 2. MODEL PREDICTION QUALITY FOR TRAINING DATASET FOR LOGISTIC REGRESSION EQUATION

Pairs	Number	Percentage
Forecast event occurs	48 465	86.2
Forecast event does not occur	7482	13.3
Ties	303	0.5

The total number of predictions is equal to the number of tornado day sets (75) multiplied by the number of non-tornado day sets (750). See text for details.

Figure 3(c) reveals that as dew-point temperature increases the number of tornado occurrences also appears to increase until the dew-point reaches about 15 °C. At higher dew-point temperatures tornadoes are rarely reported. That said, tornado days tend to have significantly higher dew-point temperatures than non-tornado days ($p = 0.01$). Air mass conditions associated with low wind speeds near ground level appear to be associated with tornado frequency (Fig. 3(d)). Only seven tornadoes occurred when wind speeds (not in the immediate vicinity of the tornado) were greater than 13 m s^{-1}, with the majority occurring when wind speeds were between 1 and 8 m s^{-1}. Despite this, the mean wind speed on a tornado day was found to be significantly greater than that on a non-tornado day ($p < 0.001$).

Figure 3(e) shows there to be little relationship between atmospheric pressure and tornado occurrence. In general, tornadoes are produced at MSL pressures of between 980 and 1030 hPa, although there is one anomaly when air pressure was exceptionally high at 1066 hPa. Although Fig. 3 suggests that only air temperature has a strong effect on tornado occurrence, all four parameters were used to generate a predictive equation for a tornado day.

(*d*) *Modelling*

Results from binary logistic regression on the training climatic dataset for both tornado and non-tornado days are impressive. Table 2 shows the percentages of tornado days the model predicts correctly and incorrectly. The results suggest that the equation was successful 86.2% of the time in predicting a tornado day. This is a high level of accuracy, especially given that this is based on the initial training data. As discussed above, air pressure has the least influence on tornado occurrence and was therefore eliminated from the equation, and the model was run again using the training dataset for wind speed, air temperature and humidity. This resulted in the model predicting 73.0% of tornado days correctly, consequently air pressure was reinstated into the equation. Dew-point temperature was then eliminated which resulted in the equation predicting 84.8% of tornado days correctly. Since this figure was still lower than the original equation's success, albeit minimally, the dew-point was also returned to the model. Air temperature and wind speed elimination also reduced the model's predictive strength, so therefore all parameters were included in the regression and the original equation was accepted as being the optimum.

The probability for the training data that all predicted tornado days are going to experience a tornado is 80%, and 20% that a tornado will not occur on a predicted tornado day. It is possible, therefore, to state that the model's 86.2% accuracy of correctly predicting a tornado day leads to an 80% probability that a tornado will actually occur on a day for which one has been predicted.

For test data there is an 81.2% probability that a tornado will occur on a predicted tornado day, and 18.8% of one not occurring on a predicted tornado day. This is an

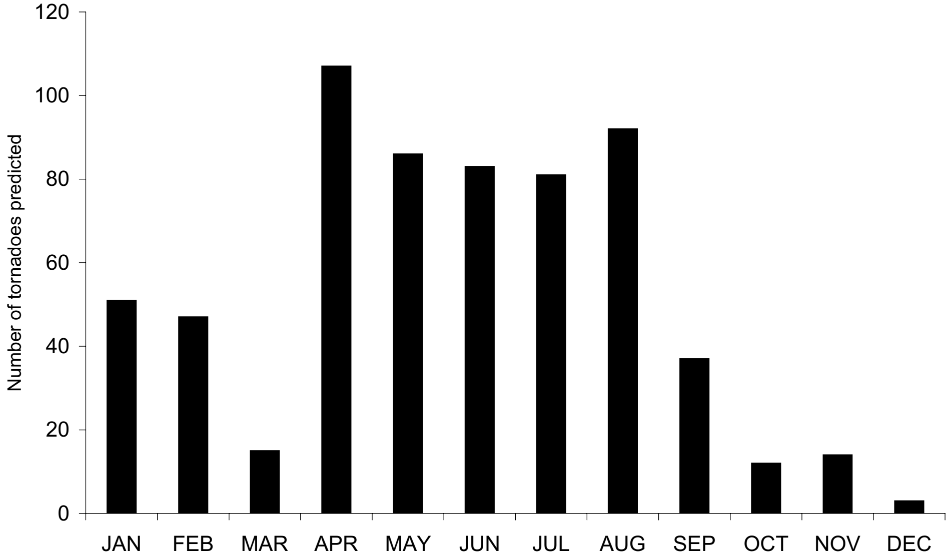

Figure 4. Predicted monthly distribution of tornadoes for the UK, 1995–99. The total number of tornadoes predicted by the model for the period was 628.

TABLE 3. PREDICTED REGIONAL TORNADO OCCURRENCES FOR 1995–99

Region	% Tornado occurrences	Tornado occurrence per 10 000 km^2
South-east England	24	75.1
Central England	26	33.4
North England	21	35.0
South-west England	11	31.2
Wales	10	30.4
Scotland	8	5.6

unexpected result because test data are slightly more accurate at predicting a tornado day than our training data. This is possibly because it was not necessary to modify the parameters of the training data used in the equation; eliminating any of them reduced the accuracy of the model. Thus the predictive equation, when applied to any air temperature, wind speed, dew-point temperature and pressure value, can predict 86.2% of potential tornado days correctly and it is 81.2% probable that a predicted tornado day will spawn a tornadic event.

For the 130 meteorological stations analysed during the 5-year period using the model, a total of 628 station-tornado days (note this is not equivalent to UK tornado days) were predicted. If we assume one tornado per station, and that the stations allow almost total representation of England, Wales and Scotland, this would be equivalent to a factor of 5.15 more tornadoes than were actually reported during the study period. Figure 4 shows the distribution of these predicted events by month of the year, and Table 3 gives predicted numbers of tornadoes by region. It can be seen that the seasonal distribution is similar to that actually reported for the study period (Fig. 2). The spatial distribution is slightly different, with remote rural areas of Scotland and Wales having a greater proportion of tornadoes than were reported during the study period (Table 1). In fact there is an even density of tornadoes for central, northern and south-western regions of England and the Welsh regions, with values ranging from 35 to 30 tornadoes per 10 000 km^2. South-eastern England has a much greater predicted density of tornadoes and Scotland a much lower density. These predictions go some way towards establishing the bias induced by population density compared to the role of spatial setting in determining reported tornado climatologies for the UK. Clearly, while the south-east region is more heavily populated and Scotland very sparsely populated the model suggests that these two regions are at two ends of a tornado density spectrum for the UK. While 31% of tornadoes are reported in south-east England and only 3% in Scotland the model predicts that 24% of tornadoes actually occur in the south-east and 8% in Scotland. Thus, we are able to estimate the population bias for the UK on a regional basis.

4. Discussion

Seasonal and monthly frequency analyses of tornado occurrence revealed that tornadic activity in the UK was at its greatest during spring and summer, and at its lowest during the months of autumn (9.8% of tornadoes). However, the UK tornado climatology carried out for the period 1960–89 showed autumn to be the period with the greatest number of tornadoes (Reynolds 1999). Reynolds suggests that the sea surface temperatures surrounding the UK in September are at their warmest, and the land throughout autumn retains sufficient warmth from summer solar heating. In addition, at this time of year the jet stream strengthens aloft over the British Isles and colder polar air begins to re-appear, resulting in atmospheric instability and a potential climatic setting for tornado outbreaks. However, in the spring and early summer period, when the surrounding sea surface temperature is at its coolest and the jet stream is weak, 65.5% of all tornado events were spawned based on the 1995–99 climatology; this result contrasts with the earlier UK tornado climatology. The predicted seasonal distribution for the UK based on model results are similar to that reported for the study period. This therefore suggests that care should be taken if the model is to be applied to earlier periods, such as 1960–89, since the seasonal distribution of tornadoes during that period was very different.

One of the main differences between the two study periods is that mean annual temperatures have been warmer since 1990 in the UK lowlands and uplands (Holden and Adamson 2002) than in the earlier period. However, the significant warming has been almost entirely confined to the winter months so that, in line with global warming predictions for the UK, the winters have warmed but the summers have not. The mean diurnal temperature range has also reduced (Holden 2001; Holden and Adamson 2001). Thus changes in tornado occurrence in the UK may well be a response to changes in the North Atlantic Oscillation that have brought about recent changes in temperature and precipitation regimes and seasonality. Small changes to local winter sea-surface temperatures may impact winter tornado frequency in the UK (Paice 1998).

The results of this paper suggest that the tornado climatology over the UK is collectively influenced by climate, land relief and population density. High-resolution Doppler radar should be consistently used across the UK in order to eliminate the effects of population density on tornado reporting. It is clear that land relief and meteorological setting determine tornado development, yet there is a strong dependency on the reporting of an event for it to be included in a climatology. Model results suggest that most UK tornadoes may go unreported. While tornado genesis processes are a result of instability aloft, and potential tornado areas in space and time can be predicted a few hours in advance by study of frontal air-mass systems, this paper has provided a possible tool for prediction of tornado days based on ground observations alone. In a sense this is a predictive tool for backward prediction, but it may be developed further for forward prediction based on forecast surface conditions. The model developed can predict a tornado day with an accuracy of 86.2%. The equation was produced using data of meteorological conditions that were known to have spawned the 122 tornado occurrences reported during the 1995–99 period. Its reliability is, therefore, dependant both on accurate tornado reports and on the degree to which the climatic conditions recorded represent a true setting for tornado development. The prediction that the period 1995–99 should have included 628 tornadoes is obviously limited by assumptions: first that the model can be applied to a range of meteorological settings that may be different to those it was developed for; and second that the meteorological stations themselves adequately represent total UK coverage. Furthermore, tornadoes of different strengths may have differing formation mechanisms, and a variety of different climatic parameters may influence tornado formation (Snow and Wyatt 1998). Nevertheless, the model allows the first quantitative estimate of real tornado occurrence in the UK compared to reported tornadoes. Our data suggest that approximately 20% of tornadoes are currently reported. This is many fewer than Brookes and Doswell (2001) have assumed for the UK (60–85%), but twice as many as Elsom and Meadon (1982) who suggested that those reported may only comprise one tenth of the true number of tornadoes. Unlike south-central Canada (King 1997) it was possible to estimate a population bias in the tornado climatology; Scotland, for example, was estimated to have a 5% greater proportion of total UK tornadoes than that actually reported.

5. Conclusions

This paper has presented principal features of tornado climatology in the UK for the first time based on data for 1995–99. Tornado spatial and temporal distributions have been analysed. Just over one third (36%) of reported British tornadoes occurred in the south-east region of England. Most tornado activity took place during the spring and summer while the least activity occurred during autumn. This is different to the seasonal distribution described by Reynolds (1999) for the period 1960–89. The reported tornado frequency distribution was shown to be significantly affected by topography and the density of potential observers. Of the ground-based meteorological variables tested, air temperature was most closely related to tornado occurrence with a peak at 13 °C. An equation incorporating air temperature, dew-point temperature, wind speed and pressure was shown to predict a tornado day with an accuracy of 86.2%; the probability that a tornado would occur on a predicted day was 81.2%. The model was used to predict actual tornado occurrence across England, Wales and Scotland during the 5-year study period, and it was estimated that over five times as many tornadoes occurred than were reported. While the model has limitations associated with the local meteorological setting, it was found to have a high probability of correctly predicting a tornado day from the data obtained; no other work has been published that incorporates such a method for the UK. The bias induced by population density was estimated to be important, but the effects of spatial setting were not simply an artefact of population density. The model allowed the population bias to be partially removed and it was predicted that Scotland had the lowest density of tornadoes per unit area for the UK. The south-east England region was predicted to have the highest density. The relative proportion of UK tornadoes predicted for these regions, however, was 7% less for south-east England than the proportion based on reported events; for Scotland it was 5% greater than the proportions based on tornado reports. Nevertheless, the model relied on observation accuracy in its development and further work is required to improve observation techniques. Doppler radar would be of great assistance in examining UK tornadoes. Improved tornado predictions and model development would surely follow from improved understanding of the processes involved.

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REFERENCES

Brookes, H. E. and Doswell, C. A. 2001 Some aspects of the international climatology of tornadoes by damage classification. *Atmos. Res.*, **56,** 191–201

Brookes, H. E., Lee, J. W. and Craven, J. P. 2003 The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67,** 73–94

Champion, T., Wong, C., Rooke, A., Dorling, D., Coombes, M. and Brunsden, C. 1996 *The population of Britain in the 1990s—A social and economic atlas.* Clarendon Press, Oxford, UK

Church, C. R., Burgess, D., Doswell, C. and Davies-Jones, R. P. (Eds.) 1993 *The tornado: Its structure, dynamics, prediction and hazards.* Geophysical Monographs 79. American Geophysical Union, Washington DC, USA

Davies-Jones, R. 1985 Streamwise vorticity: The origin of updraft rotation in supercell storms. *J. Atmos. Sci.*, **42,** 2991–3006

Elsom, D. M. and Meaden, G. T. 1982 ‘Tornadoes in the United Kingdom’. Pp. 54–57 in Preprints of the 12th conference on severe local storms, San Antonio, Texas. American Meteorological Society, Boston, USA

1984 Spatial and temporal distribution of tornadoes in the United Kingdom 1960–82. *Weather*, **39,** 317–323

Elsom, D. M., Meaden, G. T., Reynolds, D. J., Rowe, M. W. and Webb, J. D. C. 2001 Advances in tornado and storm research in the United Kingdom and Europe: The role of the Tornado and Storm Research Organisation. *Atmos. Res.*, **56,** 19–29

Holden, J. 2001 Recent reduction in frost in the north Pennines. *J. Meteorol. UK*, **26,** 369–374

Holden, J. and Adamson, J. 2001 Gordon Manley and the north Pennines. *J. Meteorol. UK*, **26,** 329–333

2002 The Moor House long-term upland temperature record—new evidence of recent warming. *Weather*, **57,** 119–126

King, P. S. W. 1997 On the absence of population bias in the tornado climatology of southwestern Ontario. *Weather and Forecasting*, **12,** 939–946

McCullagh, P. and Nelder, J. A. 1992 *Generalised linear models.* Chapman and Hall, London, UK

Markowski, P. N. 2002 Hook echoes and rear-flank downdrafts: A review. *Mon. Weather Rev.*, **130,** 852–876

Meaden, G. T. 1985 *Tornadoes in Britain.* Report prepared for HM Nuclear Installations Inspectorate. TORRO, Bradford-on-Avon, UK

Paice, N. 1998 Autumnal funnel clouds over west Hampshire: A precursor to wintertime tornadoes. *Weather*, **53,** 419–424

Pike, W. S. 1998 The overnight tornadoes of 7/8 January 1998 and a coastal front. *Weather*, **53,** 244–257

Press, S. J. and Wilson, S. 1978 Choosing between logistic regression and discriminant analysis. *J. Am. Stat. Assoc.*, **73,** 699–705

Rasmussen, E. N. and Blanchard, D. O. 1998 A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Weather and Forecasting*, **13,** 1148–1164

Reynolds, D. J. 1999 Revised UK tornado climatology, 1960–1989. *J. Meteorol. UK*, **24,** 290–321

Rowe, M. W. and Meaden, G. T. 1985 Britain’s greatest tornado outbreak. *Weather*, **40,** 230–235

Snow, J. T. and Wyatt, A. L. 1998 Back to basics: The tornado, nature’s most violent wind: Part 2—Formation and current research. *Weather*, **53,** 66–71