A PROVISIONAL CLIMATOLOGY OF COOL-SEASON QUASI-LINEAR CONVECTIVE SYSTEMS IN THE UK

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I. INTRODUCTION

Quasi-linear convective systems (QLCSs) occur frequently during the autumn and winter months in the UK. Many of these systems occur along cold fronts, though they may also be observed in polar-maritime air-masses to the rear of frontal systems. Tornadoes and other localised, damaging winds have been documented in association with these autumn–winter (hereafter, 'cool-season') QLCSs on numerous occasions. Indeed, at least 80% of UK outbreaks comprising 10 or more tornadoes in recent decades may be attributed to cool-season QLCSs. Despite their association with severe weather, no UK climatology of cool-season QLCSs has yet been constructed. To address this issue, a provisional climatology of these events has been compiled, for the seven cool-seasons 2003–4 to 2009–10.

Although tornadoes frequently occur in association with cool-season QLCSs, there are also many non-tornadic examples. Superficially, the environments of tornadic and non-tornadic events appear similar, which makes it very difficult to assess the tornado risk for any given event. In an attempt to tackle this issue, the environments of tornadic and non-tornadic QLCSs have been compared, to determine whether any statistically significant differences exist.

II. METHOD

QLCSs were manually identified using a seven-year archive of Met Office composite radar rainfall imagery, available at 30-minute temporal resolution. An adapted version of the methodology of Trapp *et al*. (2005) was used for this purpose. Only convective lines meeting minimum size, duration and intensity criteria were selected (Table 1). The duration criterion was designed to exclude short-lived features, such as the apparently linear conglomerations of showers that sometimes occur in situations of widespread cellular convection, which do not constitute true, organised QLCSs. In all, 103 QLCSs were identified using this method.

The TORRO tornado database contains information about all known tornadoes in the UK and Ireland. Initial reports are verified, where possible, by eyewitness interview and site investigation. Each database entry includes the date and time of occurrence (usually to the nearest hour), coordinates of the start and end points of the damage track, and, where sufficient information about the damage is available, an intensity rating according to the International Tornado Intensity (T) Scale (Meaden, 1983). A QLCS was classified as tornadic if one or more tornadoes could be unambiguously attributed to it. This was determined by comparison of the radar-observed time of QLCS passage at the tornado's location with the recorded time of tornado occurrence in the TORRO database. Where no tornado reports existed for the duration of the event, or where no tornadoes could be unambiguously attributed, the line was classified as non-tornadic. The tornadic class was further sub-divided into weakly- and strongly-tornadic classes. Weakly-tornadic lines were those in which only a single, weak (T0 – T3) tornado could be attributed to the line (for this purpose, tornadoes with no intensity rating were assumed to have been weak). Strongly-tornadic events were those in which one tornado of intensity ≥ T4, or two or more tornadoes of any intensity, could be attributed to the line.

Parameter	Threshold criteria
Dimensions	Length ≥ 100 km, at the time of maximum extent; length ≥ 10 x width
Duration	A coherent line (meeting the below intensity criteria) must persist for ≥ 2 hours
Intensity	A continuous, or near continuous, line of rainfall rates ≥ 4 mmh^{-1} (equivalent to 32.6 dBZ)

TABLE 1: criteria for the selection of QLCSs from archived radar rainfall data

A number of environmental parameters were investigated with a view to identifying differences between tornadic and non-tornadic lines. Additionally, QLCS morphology, movement, and various other attributes were derived from sequences of radar data. Cross-line temperature decrease and wind veer were assessed using available surface data. Shear parameters and CAPE were obtained from representative sounding data, modified using surface observations. Soundings deemed representative were those released ≤ 300 km ahead of the QLCS, or its source region. For post-frontal events, care was taken to ensure that pre-frontal soundings were not used. Of the 103 QLCSs identified, representative soundings were obtained for 98. Two or more representative soundings were sometimes available, in which case mean CAPE and shear values were calculated, using all available data.

Surface observations of temperature, dew point temperature, wind speed and wind direction are archived at hourly resolution. Data corresponding to the hour preceding QLCS passage were obtained for each case. In order to reduce the effects of small-scale variability, data from several surface stations were used, and mean values calculated. Only data from stations located at altitudes of ≤ 150 m above mean sea level were included, in order to minimise the effects of altitude on the surface data. For tornadic lines, data from stations located ahead of the tornadic portion of the line were used where possible. For non-tornadic lines, stations located ahead of the most intense section of the line (assessed using radar data) were chosen; for non-tornadic cases in which the line was rather uniform in intensity, data from a selection of widely-separated stations were used.

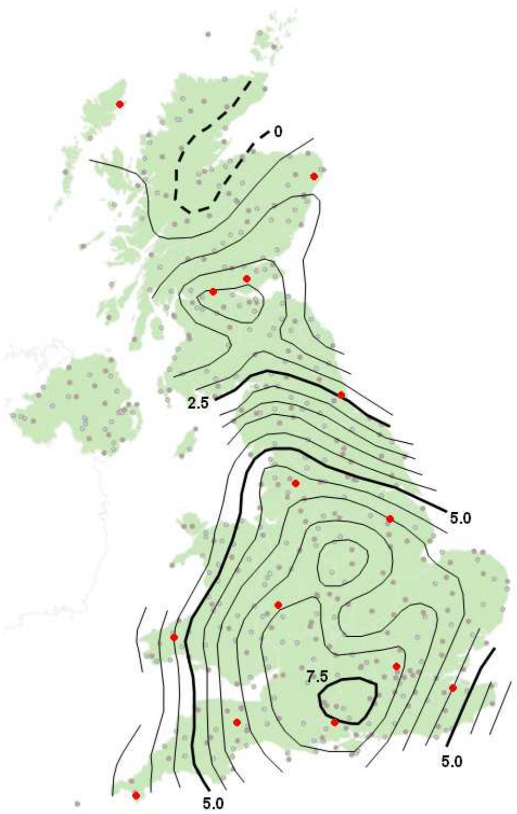

FIG. 1. Frequency of cool-season QLCSs over the UK, expressed as the number of events per 10,000 km^2 per year. Large red dots indicate the locations of radars in the current UK network.

III. RESULTS

i) Climatology

Frontal systems were responsible for 87% of cool-season QLCSs. The remaining 13% occurred in post-frontal situations. Slightly more than a quarter of QLCSs (27%) were tornadic (9% weakly-tornadic and 18% strongly-tornadic). The larger number of strongly-tornadic (compared to weakly-tornadic) events is surprising, and may highlight a significant under-reporting of weak, isolated tornadoes. QLCSs were responsible for 71% of all cool-season tornadoes. Furthermore, 67% of all T2+ tornadoes in the entire September 2003 – February 2010 period (including spring and summer events) could be attributed to cool-season QLCSs, demonstrating that these systems are the single largest source of stronger UK tornadoes.

Figure 1 shows the areal distribution of cool-season QLCSs over the UK, expressed as the number of events per 10,000 km^2, per year. The highest frequencies (≥ 7.5 events per year) are found over central southern England, with relatively high frequencies (≥ 5 events per year) occurring over much of England and Wales. Frequencies are considerably lower over Scotland. The lowest frequencies (< 1 event per year) are found over northern Scotland. Over northwest Wales, parts of East Anglia and the far southeast of England, the lower frequencies may be due, in part, to reduced radar-detection of QLCSs, owing to the large distance from the nearest radar. In order to account for the radar-range limitations, frequencies were not plotted for areas located > 175 km from the nearest radar, except where interpolation between adjacent areas was possible.

Figure 2 shows the monthly distribution of QLCSs. The frequency of events rises through the autumn months and peaks strongly in November, when 31% of all events occurred. QLCSs were also relatively frequent in December and January, but notably few events occurred in February. The frequency of QLCSs exhibited large inter-annual variability; for example, 29 events occurred during the 2006–7 season, and only 9 events during the 2008–9 season. Furthermore, the lines showed a tendency to occur in clusters, typically lasting a few days. This aspect is in agreement with the results of Gatzen (2011), for cold-frontal lines in Germany. Clusters were associated with highly mobile, westerly synoptic types, during which a succession of strong depressions tracked across, or close to, the country.

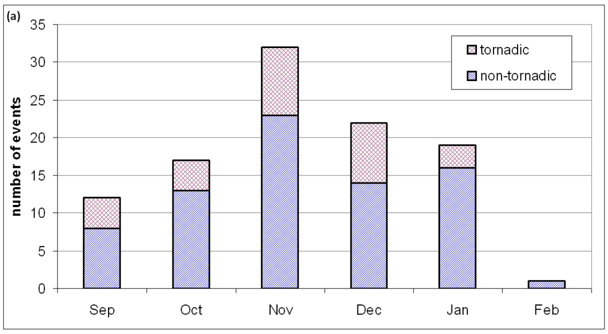

FIG. 2: Monthly totals of tornadic and non-tornadic QLCSs.

The diurnal distribution of QLCSs (not shown) does not exhibit a clear diurnal cycle. Although a weak maximum in frequency occurs in the afternoon hours, a secondary peak is also evident during the early morning. The lack of a clear diurnal cycle is not unexpected, given the association with frontal systems, which occur largely independently of surface heating. The distribution of tornadic lines shows a slightly stronger diurnal cycle. Peak values occur during the afternoon hours (maximum at 1600 UTC). No well-defined minimum is evident, and tornadoes occurred at all times of day and night. The afternoon peak in frequency does, however, suggest that surface heating has a limited influence on tornado occurrence within the cool-season QLCSs.

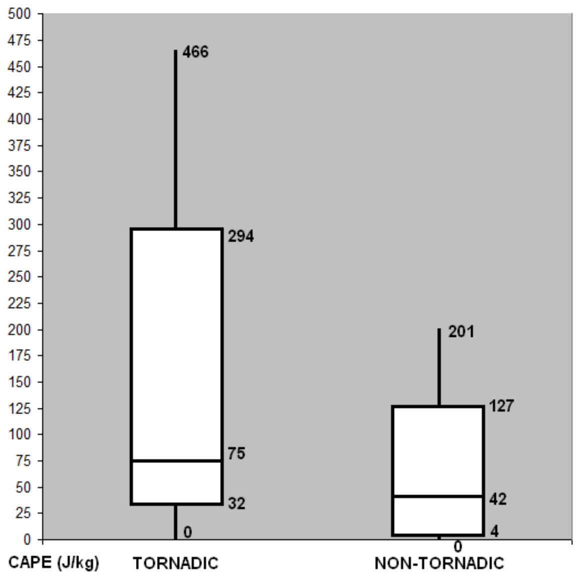

FIG. 3: Box-and-whisker plots showing CAPE distributions for tornadic and non-tornadic QLCSs. The upper and lower tails show the 10th and 90th percentile values, respectively.

ii) Environments of tornadic and non-tornadic lines

Figure 3 shows that cool-season QLCSs occur in environments of relatively small CAPE (generally < 250 Jkg^{-1}). CAPE was equal to zero for 22.2% of non-tornadic lines and 11.5% of tornadic lines. However, the median value of CAPE in tornadic lines (75 Jkg^{-1}) was almost twice that in non-tornadic lines (42 Jkg^{-1}). A Wilcoxon Rank-Sum Test confirmed that CAPE was significantly larger (at the 95% level) for tornadic lines.

The distributions of 0–1-km and 0–3-km bulk shear (not shown) reveal that strong low-level shear is an almost universal characteristic of the QLCS environments. Only 3.8% of tornadic lines, and 4.2% of non-tornadic lines, occurred in environments with less than 10 ms^{-1} of 0–1-km bulk shear**.** A Student's t-test showed no statistically significant difference between tornadic and non-tornadic classes. Given the abundance of strong-shear environments, the implication is that other limiting factors dominate in the non-tornadic cases. Further investigation, in which the 0–1-km shear was decomposed into line-normal and line-parallel components, also failed to reveal any statistically significant differences between tornadic and non-tornadic lines.

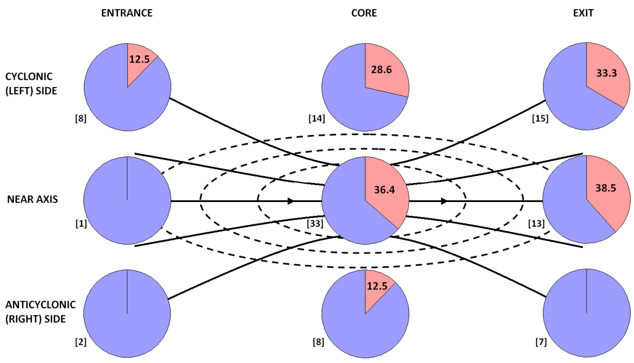

FIG. 4: Probabilities (%) of one or more tornadoes, given a QLCS, as a function of QLCS location relative to the 700 hPa jet. Numbers in brackets give total number of QLCSs in each jet-relative location.

Following Gatzen (2011), the locations of wind maxima at the 700 hPa level, relative to each QLCS, were assessed. NCEP/NCAR reanalysis geopotential height fields were used for this purpose. Wind maxima could be identified in 98% of cases. Figure 4 shows, schematically, the jet-relative locations of QLCSs. Tornadic lines showed a stronger tendency to occur near the jet core or on its cyclonic-shear side. There was also a bias towards the jet exit region. Very few tornadic QLCSs occurred at the anticyclonic-shear flank of the jet, or in the jet entrance region.

iii) Line-normal motion and cross-line parameter differences

The rate of advance of each QLCS, in the direction normal to its long-axis, was estimated from sequences of radar data. Although tornadic QLCSs showed somewhat larger line-normal forward motion, a Student's t-test showed that the difference was not quite statistically significant (p value = 0.057). However, the difference between strongly-tornadic and non-tornadic QLCSs was significant at the 99% level.

Distributions of cross-line wind veer and temperature fall are shown in Figure 5. Although the hourly resolution of archived surface data was insufficient to assess cross-line gradients in these parameters, the data provided a reasonable estimate of the general difference in wind direction and temperature across each QLCS. A Student's t-test confirmed that differences between tornadic and non-tornadic lines were significant at the 99% level.

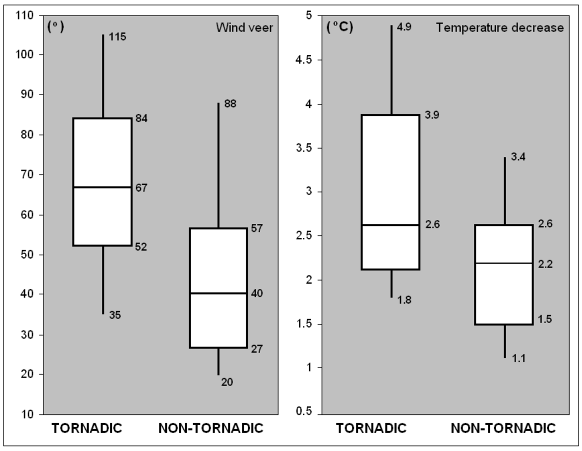

FIG. 5: Cross-line wind veer (left) and temperature fall (right) for tornadic and non-tornadic QLCSs. Upper and lower tails show the 10th and 90th percentile values, respectively.

IV. CONCLUSIONS

For the 2003–2010 study period, cool-season QLCSs were the primary source of T2+ tornadoes in the UK. 27% of identified QLCSs produced at least one tornado. A number of significant differences were found between tornadic and non-tornadic lines. Although no definite threshold values exist, the results indicate that the probability of tornadoes, given a QLCS, is substantially higher when:

- CAPE > 200 Jkg^{-1}
- Cross-frontal wind veer > 50º
- Cross-frontal temperature decrease > 3.0ºC
- Line-normal forward motion > 15 ms^{-1}
- The line is located under the core, cyclonic flank, or exit region of the mid-level jet

In practice, there are few occasions for which all these criteria are met. Nevertheless, the probability of tornadoes increases strongly as the number of satisfied criteria increases. For example, if three or more criteria are met, the probability of one or more tornadoes rises to 61%, which is more than twice the general tornado probability given a QLCS. Further research is required in order to test whether these parameters can realistically be forecast ahead of potential QLCS events and, if so, whether the above-defined criteria are of any practical benefit for tornado forecasting.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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