DOPPLER RADAR OBSERVATIONS OF A TORNADIC SQUALL LINE OVER SOUTHEAST ENGLAND

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I. INTRODUCTION

On 7 December 2006 a tornado formed over northwest London, along the leading edge of an intense squall line moving northeast over southern England. Although the tornado was rather short-lived, producing a damage path just 2.7 km in length, it was strong. Damage surveys undertaken by TORRO personnel (www.torro.org.uk) have indicated a maximum strength of T5 on the TORRO International Tornado Intensity Scale (equating to estimated wind speeds in the range 62 to 72 ms^{-1}). The squall line also produced severe (>26 ms^{-1}) wind gusts, small hail and cloud to ground lightning at many locations over southern England.

The squall line developed within cyclonic southwesterly flow to the south of a vigorous depression moving northeast over northern Scotland, and west of the associated frontal system which had cleared the UK in the early hours of the 7th. Available tephigrams show that the line developed within a relatively shallow unstable layer contained within the lowest 3 to 4 km above ground level (AGL). This layer was capped by a strong inversion associated with the base of a dry intrusion. Satellite derived cloud top heights confirm that the convective cloud tops associated with the squall line did not penetrate this inversion significantly. Approximately 140 Jkg^{-1} of CAPE was contained within the shallow convective layer. Strong, though largely unidirectional shear was also present within this layer; 0 – 1 km and 0 – 3 km bulk shear were found to be equal to 15.7 ms^{-1} (31 knots) and 22.4 ms^{-1} (43.5 knots) respectively.

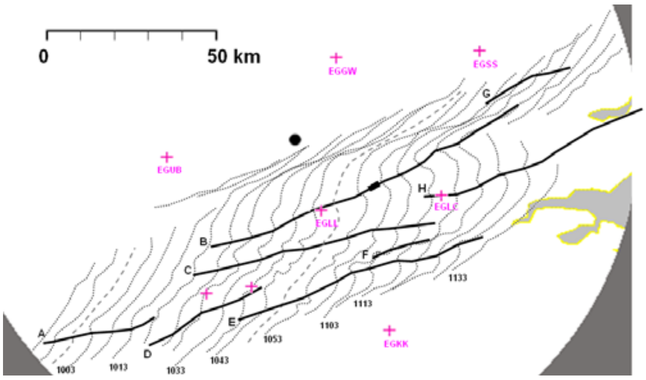

FIG. 1: Squall line leading edge (grey lines) as shown by Met Office Chenies radial velocity field at 5 minute intervals beginning 0948 UTC, and observed tracks of leading line mesovortices (bold lines). Vortices are labelled A to H in chronological order of detection. Bold section of Vortex B's track indicates tornadic phase. Black dot indicates radar location.

II. ANALYSIS OF DOPPLER RADAR DATA

During much of its most active phase the squall line was located within range of the Met Office's network of Doppler radars. In operational mode these radars produce 360º azimuthal scans at several elevation angles every five minutes, from which radar reflectivity and radial velocity plan position indicator plots are produced. These data have allowed a detailed analysis of the evolution of the squall line before, during and after its tornadic phase. Of particular interest, the radial velocity field revealed the development of several cyclonic vortices along the leading edge of the squall line, typically of order 1 – 4 km in diameter (hereafter referred to as 'mesovortices', after Weisman and Trapp (2003)). Several of these mesovortices were traceable in sequences of radial velocity plots for periods of between 15 minutes to over one hour. Figure 1 shows the tracks of these mesovortices, together with the position of the squall line gust front, as revealed by the abrupt change in radial velocity along the leading edge of the line, at 5 minute intervals beginning 0948 UTC. Figure 1 shows that as the squall line moved northeast over southeast England, bowing became increasingly evident along a ~50 km long segment of the line. In general, the longest lived mesovortices appear to have occurred close to and north of the apex of the bow. Typically, mesovortices could be traced back to areas of enhanced cyclonic shear across the leading edge of the line, which tended to be collocated with much smaller bulges in the leading edge of the line (for example, see vortices B and C in Figure 1). In most cases, within 15 to 30 minutes of detection, these areas of enhanced cyclonic shear evolved into discrete velocity couplets. The strongest mesovortices significantly modified the shape of the squall line reflectivity echo in their vicinity as they evolved, with marked, localised bowing noted to the south of the vortices and an inflow notch forming immediately to the north. Some mesovortices eventually became collocated with a line break in the reflectivity field, surrounded by a cyclonic 'swirl' of >40 dBZ echoes.

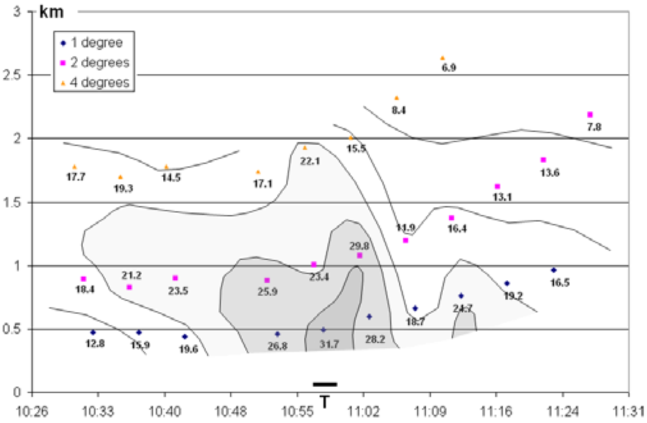

FIG. 2: Time-height plot of Vortex B's rotational velocity (knots) between 1026 and 1131 UTC. Contours are at 5 knot intervals and values >20 knots are shaded. Approximate time of tornado occurrence is marked by the 'T'.

Vortex 'B', with which the tornado over northwest London was associated, was the strongest and longest-lived of all observed mesovortices. Figure 2 shows a time height plot of vortex B's rotational velocity between 1026 and 1131 UTC. The tornado occurred as the vortex attained maximum rotational velocity, shortly after 1055 UTC, following a period of vortex strengthening and deepening. Although the vortex eventually became collocated with a line break in reflectivity fields at low levels, the strengthening and deepening appears to have been associated with the rapid development of a transient, discrete reflectivity maximum aloft (at approximately 2 km AGL) suggesting that vortex strengthening (and possibly tornadogenesis) were promoted by stretching of the existing vortex by a local updraft maximum along the squall leading line. The vortex weakened and broadened following its tornadic phase, but remained conspicuous in the reflectivity field, being collocated with a large, hook shaped reflectivity echo embedded within the line (Figure 3).

In general, the strongest and tallest echoes along the squall line leading edge appear to have been located close to the apex of bowing segments within the line. Figure 3 illustrates this well, with core reflectivity exceeding 56 dBZ close to the bow apex south of vortex B, compared with typical core reflectivity values of around 40 to 48 dBZ elsewhere along the line. This observation could be attributed to increased rear to front flow behind the bow apex, leading to increased convergence and forced ascent along the leading edge of the line in the vicinity. The radial velocity field in Figure 3 reveals the presence of enhanced rear to front flow within this section of the line. These bowing segments were also observed to be preferred locations for the development of new mesovortices. Figure 3 shows one such vortex (marked by an arrow), developing along the leading line near the apex of the bowing segment located south of the now weakening vortex B. This new vortex ('H' in Figure 1) subsequently strengthened rapidly, and within 20 to 30 minutes the circulation around this vortex had distorted the reflectivity pattern significantly, with a new bowing segment having developed immediately to its south and smaller hook shaped echo surrounding the vortex centre. Again, the strongest echoes were located close to the apex of the new bowing segment. Some evidence exists that a further mesovortex subsequently developed close to the apex of this new bowing segment, though increasing distance of the area of interest from the radar prevented tracking and analysis of any further vortices. In this way, mesovortex genesis on this occasion exhibited a degree of cyclicity. A similar cyclic pattern of genesis was observed for vortices A, D and E (see Figure 1).

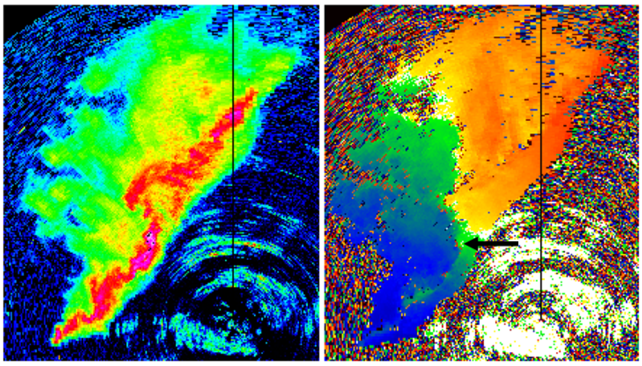

FIG. 3: Radar reflectivity (left) and radial velocity (right) as observed by the Met Office Thurnham (Kent) radar at 1116 UTC, 07 December 2006. Location of developing vortex 'H' is shown by arrow in the velocity panel.

III. CONCLUSIONS

The squall line studied herein produced several long-lasting mesovortices as it traversed southeast England, one of which is known to have been associated with a short-lived, but strong, tornado. The strongest mesovortices were observed to extend to at least 2 km AGL, which is over half the total observed depth of the squall line. The association between such strong, deep squall line mesovortices and severe weather, including enhanced straight line winds and tornadoes, has been shown by many observational studies in the US (e.g. Przybylinski, 1995; DeWald *et al*., 1998; Funk *et al*., 1999). The behaviour of the mesovortices observed in this case exhibited many other similarities to those observed in association with severe squall lines in the US. An example is the general tendency for the strongest and longest-lived vortices to occur along and north of the apex of the primary bowing line segment. In this case, the strongest vortices significantly affected the overall morphology of the squall line and appeared to play a role in subsequent vortex genesis. Evidence was found of a type of cyclic vortex genesis, in which the generation of new mesovortices occurred in the area of increased convergence associated with localised line bowing, which resulted from enhanced westerly (rear to front) flow on the southern flank of existing vortices in their mature or decaying stages. A very similar type of cyclic vortex genesis was observed by Funk *et al*. (1999) in a severe squall line affecting parts of Kentucky and Indiana.

The environment in which this squall line developed was characterised by strong shear, particularly in low levels, and small CAPE. Although the values of shear observed are comparable to those associated with squall lines producing strong, long-lived mesovortices in the US, the observed CAPE is considerably smaller. Furthermore, the observed squall line depth was much shallower (one third to one half the typical depth of US squall lines) owing to the presence of the strong inversion at 3 to 4 km AGL. At first glance, such an environment may have appeared less than favourable for the development of a severe squall line. Compensating for these 'negative' factors may have been the combination of CAPE, steep lapse rates and strong shear within the shallow layer at low levels. A second compensating factor may have been the presence of an externally forced (or at least enhanced) squall line rear inflow jet; wind profiler data revealed the presence of a ~35 ms^{-1} (70 knot) wind maximum centred at 2 km AGL, some 150 km to the rear of the line. This wind maximum gradually approached the squall line from the rear as it moved over southern England, and may have increased storm relative rear to front flow and entrainment of the dry air present at this level into the line, promoting cold pool strengthening, acceleration of the line and increased leading line convergence.

IV. ACKNOWLEDGEMENTS

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V. REFERENCES

DeWald, V. L., Funk, T. W., Kirkpatrick, J. D., Lin, Y. J., 1998: The 18 May 1995 squall line over south-central Kentucky: An examination of complex storm reflectivity trends and multiple mesocyclone development. Preprints, *16th Conf. on Weather Analysis and Forecasting*, Phoenix, AZ, Amer. Meteor. Soc., 148 – 151.

Funk, T. W., Darmofal, K. E., Kirkpatrick, J. D., DeWald, V. L. 1999: Storm Reflectivity and Mesocyclone Evolution Associated with the 15 April 1994 Squall Line over Kentucky and Southern Indiana. *Wea. Forecasting*, **14**, 976 – 993.

Przybylinski, R. W., 1995: The Bow Echo: Observations, Numerical Simulations, and Severe Weather Detection Methods. *Wea. Forecasting*, **10**, 203 – 218.

Weisman, M. L., Trapp, R. J., 2003: Low-level mesovortices within squall lines and bow echoes. Part I: Overview and sensitivity to environmental vertical wind shear. *Mon. Wea. Rev.*, **131**, 2779 – 2803.