THE RELATIONSHIP BETWEEN LONGER-LIVED SURFACE BOUNDARIES AND LOW PRESSURE CENTERS WITH THE OCCURRENCE OF STRONG AND VIOLENT TORNADOES

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Abstract

The association of longer-lived surface boundaries and surface low pressure centers with strong and violent tornadoes is investigated over the United States east of the High Plains for 1993. The results showed an overwhelming majority of F2 or stronger tornadoes developed within 100 km of a surface thermal or moisture boundary which had a temporal and spatial continuity of at least 6 hours. The most common boundaries associated with tornadogenesis were cold fronts, outflow boundaries and dry lines. Considerably less correlation was detected between tornadoes F2 or stronger and the location and intensity of longer-lived (i.e., a time and space continuity of at least 6 hours) surface lows.

1. Introduction

It has long been recognized that the development of strong (F2 and F3 on the Fujita scale) and violent (F4 and F5) tornadoes require favorable thermodynamic, dynamic and vertical wind shear characteristics throughout the troposphere. In addition to convective instability, the environment must almost always include mechanisms which force upward vertical motion such as middle and upper tropospheric troughs and jet streaks (McNulty 1978), low-level warm advection, centers of low pressure in the boundary layer (Tegtmeier 1974) and surface boundaries separating air masses of contrasting temperature and/or moisture content (Doswell 1982).

More recently, it has been proposed that the spatial scale of a given forcing mechanism may determine how it actually contributes to the initiation of deep convection. As discussed by Doswell (1987), the vertical motions produced by synoptic or larger meso-alpha scale extratropical weather systems, such as upper tropospheric troughs, are often insufficient to lift a parcel to its level of free convection. Instead, weather systems of these dimensions contribute to thunderstorm formation by bringing about cooling aloft, which contributes both to the erosion of capping inversions and to the increase in convective instability. In contrast, smaller scale features, such as surface air mass boundaries and centers of low pressure (McGinley 1986) most often directly force convection by concentrating relatively high values of convergence and attendant upward motion below the convective cloud base.

These concepts have important applicability in the shorter range forecasting of tornadic thunderstorms. Given other favorable parameters including high instability, strong vertical wind shear or helicity, and large scale upper tropospheric divergence, one should expect the highest probabilities of tornadoes in comparatively close proximity to fronts, dry lines and surface low pressure or extratropical cyclone centers where convergence is maximized. Conversely, there should be less likelihood of the most destructive tornadoes where such features are distant from existing convection. (An important exception is in the vicinity of tropical cyclones which are not included in this study.)

A primary objective of this inquiry was to determine to what extent surface boundary and surface low pressure center (or extratropical cyclone) proximity and characteristics can be applied to the short range prediction of the more destructive tornadoes. To be consistent with this purpose, this study investigated if the highest probabilities of stronger tornadoes may be found within thunderstorms propagating in close proximity to a longer-lived or persistent surface boundary (hereafter designated as an LSB) and extratropical surface low pressure center (SLC). By persistent, the LSB and SLC are defined respectively as a surface boundary and surface low pressure center exhibiting a time and space continuity of at least 6 hours prior to tornadogenesis. In addition, this project explored relative frequencies of tornadoes with particular boundary types and briefly examined if extratropical cyclone intensity correlated with tornadic activity.

This approach avoided considering transient convectively induced weather systems whose analysis and detection, when and where possible, are more applicable for issuing nowcasts and severe weather warnings at local National Weather Service Offices.

Also not considered were tornadoes over the western portions of United States including the high plains, the Rocky Mountain region and the Pacific Coast (areas approximately west of longitude 102W). As documented by Doswell (1981) and Hales (1985), synoptic conditions related to severe convection over the western United States are often uniquely different from the rest of the country and should be the subject of separate studies.

2. Previous Related Research

Beebe (1956) examined 229 cases for which three or more tornadoes occurred, with his focus primarily over central and southern portions of the United States. His results were presented in the form of composite charts for mean synoptic conditions 0 to 12 hours prior to the commencement of tornadic storms. From the provided fields of surface pressure, temperature and dew point it can be inferred that tornadoes would be most favored in a sector of relatively warm moist air south and southeast of a surface low and east of an approaching cooler, drier air mass. Also, it was apparent from the composite charts that the greatest threat of tornadoes was within 500 km of a surface thermal boundary and within 700 km of the low pressure center. But, because the composites comprised a 12-hour time period and included weaker tornadoes, it is impossible to estimate more precisely the location of stronger tornadoes with respect to the positions of any LSB or SLC not lost in the compositing process.

Miller (1972) analyzed synoptic patterns favorable for severe thunderstorms. His findings also showed the greatest tornado threat is usually within several hundred kilometers of a surface boundary. Although Miller's composites lacked detailed surface pressure analyses, from his figures one may surmise that tornadoes are relatively common within the warm sector of an extratropical cyclone. In addition, surface parameters considered favorable for severe thunderstorms included 12-hour pressure falls in excess of 5 mb and actual pressure values below 1005 mb.

Charba (1975) found severe thunderstorms occurred in relatively close proximity to areas displaying high values of surface moisture convergence. Ostby (1975) demonstrated that for a major tornado outbreak, most tornadoes developed in close proximity to surface boundaries where moisture convergence was maximized.

Livingston and Wilson (1986), using a very limited data set, attempted to relate antecedent surface conditions to tornadic storms by applying a band pass filter toward constructing a series of composite analyses. Their derived data revealed that, on average, tornadogenesis was most pronounced near or along an axis of low pressure and enhanced moisture convergence, strongly suggesting the presence of an advancing front. Although based on only 5 cases, pressure field composites plus temperature and wind data reflected that violent tornadoes (F4 and F5) ensued within the warm sector of a well defined extratropical cyclone.

3. Methodology

Using *Storm Data* and other information on tornadoes available at the NWS Storm Prediction Center, the time and location of all F2 or stronger tornadoes east of the High Plains were obtained for the year 1993. Surface maps, radar charts and available satellite images were examined for a 6-hour period prior to each case of tornado formation to check for temporal and spatial continuities of surface boundaries and low pressure centers which would be categorized as a LSB and SLC respectively. The location of each initial tornado touchdown was subsequently measured in relation to the position of the LSB and SLC at the time of touchdown. The central pressure and 6-hour pressure tendency of each tornado-associated SLC was noted at the approximate time of tornadogenesis.

Boundaries were further classified into six categories, namely cold fronts, occluded fronts, warm fronts, stationary fronts, dry lines and rain cooled outflows (including prefrontal squall lines) to determine the relative frequency of stronger tornadoes for each type. The scarcity of surface data in some regions created uncertainties of up to 100 km in the positioning of boundaries and low pressure centers. Accordingly, tornadoes reported within 100 km of a LSB or SLC were simply categorized as closest proximity storms and no further attempts were made to determine a more exact distance.

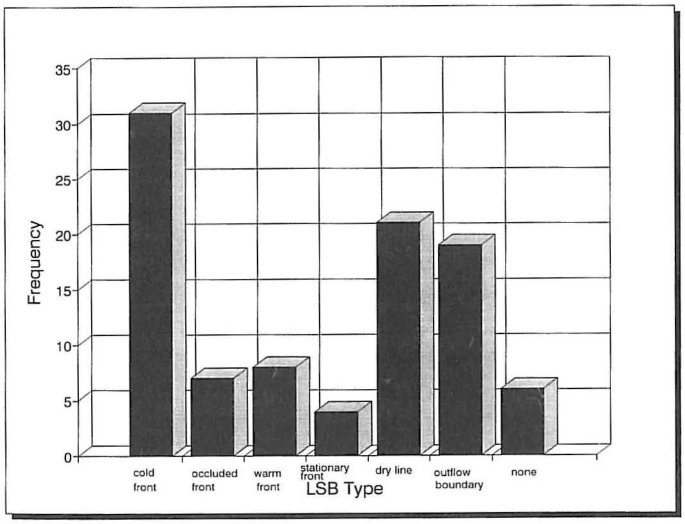

Fig. 1. Frequency of strong and violent tornadoes for each type of longer-lived surface boundary (LSB).

Another uncertainty factor involved tornadic storms within 100 km of at least two boundaries, as would occur near an open wave cyclone center. In such cases the LSB believed most responsible for tornadic thunderstorm initiation or sustenance was subjectively chosen as being the primary surface boundary associated with the storm. Likewise, in cases of multiple surface lows, only the SLC closest to each tornado underwent a distance and pressure analysis. Hence, each tornado was "assigned" no more than one LSB and SLC.

4. Results

A total of 96 strong and violent tornadoes were considered for the study with the storms of interest occurring over various regions of the United States east of the High Plains. The results overwhelmingly support the idea of the LSB being among the most essential precursors for strong and violent tornadoes.

Of the 96 tornadoes, 90 (94 percent) were generated within 100 km of a LSB. This included all of the 28 tornadoes having strength F3 or higher. As illustrated in Fig. 1, cold fronts and dry lines were the most common LSB's with 31 (32 percent) and 21 (22 percent) cases respectively. Outflow boundaries (including prefrontal squall lines) comprised 19 of the events with a considerably lesser number of storms more directly attributable to warm fronts, occluded fronts and stationary fronts.

For the cases occurring within 100 km of a LSB, there were instances where tornadoes formed in advance of more than one type of boundary (Fig. 2), or near the intersection of a LSB

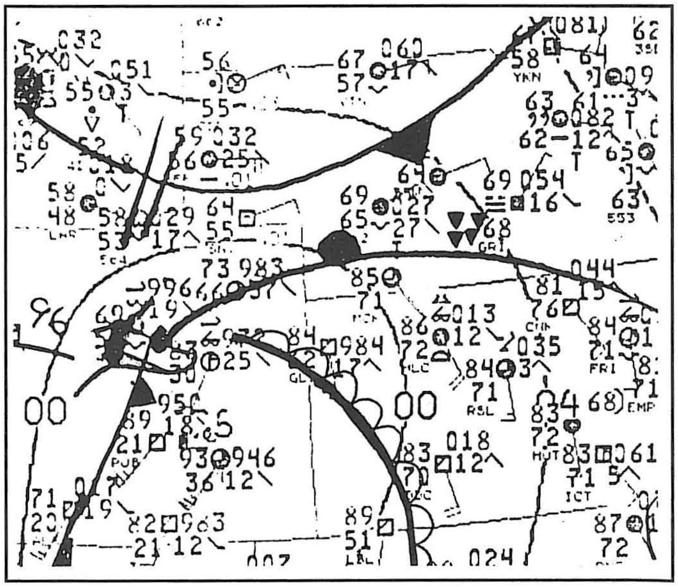

Fig. 2. Surface analysis for 0000 UTC 7 June 1993 illustrating significant tornado development occurring near multiple surface boundaries. Triangles (▼) show location of tornadoes which developed between 0000 and 0300 UTC.

and a shorter-lived convectively induced outflow. However, for these events, the LSB closest to the report was classified as the LSB most directly associated with the tornadogenesis.

For the six storms where no LSB was detected within 100 km, tornadoes attained no intensity above F2. Five of the six tornadoes occurred downstream of a well-defined upper-level trough where lifting may have been enhanced, despite the absence of a surface boundary meeting LSB criteria. For each of the six cases, tornadic storms developed along convective outflow boundaries which had temporal continuities under six hours.

There was a distinctly wider variation between tornadogenesis and SLC proximity. As recorded in Table 1, an unexpectedly small fraction of storms (14 tornadoes or 15 percent) was within 100 km of a SLC with only 30 tornadoes (31 percent) touching down within 250 km. Surprisingly, as many as 22 tornadoes (23 percent) were found over 750 km from a SLC. Although all tornadoes beyond 750 km were no stronger than F2, for storms within the 750 km range there was little correlation between tornado intensity and SLC distance.

SLC's accompanying tornadoes displayed a wide variation of intensity; 70 percent were deepening near the time of tornado initiation. For example, as illustrated in Fig. 3, the extremely powerful extratropical cyclone of 12–13 March 1993 provided dynamic support for several strong tornadoes over Florida. In contrast, Fig. 4 demonstrates how the deadly (7 fatalities) and destructive F4 and F3 tornadoes near Tulsa, Oklahoma, on 24 April 1993, developed ahead of a weakly energetic subsynoptic low (associated with a cold front and dry line intersection) with a circulation encompassing a very limited area. Consistent with these findings was the broad range of SLC central pressures (not shown), which ranged from a minimum of 984 mb to a maximum of 1011 mb. SLC intensity and location thus appeared to have considerably less forecasting utility for short-term tornado prediction than LSB proximity.

5. Discussion

The above results lend further credence to Doswell's (1987) contention that smaller meso-alpha scale weather systems, especially surface boundaries, are usually required to force severe convective storms. As explained by Bluestein (1986), frontal circulations, having substantial ageostrophic wind components, may provide higher magnitudes of lift in comparison to larger synoptic scale weather systems. Purdom (1993) demonstrated how low-level convergence and lifting in the planetary boundary layer is further increased where surface boundaries intersect thus making such areas preferred regions for deep convection.

It is not as apparent why an overwhelming majority of the tornadic storms were within 100 km of at least one of the longer-lived type boundaries. It is conjectured that a LSB, having an existence of at least six hours, has a stronger, deeper and better organized solenoidal circulation when compared to thermal discontinuities of shorter lifetimes. In addition, environments which include LSB's are frequently baroclinic with thermal and pressure gradients resulting in a vertical wind profile favorable for tornadogenesis (McGinley 1986).

While surface boundaries categorized as LSB's may force deep convection, there is some question as to how directly they induce tornadogenesis. Hoxit and Chappel (1975) have documented initially non-tornadic thunderstorms producing tornadoes only after they moved away from the LSB along which they were initiated. Studies by Maddox et al. (1980) have verified that while some thunderstorms are forced along a particular LSB, they may not become tornadic until they approach a second surface boundary which may not always meet LSB criteria.

Table 1. Distribution of nearest SLC distances from strong to violent tornadoes for 1993 (over the U.S. east of the High Plains).

Distance (km)	≤100	101–250	251–500	501–750	>750
No. of events	14	16	25	19	22

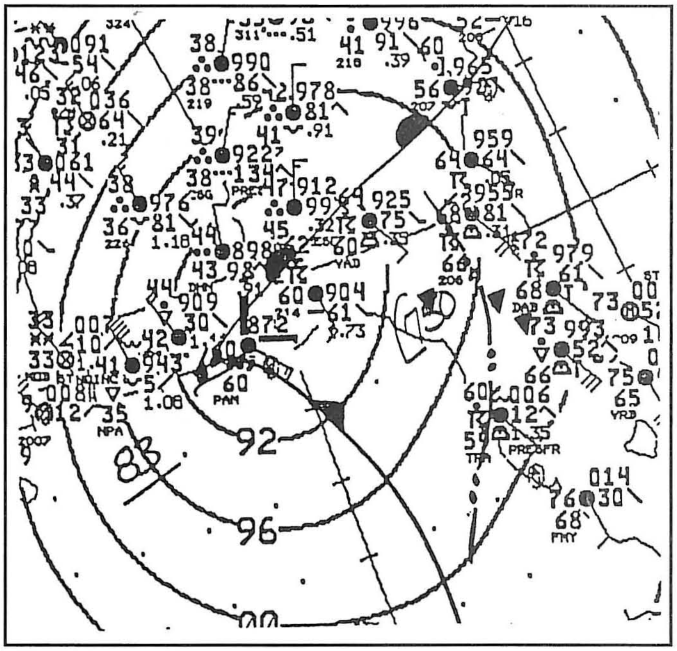

Fig. 3. Surface analysis for 0600 UTC 13 March 1993 depicting an intense cyclone and associated thunderstorms and tornadoes over Florida. Triangles (▼) show locations of strong (F2) tornadoes occurring between 0300 and 0600 UTC.

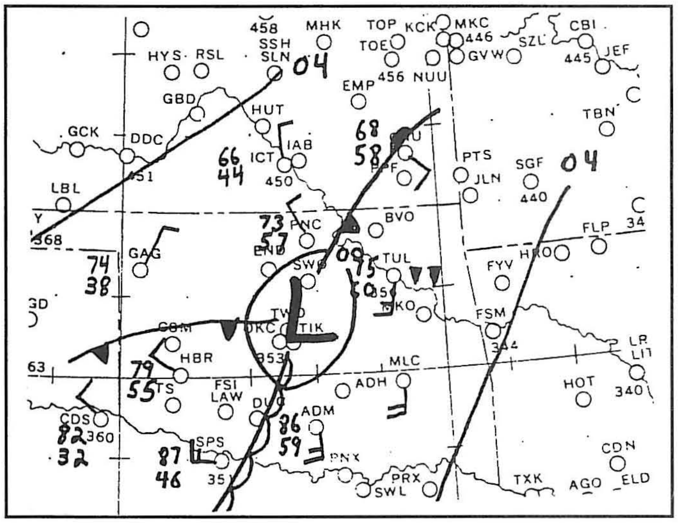

Fig. 4. Surface analysis for 2100 UTC 24 April 1993 illustrating a weak subsynoptic low associated with deadly tornadoes occurring near Tulsa, Oklahoma (TUL) between 2300 and 0000 UTC.

Numerical modeling experiments (Klemp 1987) have indicated that low-level thunderstorm rotation, which is usually a necessary precursor of strong and violent tornadogenesis, may be induced by updraft tilting and convergence of vorticity generated along rain cooled outflow boundaries. However these studies also revealed such outflow boundaries can be smaller scale features generated by the individual storms themselves and thus have lifetimes well under six hours at the time of tornado formation. From the available evidence, it is concluded that while LSB's may directly force deep convection, they do not always play a direct role in the production of tornadoes.

It still must be emphasized that tornadoes, both in this study and in others (Hoxit and Chappell 1975), can and do initiate at considerable distances away from an LSB. While such events appear to be in the minority, forecasters must not totally preclude stronger tornadogenesis where all longer-lived surface boundaries remain relatively distant, especially if a rather vigorous upper tropospheric short wave is approaching a region where the combination of helicity and instability are optimal for severe convection.

Despite weaker correlations between stronger tornadoes and SLC strength and proximity, there may be situations where the development or intensification of surface lows play a decisive role in forcing severe convection. As discussed by Maddox (1993), and McGinley (1986), the isallobaric field concurrent with small scale cyclone development can produce significant increases in low-level convergence and vertical wind shear.

These findings strongly support severe weather forecasters continuing to closely monitor areas of maximum surface convergence, especially where the convergence coincides with surface boundaries. By delineating such regions, one may more effectively anticipate locations of highest tornado threat in an environment where other factors also favor such storms.

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