SOME METEOROLOGICAL ASPECTS OF STRONG AND VIOLENT TORNADO EPISODES IN NEW ENGLAND AND EASTERN NEW YORK

Robert H. Johns[1]

National Weather Service
Storm Prediction Center
Kansas City, Missouri

Russell A. Dorr, Jr.

National Weather Service
Eastern Region Headquarters
Bohemia, New York

Abstract

Storm Data and the NOAA/NWS Storm Prediction Center (formerly known as the National Severe Storms Forecast Center) data base were examined systematically for the years 1950 through 1991 to identify strong and violent tornado episodes occurring in the eastern New York and New England region. Only those cases in which one or more violent (F4–F5) tornadoes occurred or those cases in which the total path length of all strong (F2–F3) tornadoes was 10 miles or greater were accepted into the data set. The qualifying cases were termed significant tornado episodes (STEs) and were subdivided into three classes based on the associated mid-tropospheric (500 mb) flow direction. These classes include northwest flow (NWF; greater than 270°) west flow (WF; 250° to 270°), and southwest flow (SWF; less than 250°). For each of the three classes of flow direction, composite parameter values, synoptic patterns, and hodographs were prepared using surface and radiosonde standard level data. For those violent tornado episodes in the data set, individual proximity soundings were constructed.

Using this methodology, it was found that 22 STEs occurred during the study period, or about one every other year. The STEs were most frequent in summer (June, July, and August) and more occurred in fall than spring. The seasonal frequency distribution also varied with mid-tropospheric flow direction. Cases in WF and NWF regimes occurred only in the warm season (May through August), while cases in SWF regimes occurred from summer into fall (June through November). Possible explanations for these variations in frequency distribution are given.

All of the STEs occurred ahead of a cold front with strong low and mid-level wind fields for the time of year. Instability varies from weak in those SWF cases occurring in the fall to very strong in warm season WF and NWF cases. Violent tornadoes were associated with four episodes. Three of the four violent tornado episodes were associated with warm season WF/NWF regimes and these cases appeared to be associated with modified elevated mixed layer air that had advected into the area from higher elevations of western North America.

[1]Current affiliation and corresponding address is Storm Prediction Center, National Weather Service, NOAA, 1313 Halley Circle, Norman, Oklahoma, 73069.

1. Introduction

Strong and violent tornadoes (F2–F5 intensity, Fujita 1971) are relatively infrequent in that portion of the northeastern United States along and east of the Appalachian ridge crests. However, because of the high population density in portions of this region, the potential for a major tornado disaster cannot be dismissed. Historical studies by Ludlum (1970) indicate that significant tornado episodes have been recorded in the region periodically since the 17th century. Some of these events (e.g., 15 August 1787; 9 September 1821; and 9 August 1878) appear to have been tornado outbreaks resulting in deaths, injuries, and tremendous property damage. More recently, the strong and violent tornadoes that struck Massachusetts and extreme southeastern New Hampshire on 9 June 1953 (known as the Worcester outbreak) resulted in 90 deaths and 1,288 injuries (Penn et al. 1955; Grazulis 1991). Other recent violent (F4) tornado events affecting the region occurred on 28 August 1973 (Grazulis 1991); 3 October 1979 (Hales 1980; Mogil and Campbell 1980; Riley and Bosart 1987; Fujita and Smith 1993), and 10 July 1989 (LaPenta et al. 1990; LaPenta 1992).

Several studies have examined the meteorological conditions associated with severe thunderstorms in the northeastern United States (e.g., Harnack and Quinlan 1988), some specifically focusing on tornado situations (e.g., David 1977; Giordano and Fritsch 1991; LaPenta 1995). Giordano and Fritsch (1991) restricted their investigation to F3 and greater intensity tornadoes. In this study the focus has also been narrowed to strong and violent tornadoes (F2–F5). However, the area of focus is primarily to the northeast of the region studied by Giordano and Fritsch. The region of this study has been restricted to that portion of the northeastern United States generally along and east of the Appalachian mountain axis and north of New Jersey (eastern New York and New England; see Fig. 1), an area that is subject to both marine and continental influences. Although the frequency of strong and violent tornado occurrence in this region is relatively low, it is important for forecasters to recognize situations when there is the potential for a significant event. This study attempts to focus such recognition by examining all strong and violent tornadoes recorded in the region between 1950 and 1991, thus determining the times of year such events are most likely to occur and the synoptic patterns and parameter values associated with their occurrence.

2. Methodology

For the years 1950 through 1991, *Storm Data* and the NWS Storm Prediction Center (SPC; formerly the NSSFC) tornado

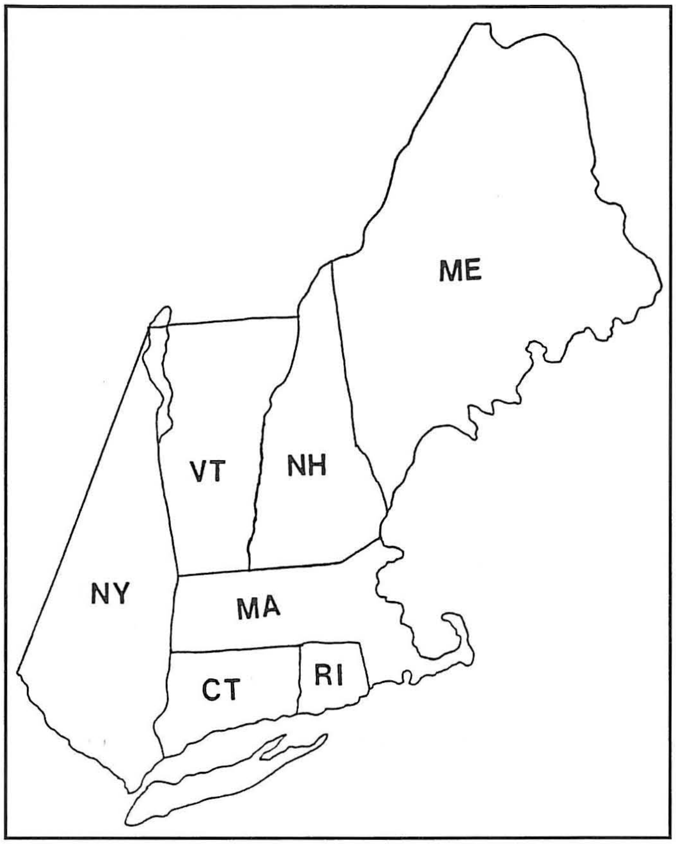

Fig. 1. Area of contiguous United States considered in this study.

data base were examined systematically to identify those severe weather episodes in which F2 or greater intensity tornadoes occurred within the study area. Further, from this preliminary data set only those cases in which: 1) either one or more violent intensity (F4–F5) tornadoes occurred, or 2) the total path length of all strong intensity (F2–F3) tornadoes in a particular episode was 10 miles or greater, were accepted for this study. These criteria were selected in an attempt to eliminate isolated tornado events of a non-mesocyclone nature.

The qualifying tornado episodes (hereafter identified as STEs for significant tornado episodes) were subdivided into three classes depending on the associated mid-tropospheric (500 mb) flow direction. These classes include northwest flow (NWF; greater than 270°), west flow (WF; 250° to 270°), and southwest flow (SWF; less than 250°). The NWF criterion was selected so that comparisons could be made with data sets based on David's (1977) upper flow criteria. David (1977) and subsequent studies by others (e.g., Johns 1982, 1984) defined NWF as 500 mb flow from a direction of greater than 270°. The 500 mb flow direction criterion for SWF was chosen in an attempt to capture most of those cases in which the boundary layer flow (surface through 850 mb) appeared to be significantly modified by the adjacent Atlantic ocean waters. The remaining direction sector between NWF and SWF (250° to 270°) was classified as WF.

For each of the three classes of flow direction (NWF, WF, SWF) composite parameter values, synoptic patterns, and hodographs were prepared using surface and radiosonde standard level data. The composite parameter values were determined by recording values at the midpoint of an episode in both time and area, and then averaging all the values for that particular class. Surface-based lifted index values (Hales and Doswell 1982) were computed using 500 mb as the comparison level. The hodographs for each class were constructed by using the average parameter wind values. The composite synoptic patterns were determined by plotting the locations of synoptic features (e.g., the 850 mb jet) for the midpoint time of each STE and visually determining the mean position of all features in that class.

An enhanced subset of data was obtained for those four STEs that included violent intensity (F4–5) tornado events. Radiosonde soundings and pibal (pilot balloon) vertical wind profiles for those operational balloon releases occurring closest in space and time to the midpoint of each violent episode were examined for pertinent features. Further, using the SHARP workstation (Hart and Korotky 1991) proximity soundings were constructed for the midpoint of each episode using surface data and interpolated sounding and pibal data. Refined wind and instability parameter values were determined from these proximity soundings. Instability values [convective available potential energy (CAPE) and lifted index using 500 mb as the comparison level] were determined using the lowest 100 mb AGL as the lifted layer. Storm motions were obtained either by making time-distance calculations from published accounts of times and locations of tornado occurrence or from radar observations.

3. Results

a. Total cases and monthly frequency distribution

Using the criteria defined in section 2, twenty-two STEs were identified for the period 1950–1991. The STEs included a total of 47 individual strong and/or violent tornado events, or an average of 2.1 per episode. The monthly distribution of STEs agrees with the results of David (1977), with most cases (16) occurring in the summer months of June, July, and August (Fig. 2). Further, the results suggest that STEs are more likely to occur in the fall (Sept—Nov; 5 cases) than in the spring (March—May; 1 case).

Mid-tropospheric flow direction (at 500 mb) associated with the 22 STE cases in the data set varies from 200° to 320°. Further, the monthly frequency distribution appears to vary with the mid-tropospheric flow direction. Those STEs (12) that are associated with WF and NWF (250° or greater) at 500 mb occurred in the period May through August (Fig. 3). The ten STEs that are associated with SWF (less than 250°) at 500 mb occurred in the period June through November, with half of these occurring in the fall months of September through November (Fig. 3). A hypothesis for this seasonal variation in upper flow distribution will be presented in Section 4.

Examination of the times of occurrence of the individual strong and violent tornado events in this study reveals a diurnal frequency pattern similar to what David (1977) found for New England tornadoes in general. David found that 92% of New England tornadoes occur between 1200 and 1900 LST. In this data set 85% of the strong and violent tornadoes occurred during that period (Fig. 4). The remainder of the strong and violent tornadoes occurred during the morning between 0800 and 1200 LST. No strong or violent tornadoes were reported in the study region between the hours of 1900 and 0800 LST over the 42 year period of this study.

b. Synoptic patterns

All but one of the STEs in the data set fit into well-defined synoptic patterns (Figs. 5–8). That one case, the tornado episode

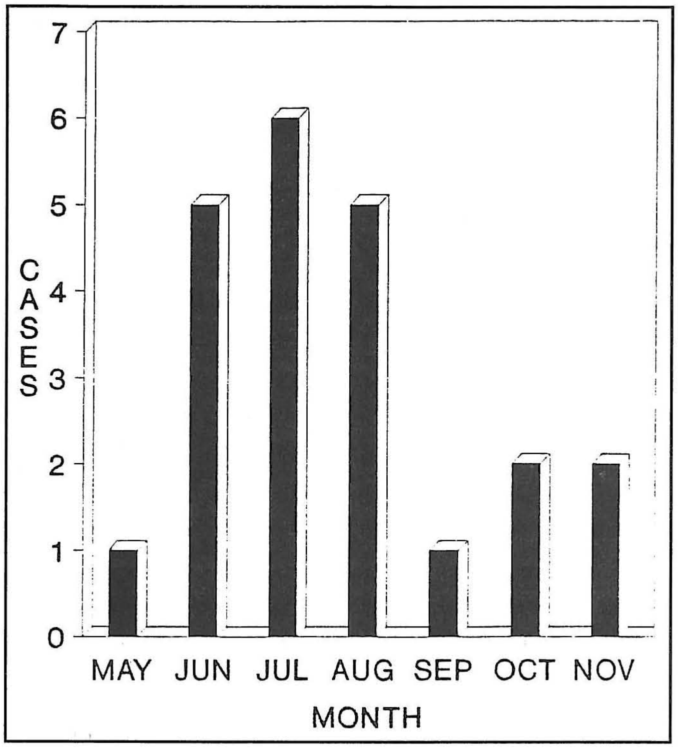

Fig. 2. Monthly frequency distribution for all 22 strong and violent tornado episodes in the 1950-1991 data set.

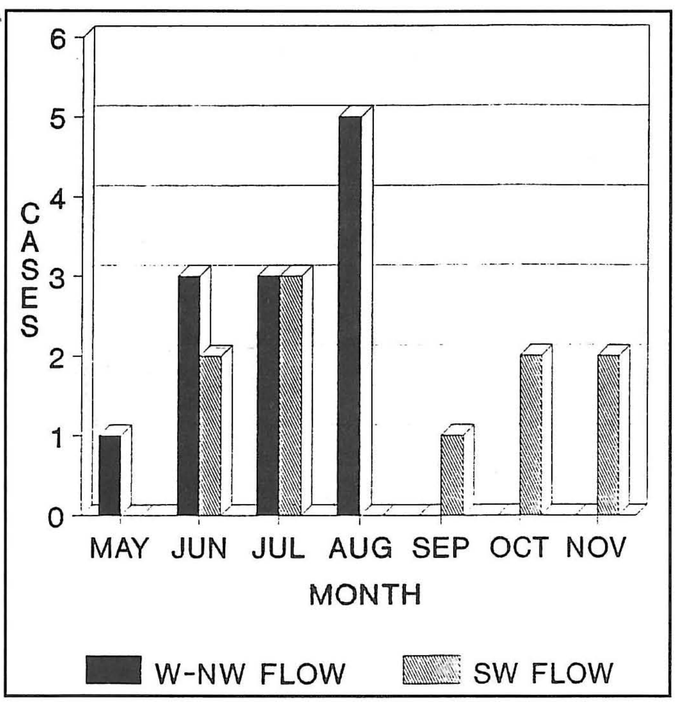

Fig. 3. Monthly frequency distribution of strong and violent tornado episodes by 500 mb flow direction. Episodes associated with a flow direction from 250° or greater (less than 250°) indicated by solid bars (hatched bars).

of 3 October 1979, has not been included in the fall SWF composite (Fig. 8). However, unique synoptic features associated with this case are discussed separately in Section 3e.

The composite synoptic patterns for the different flow regimes (Figs. 5–8) suggest that relatively strong low and mid-level wind maxima (Uccellini and Johnson 1979) and an approaching surface cold front are common features associated with STEs in the study region, regardless of upper flow direction. The orientation of the cold front varies from north northeast-south southwest in the SWF composites (Figs. 7 and 8) to nearly east-west in the NWF composite (Fig. 5). The most common location of surface lows for the STEs in this data set is over southeastern Canada, similar to the location of the lows on David's (1977) surface composites. However, in some of the WF and NWF cases in this study, the low was located over northern New England. A quasistationary or warm front, extending eastward to southeastward from the cold front, was present across the study area in all of the WF and NWF cases, and in all but one of the SWF cases. In the SWF cases this frontal boundary was typically farther north than in the WF and NWF cases, and in one fall SWF case the boundary was north of Maine.

The most common mid-level flow direction associated with STEs in the data set is SWF, which includes almost half (10) the cases. Typically, a broad scale moderate-to-high amplitude upper trough is west of the study region, with a closed low often present to the north of the Great Lakes (Figs. 7 and 8). Also, an embedded short-wave trough and wind maximum are typically approaching the region from the southwest. The wind fields in both low and mid-levels are usually stronger than with either WF or NWF episodes, particularly with the SWF fall cases, and the mid-level maximum lags well behind the cold front.

The jets, upper short-wave troughs, and surface boundary features associated with the WF and NWF STEs (Figs. 5 and 6) display a pattern similar to that with the SWF cases, but with the features shifted clockwise with increasing mid-level flow direction. One difference from the SWF episodes is that the low and mid-level wind maxima are in relatively close proximity in the WF and NWF episodes, with the mid-level maximum sometimes occurring over the surface warm sector.

The question arises as to why the 500 mb maximum in the NWF composite (Fig. 5) is stronger than the maximum in the WF composite (Fig. 6), since both composites represent warm season cases and display upper troughs of similar amplitude. One reason for this difference may be that the NWF value is unrepresentative. The data sample used to prepare the NWF composite is small (only 4 cases) and examination of the data set indicates that one case with an unusually strong 500 mb wind maximum dominated the composite.

Most of the synoptic pattern features associated with NWF and SWF composites in this study are similar to the composites presented by David (1977) in his study of New England tornadoes. The primary differences are that the 500 mb and 850 mb wind maxima are weaker in David's composites. A possible explanation for this difference is that David's data set likely contained many weak (F0–F1) and possibly non-mesocyclone associated tornado events, whereas the current study is limited to cases involving strong and violent tornadoes, which typically are associated with stronger wind fields.

c. Composite parameter values

The composite parameter values associated with the 22 STEs (Fig. 9) show that winds in the low levels (surface and 850 mb) veer correspondingly as the mid-level flow veers. The

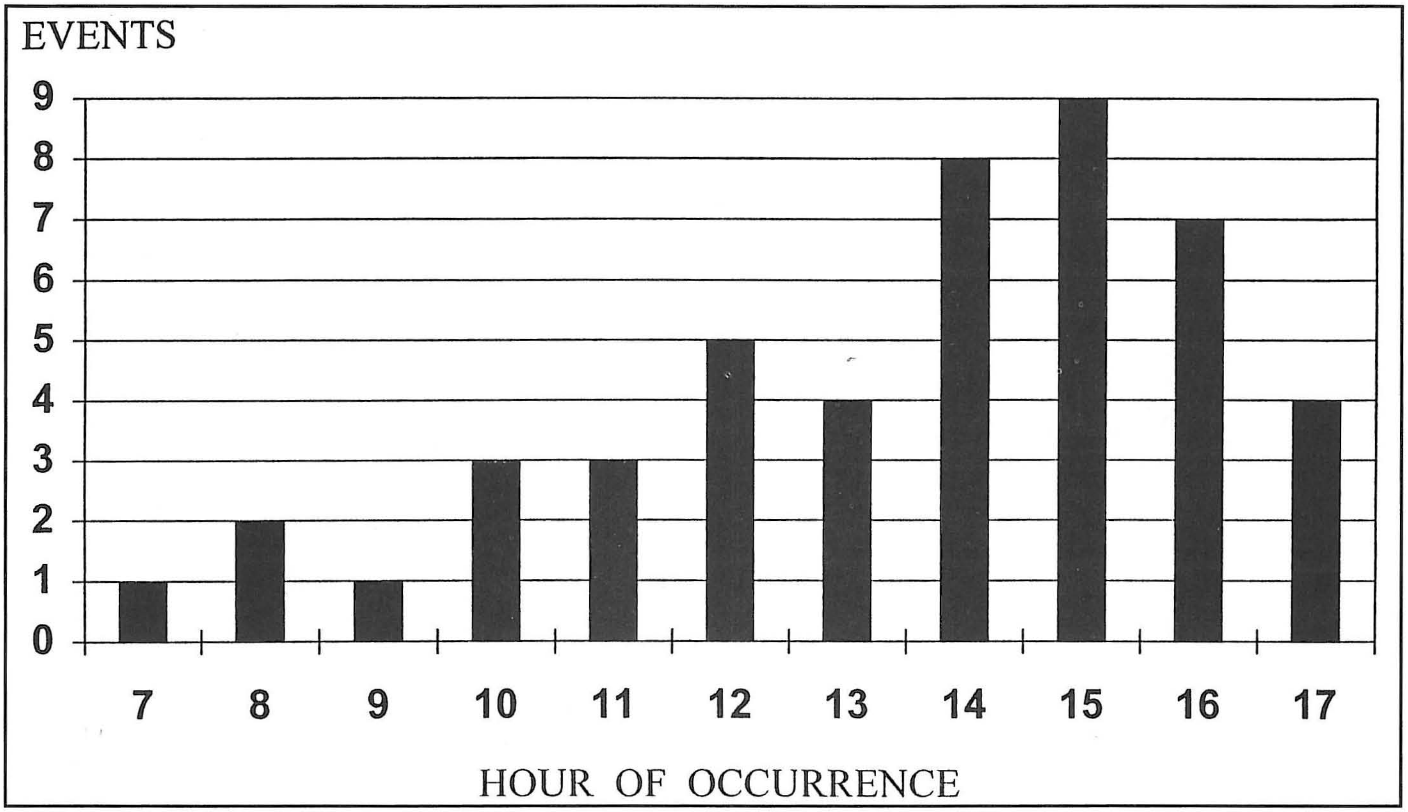

Fig. 4. Hourly distribution in Eastern Standard Time of the beginning times of all strong and violent tornadoes (47) included in the data set. Each time category includes all tornadoes beginning from that hour until 59 minutes past the hour.

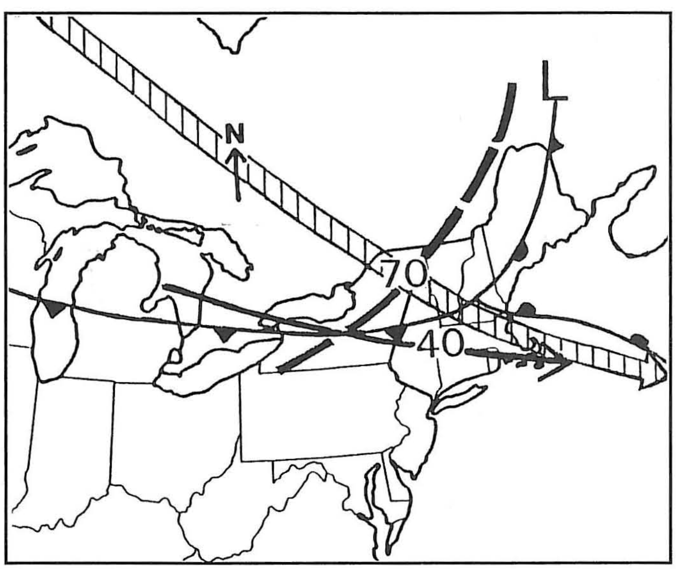

Fig. 5. Composite synoptic features associated with NWF at 500 mb (from 4 cases). Surface frontal symbols conventional. Surface low center indicated by "L". Jet at 500 mb (850 mb) indicated by broad hatched (narrow solid) arrow. Numerical values indicate jet maxima in kt. Dashed line indicates 500 mb short-wave trough position.

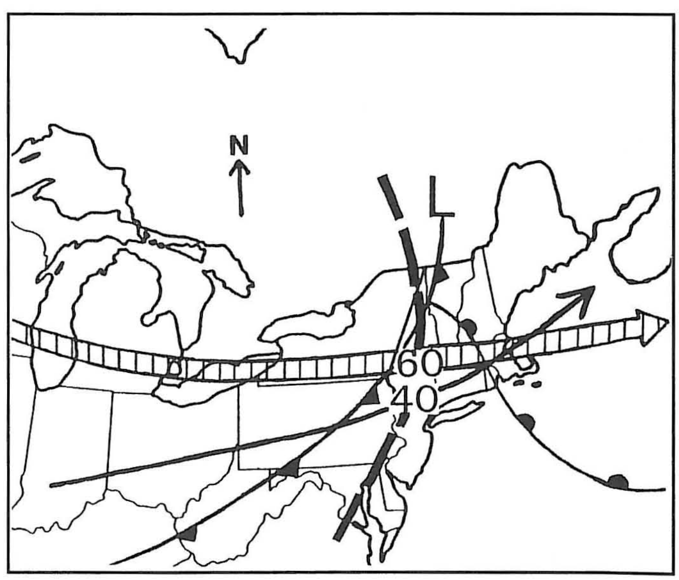

Fig. 6. As in Fig. 5, except for composite synoptic features associated with WF at 500 mb (from 8 cases).

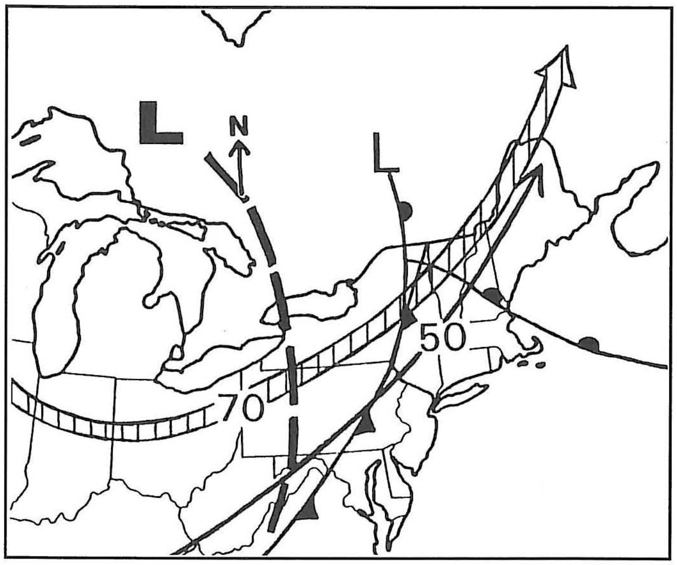

Fig. 7. As in Fig. 5, except for composite synoptic features associated with SWF at 500 mb in the summer (June through August; from 5 cases). Position of 500 mb closed low indicated by bold "L".

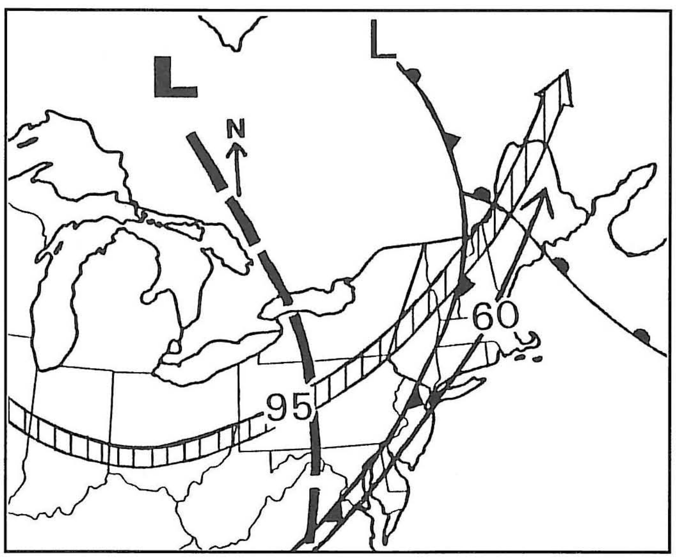

Fig. 8. As in Fig. 7, except for SWF at 500 mb in the fall (September through November; from 4 cases). The SWF case of 3 October 1979 was not included in this composite.

composite 850 mb wind direction for the NWF cases is north of west which agrees with the results of David (1977) and Johns (1984). The low and mid-level wind speeds are strongest in the fall SWF cases, reflecting the stronger wind fields that typically exist in the cooler months of the year.

Low-level moisture values associated with those STEs occurring during the warm season (May-August) are very high, regardless of mid-level flow direction (Fig. 9). Low-level temperatures in the warm season generally increase as the mid-level flow direction increases. The NWF composite 850 mb temperature of 18°C is quite warm for the eastern New York/New England region, even for summer. However, this value compares favorably with what Johns (1984) found with NWF severe weather outbreaks over a larger area of the northeastern United States and with what Giordano and Fritsch (1991) found with strong and violent summer tornadoes over the adjacent mid-Atlantic states region. It appears that the very warm 850 mb temperatures may be associated with modified elevated mixed layer air (Carlson et al. 1983 and others) that has been advected into the area from the higher elevations of the western United States and possibly southwestern Canada. This hypothesis will be discussed in more detail in Sections 3e and 4 .

Temperatures in the mid levels (at 500 mb) associated with the three warm season flow regimes are moderate for the season and, when combined with the high low-level thermodynamic values, result in strong instability (Fig. 9). The strongest instability occurs in the NWF cases (average surface-based lifted index value of -8), possibly reflecting modified elevated mixed layer effects on the instability of the air mass.

Low-level temperature and moisture values associated with those SWF STEs occurring in the fall are much lower than the corresponding values associated with the three warm season regimes (Fig. 9). These lower values contribute to the weak

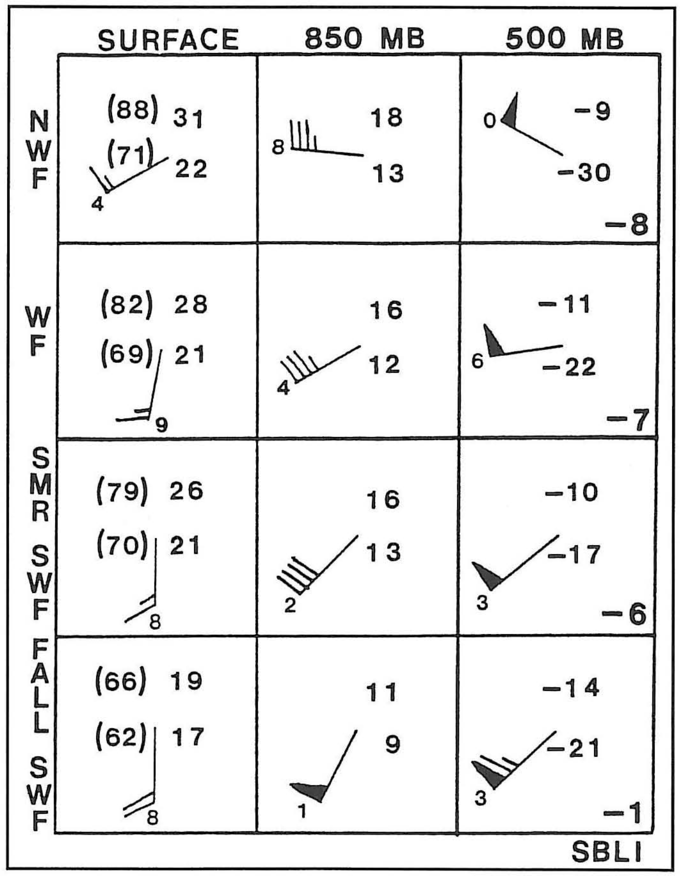

Fig. 9. Composite surface, 850 mb, 500 mb, and surface-based lifted index (SBLI) values (Hales and Doswell 1982) by mid-level (500 mb) flow direction for the midpoint of tornado episodes. Wind symbology conventional with sustained values in kt. Direction of wind indicated by orientation of barb and small number indicating nearest 10° (tens unit only). Number above composite location center indicates temperature, while number near or below location center indicates dew point with values in°C (for surface composites, values in°F are included within parentheses). SBLI values for each flow regime are printed in the lower right section of the 500 mb composite displays.

instability associated with the fall cases. Mid-level (500 mb) temperatures are also colder in fall SWF cases, but apparently do not fully compensate for the weaker low-level thermodynamic values (note small average lifted index value in Fig. 9). The weak instability/strong wind field regime is a common one associated with strong and violent tornadoes occurring during the cooler months of the year (Johns et al. 1990 and 1993).

d. Composite hodographs

Rough mean hodographs have been prepared for each flow regime using the composite surface, 850 mb, and 500 mb wind values discussed in Section 3c (Fig. 10). Although using only three wind levels does not allow one to observe the finer detail of the mean hodographs, some differences are clearly noted. All of the hodographs curve at least somewhat to the right (veer with height), with the summer SWF flow hodograph being the straightest. Since the low-level jet is typically between the surface and 850 mb, these hodographs probably underestimate the degree of curvature below 850 mb.

A major difference between the different flow regimes is the location of the hodograph trace relative to the center point of the hodograph grid. The fall SWF mean hodograph lies generally above the center point owing to the strong southerly component of the winds in such regimes. Also note that the fall SWF hodograph is longer than those of the other regimes, owing to the very strong wind shear between the surface and 500 mb. The summer SWF mean hodograph lies to the right (clockwise relative to the center point) of the fall SWF mean hodograph, since the southerly component of the mean wind is somewhat less than that for the fall SWF mean hodograph. As the flow veers into WF and NWF regimes, the hodograph traces appear farther to the right on the hodograph grid. The NWF mean hodograph lies to the right of the center point and resembles the Giordano and Fritsch (1991) mean hodograph for F3 and greater intensity tornado episodes occurring in July in the mid-Atlantic states, most of which are associated with NWF aloft (see their Fig. 8).

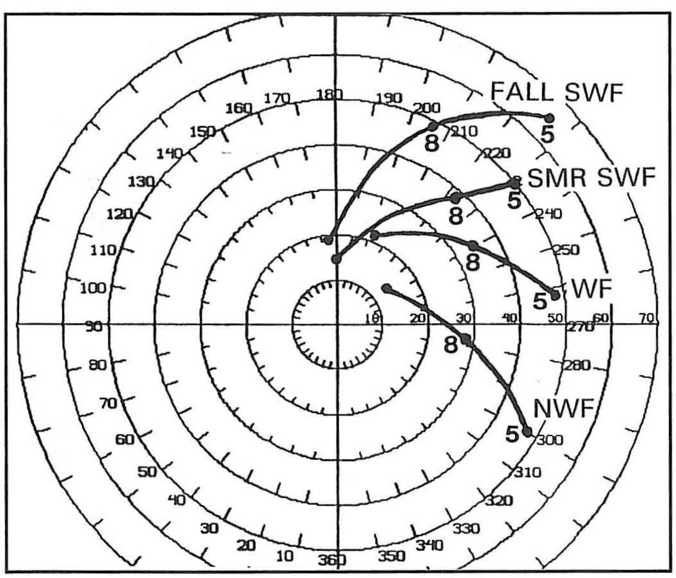

Fig. 10. Composite representation of hodographs for fall SWF, summer SWF, WF, and NWF cases using surface, 850 mb (8), and 500 mb (5) winds (in kt) only. Each ring represents 10 kt.

e. Violent tornado episodes

Violent tornado occurrences (F4–5 intensity) are relatively rare in any portion of the country. For example, during the 1980–1989 decade, the average annual total number of violent tornadoes reported in the entire United States was only seven. Further, in that portion of the northeastern United States considered in this study, only four violent tornado episodes have been recorded during the 42 year period from 1950 through 1991. However, these events resulted in 97 deaths, 1,958 injuries, and tremendous property damage. Because of the impact of these extreme events, we have examined them in more detail for specific characteristics.

Three of the four violent tornado episodes occurred during the warm season. These were the Worcester, MA tornado episode (WOR) of 9 June 1953, the West Stockbridge, MA episode (STK) of 28 August 1973, and the Hamden, CT episode (HAM) of 10 July 1989. The WOR case occurred under mid-level WF while both the STK and HAM cases occurred under NWF. In all three cases, the air mass in the warm sector of the synoptic scale low pressure system was extremely unstable with surface-based lifted index values of -9 to -10 and 100 mb AGL lifted layer CAPE values in the 3000–4000 J kg^{-1} range (Table 1). Very strong instability is typical of NWF and WF cases in the study region (see Fig. 9), and the surface-based lifted index values for these three violent episodes were the lowest among the 22 STE cases in the data set. The strong instability appears to be associated primarily with high values of low-level moisture and very warm 850 mb temperatures. Temperatures of 18 to 20° C were present in or adjacent to the area of event occurrence in all three cases prior to the event (Figs. 11 and 12) and appear to reflect a capping inversion or lid (Farrell and Carlson 1989) that is just above the 850 mb level. Examination of the synoptic patterns and the associated wind and thermal fields in these cases suggests that modified elevated mixed layer air from high elevations of the western North America could be associated with the capping inversion. To test for this possibility, precursor (1200 and 1500 UTC) soundings immediately to the south and/or west of the areas of occurrence were examined. In all three cases, the criteria used by Lanicci and Warner (1991) to determine if an elevated mixed layer capping inversion is present were met[2] For example, in the STK episode, the precursor sounding at John F. Kennedy Airport in New York, NY (Fig. 13), immediately to the south of the area of occurrence, meets all three criteria proposed by Lanicci and Warner, as follows. The relative humidity gradient at the base of the elevated layer exceeds .87% mb^{-1}. Above the base, the saturation wet-bulb potential temperature is greater than zero, and the static stability is less than 4.5° C per 100 mb. The precursor sounding at Albany, NY (Fig. 14), near the area of occurrence, does not meet the relative humidity criterion. However, it does display increasing humidity with height above the inversion, a trait common to elevated mixed layer air.

The wind fields associated with the warm season cases are moderate to strong for summer, particularly in mid levels. However, in two of the cases (WOR and STK) the proximity soundings yield relatively weak helicity values (Davies-Jones et al. 1990; Table 1). Despite this finding, the combinations of instability and 0–2 km helicity values for both cases fall into the

[2]The criteria used by Lanicci and Warner are three primary criteria previously proposed by Farrell and Carlson (1989).

Table 1. Instability and storm relative low-level wind characteristics associated with the four violent tornado episodes occurring in the study region. Storm motion and inflow speeds are in kt. Helicity values are in $m^2\ s^{-2}$ using computed storm motions. CAPE values are in $J\ kg^{-1}$ computed using the lowest 100 mb AGL layer as the lifted parcel. Lifted Index values are computed using 500 mb as the reference level and values are indicated for both 100 mb AGL layer and surface-based parcels.

EPISODE	STORM MOTION	HELICITY 0-2 KM	HELICITY 0-3 KM	INFLOW 0-1 KM	100MB-LYR CAPE	100MB-LYR LI	SFC-BASED LI (SBLI)
WOR 06/09/53	295/30	245	315	160/27	2920	−9	−10
STK 08/28/73	345/30	205	250	201/30	4230	−9	−10
HAM 07/10/89	325/38	590	665	181/46	3070	−7	−9
BDL 10/03/79	180/36	525	555	044/42	580	−3	−4

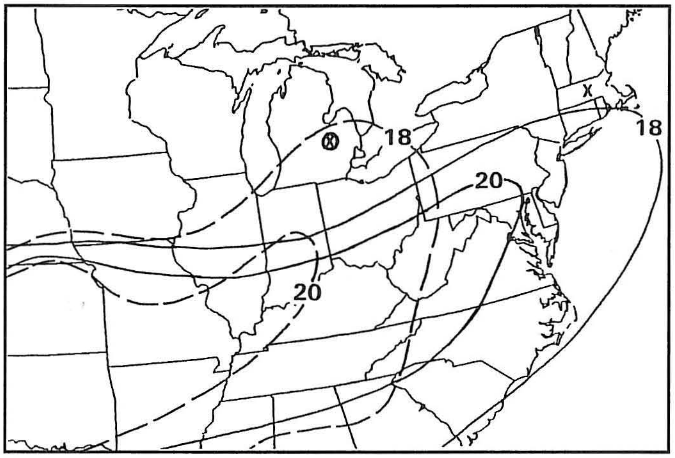

Fig. 11. Depiction of the 18 and 20° C isotherms at 850 mb for 1500 UTC 8 June 1953 (dashed) and 1500 UTC 9 June 1953 (solid). Location of the violent Flint, MI tornado that occurred on the afternoon of 8 June is indicated by a circled "X". Location of the violent Worcester, MA tornado that occurred on the afternoon of 9 June is indicated by an "X".

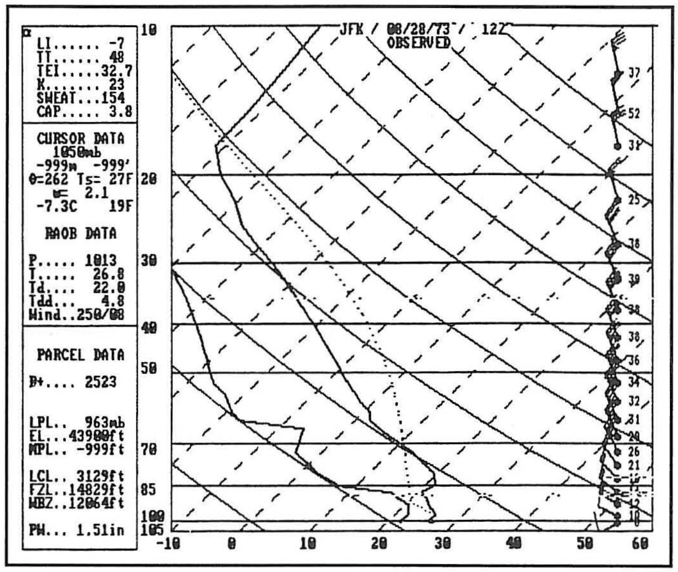

Fig. 13. Skew *T*-log *p* diagram displaying the 1200 UTC 28 August 1973 sounding for John F. Kennedy Airport in New York, New York. Lifted parcel is from the lowest 100 mb AGL.

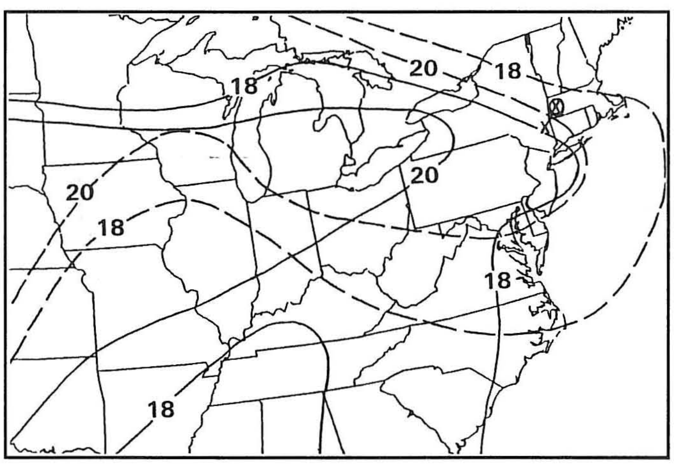

Fig. 12. As in Fig. 11, except for 1200 UTC 28 August 1973 (dashed) and 1200 UTC 10 July 1989 (solid). Location of the violent West Stockbridge, MA tornado that occurred in the early afternoon of 28 August 1973 is indicated by a circled "X". Location of midpoint of violent tornado activity that occurred during afternoon of 10 July 1989 indicated by "X".

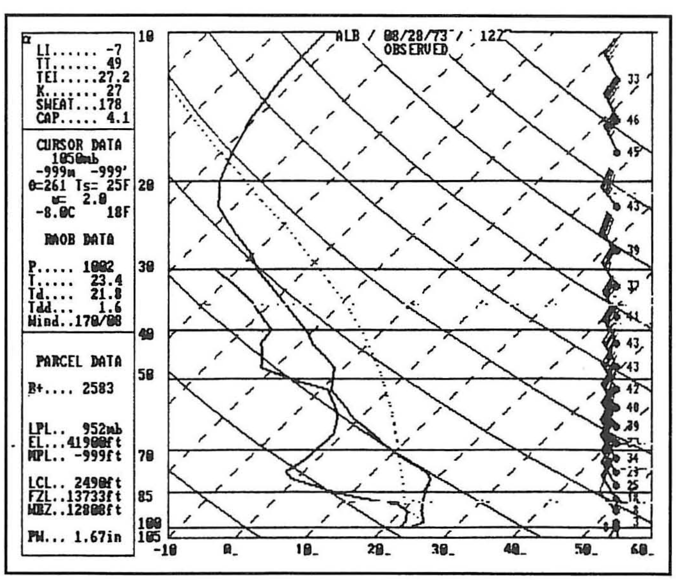

Fig. 14. As in Fig. 13, except for Albany, New York.

range of values associated with violent tornado development generally (see Fig. 15).

The one violent tornado episode in the data set occurring under SWF in the mid levels is the Windsor-Locks, CT (BDL) case of 3 October 1979. The synoptic pattern for this fall episode differs significantly from the fall SWF composite (Fig. 8). In the BDL case, a mid-level closed low was being ejected northeastward across the study region as a strong mid-level trough dug into the Great Lakes region (Fig. 16). The ejecting mid-level low was accompanied by an occluded surface front with the point of occlusion just inland from the Atlantic Ocean (Fig. 17). The violent tornado episode occurred near the warm front just ahead of the point of occlusion as it moved northeastward into the region. The reader is referred to Hales (1980), Mogil and Campbell (1980), and particularly, Riley and Bosart (1987) for additional details on the meteorological evolution of this case.

A proximity sounding constructed for the BDL episode displays weak instability (Table 1). However, the wind fields, particularly in the low levels, are relatively strong and contribute to a large 0–2 km AGL helicity value of greater than 500 $m^2 s^{-2}$. Weak instability and strong helicity values are typical of cool season strong and violent tornado cases and the combination of values associated with the BDL case falls into the range generally associated with violent tornadoes (see Fig. 15).

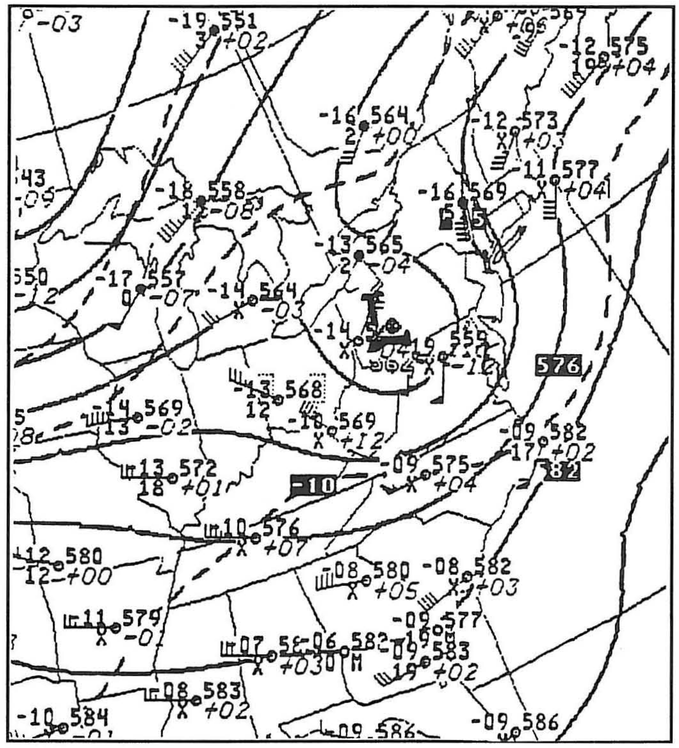

Fig. 16. Ejecting mid-level closed low in the BDL tornado episode as depicted on the 500 mb chart for 1200 UTC 3 October 1979.

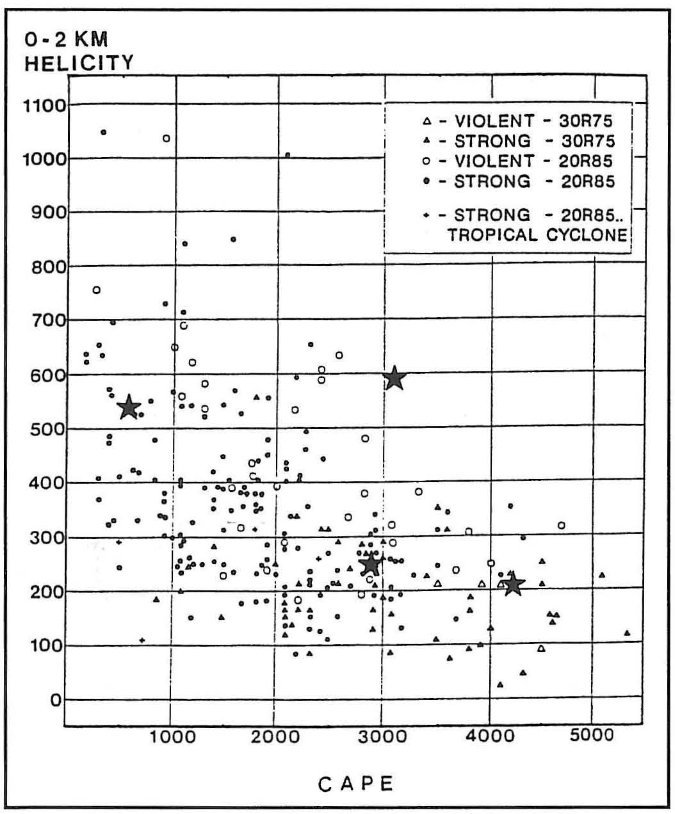

Fig. 15. Scatter diagram (after Johns et al. 1993) showing combinations of CAPE (J kg^{-1}) and 0-2 km AGL helicity (m^2 s^{-2}) using estimated storm motions associated with 242 strong and violent tornado cases. Open circles and open triangles represent violent tornadoes (F4-5 intensity). Superimposed upon this historical data set are large solid "stars" representing the combinations of CAPE and 0-2 km helicity values for the four violent tornadoes in the current study (from Table 1).

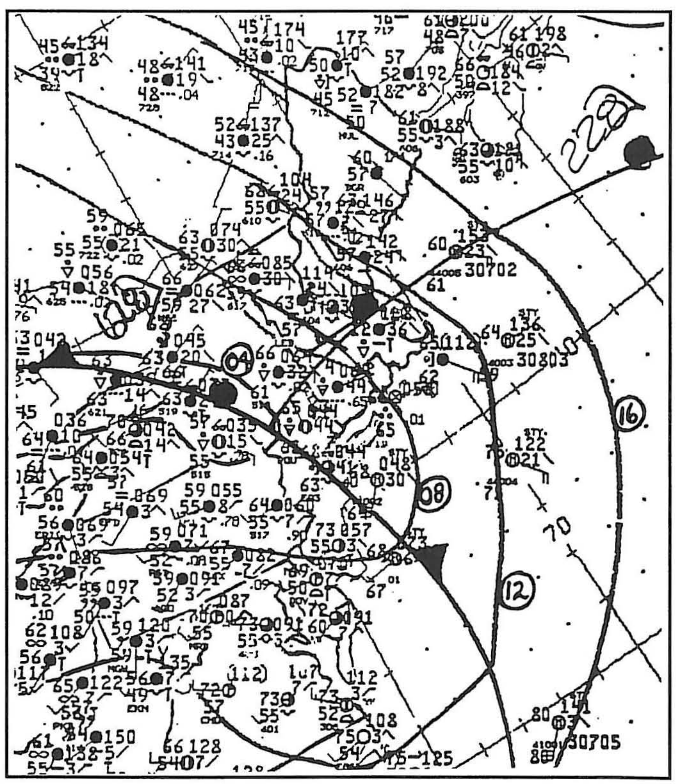

Fig. 17. Surface chart for 1800 UTC 3 October 1979 showing frontal features and point of occlusion just prior to occurrence of BDL tornado episode.

Although the combinations of CAPE and helicity associated with the violent tornadoes in this data set are consistent with what has been found by others (e.g., Johns et al. 1993), readers are cautioned not to limit their expectations for violent tornado development in the study region to those conditions associated with the four violent cases discussed here. The data sample is too small. Rather, one should expect that there could be a wide range of possible combinations of CAPE and helicity associated with violent tornado development in the region, similar to the range displayed in Fig. 15.

4. Discussion

The results of this study indicate that strong and violent tornado episodes (STEs) in the eastern New York-New England region occur, on average, about once every other year. Further, the most likely time of year for such an event to occur is in the summer (June, July, and August), which is later than the spring frequency maximum for all United States tornadoes (e.g., Kelly et al. 1978). There also appears to be a greater risk of STEs occurring in the fall than in the spring.

The seasonal frequency distribution of cases also varies with direction of the mid-level flow. The risk of STEs associated with WF to NWF at 500 mb is primarily restricted to the warm season (cases occurred from May through August). However, the risk of STEs associated with SWF at 500 mb extends from warm season into fall (cases occurred from June through November). The reasons for both the very low risk of STE occurrence in the spring and for the seasonal variation of occurrence with mid-level flow direction appear to be related to the availability of unstable air in the region.

Surface charts associated with STEs occurring with SWF aloft indicate that onshore flow of oceanic air is typical through much of the region in such synoptic patterns. Therefore, instability in the region in SWF regimes is greatly affected by annual temperature cycle of the adjacent sea surface water. In the spring, the stabilizing influence of relatively cold ocean water tends to inhibit strong thunderstorm development when the upper-flow is southwesterly. However, as sea surface temperatures warm to a late summer maximum this inhibiting effect weakens. And, in late summer and fall onshore flow may actually enhance instability in SWF regimes (e.g., see Riley and Bosart 1987). Thus, it appears the annual temperature cycle of the Atlantic Ocean with its delayed late summer maximum plays a primary role in the warm season through fall frequency range for STEs associated with SWF aloft.

In WF to NWF aloft regimes, the surface flow is typically from the southwest to west, and the effects of onshore flow are minimized. However, in such synoptic situations, a high pressure ridge is usually south to southwest of the eastern New York/New England region. Low-level moisture is advected around the ridge from the Gulf of Mexico. It is usually not until late spring or early summer that the subtropical high is persistent enough over the southeastern United States to allow high values of moisture from the Gulf source region to advect all the way to the northeastern United States (Johns 1984).

Two other factors common to the warmer months of the year may significantly affect instability in the region in WF and NWF flow regimes. These are: 1) the effects of transpiration from vegetation, and 2) the advection of elevated mixed layer air into the region from the higher elevations of western North America. Observations (e. g., Segal, et al. 1989; Johns 1993) and numerical simulations (Chang and Wetzel 1991) strongly suggest that during the growing season (late spring and summer) transpiration from vegetation can add significantly to the moisture content of the boundary layer. The contribution to low-level moisture values and potential instability from this source may be an important factor in the development of STEs in WF and NWF regimes.

It appears that modified elevated mixed layer air also plays a role in many of the strong and violent tornado episodes occurring in WF and NWF regimes in the northeastern United States. For example, Farrell and Carlson (1989) have shown that the violent tornado outbreak which occurred on 31 May 1985 in a WF regime in the northeastern United States (close to the region of this study) was associated with elevated mixed layer air that advected into the area from the higher elevations of western North America. Examination of conditions associated with the three violent tornado episodes from WF and NWF regimes in the STE data set suggests also that modified elevated mixed layer air had been advected into the region in all three cases. Further, the very warm 850 mb temperatures associated with most WF and NWF STEs in the data set suggests that when STEs occur with such flow regimes, they are typically associated with modified elevated mixed layer air. The steep lapse rates and capping inversion (or lid) associated with this modified layer serves to enhance instability. This instability is typically released as violent convection near the edge of the lid, as conditionally unstable boundary layer air underruns the lid edge from the west or southwest (see surface and 850 mb flow for WF and NWF regimes on Fig. 9).[3]

In summary, strong and violent tornado episodes are relatively infrequent in the eastern New York/New England region. However, they do occur periodically and, therefore, pose a problem for forecasters. Although this study has examined a relatively small data set and is not expected to depict the entire range of STE scenarios possible, it does highlight meteorological patterns and a limited range of parameter values that have been associated with significant tornado events in the region. When evaluating the potential for tornadoes within the region, forecasters should consider the following points:

1) Violent tornado events (F4–F5 intensity) do occur periodically.
2) Significant tornadoes (F2 or greater intensity) occurring during the warm season are often associated with WF or NWF regimes.
3) Significant tornadoes can occur with onshore boundary layer flow in SWF cases from mid summer into fall.
4) Significant tornado episodes are almost always associated with strong wind fields for the time of year in the low and mid levels of the troposphere.
5) Modified elevated mixed layer air is often associated with significant tornado episodes occurring in WF and NWF regimes.
6) The presence of **both** strong wind fields (see point 4) and modified elevated mixed layer air (see point 5) within or near the region should raise a "red flag" for the potential of **significant** severe convection. If the vertical wind profile is favorable, this convection may take the form of supercells with the possibility of strong or violent tornadoes.

[3]Given a favorable vertical wind profile, this synoptic and thermodynamic pattern can also be associated with vigorous bow echo development (Johns 1993) within the region. The particularly violent progressive derecho event (Johns and Hirt 1987) that crossed the region during the morning hours of 15 July 1995 is an example of such a case (personal communication with Donald Baker, SELS Lead Forecaster).

Hopefully, this information will be helpful in alerting forecasters to some situations in which they should have a heightened awareness for the possibility of a significant tornado event in the eastern New York/New England region.

Acknowledgments

The authors wish to thank Barry Schwartz and Mark Govett of NOAA Forecast Systems Laboratory, and Robert Thompson, Meteorologist in Charge of the NWS Forecast Office (NWSFO) in Taunton, MA for supplying data for this study. The authors also appreciate the many suggestions for improving the manuscript from reviewers, Steve Hunter (Science and Operations Officer at the NWS Forecast Office in Morristown, TN) and George Taniguchi (USAF Ret.). Suggestions for improvement from Ed Szoke of the National Center for Atmospheric Research, Ken LaPenta of the NWSFO in Albany, New York, and by personnel in the Scientific Services Division of National Weather Service Eastern Region Headquarters were also appreciated.

Authors

Robert H. Johns received a B. S. degree in Meteorology at the University of Oklahoma in 1965. He began his employment with NOAA/NWS as a Student Trainee at Indianapolis in 1962. Since then, he has served in the NOAA Corps as an officer on the research ship Oceanographer based in Seattle, and held NWS positions at Ft. Wayne, Chicago, Suitland, MD (NMC), and Kansas City, MO (NSSFC). He was a Lead Forecaster in the SELS unit of NSSFC from 1979 until 1994, when he accepted a position as Science and Operations Officer at the Storm Prediction Center in Norman, OK. While at SELS, he and other SELS team forecasters received the Dept. of Commerce's Silver Medal Award for accurately forecasting the widespread tornado outbreak of 2 April 1982. Mr. Johns is interested in forecasting, applied research, and forecaster training and certification. Besides working as an operational forecaster for most of his career, he has published a number of applied research papers and developed and conducted numerous severe local storms forecasting workshops.

Russell (Bud) A. Dorr, Jr. received a B. A. degree in mathematics from the University of Hawaii in 1966 and his M.S. degree in meteorology from there in 1971. He began his NWS career as a climatologist in 1967. After receiving his degree in 1971, he accepted a position as Hurricane Preparedness Meteorologist at the NWS Forecast Office in Boston, MA. In 19 years at Boston, he served as Satellite Meteorologist, General Forecaster, and Lead Forecaster. In 1990, he became Chief, Meteorological Services Division, for the NWS Eastern Region, where he is currently employed. He authored or co-authored several papers on severe weather, satellite applications and on the March 1993 Superstorm.

References

Carlson, T. N., S. G. Benjamin, G. S. Forbes, and Y. F. Li, 1983: Elevated mixed layers in the regional severe storm environment: Conceptual model and case studies. *Mon. Wea. Rev.*, 111, 1453–1473.

Chang, J., and P. W. Wetzel, 1991: Effects of spatial variations of soil moisture and vegetation on the evolution of a prestorm environment: A numerical case study. *Mon. Wea. Rev.*, 119, 1368–1390.

David, C. L., 1977: A study of synoptic conditions associated with New England tornadoes. Preprints, *10th Conf. Severe Local Storms*, Omaha, Amer. Meteor. Soc., 180–185.

Davies-Jones, R., D. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 588–592.

Farrell, R. J., and T. N. Carlson, 1989: Evidence for the role of the lid and underrunning in an outbreak of tornadic thunderstorms. *Mon. Wea. Rev.*, 117, 857–871.

Fujita, T. T., 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. SMRP Res. Pap. No. 91, Dept. of Geophysical Sciences, University of Chicago, 42 pp.

____________, and B. E. Smith, 1993: Aerial survey and photography of tornado and microburst damage. *The Tornado: its Structure, Dynamics, Prediction, and Hazards. Geophysical Monograph 79,* C. Church, Ed., Amer. Geophys. Union, 479–493.

Giordano, L. A., and J. M. Fritsch, 1991: Strong tornadoes and flash-flood producing rainstorms during the warm season in the Mid-Atlantic region. *Wea. Forecasting*, 6, 437–455.

Grazulis T. P, 1991: *Significant Tornadoes 1880–1989. Volume I: Discussion and Analysis.* Environmental Films, St. Johnsbury, Vermont. 526 pp.

Hales, J. E., 1980: The Windsor Locks tornado. Preprints, *8th Conf. Wea. Forecasting and Analysis*, Denver, Amer. Meteor. Soc., 69–73.

____________, and C. A. Doswell III, 1982: High resolution diagnosis of instability using hourly surface lifted parcel temperatures. Preprints, *12th Conf. Severe Local Storms*, San Antonio, Amer. Meteor. Soc., 172–175.

Harnack, R. P. and J. S. Quinlan, 1988: Some synoptic scale relationships involving severe weather in the northeastern United States. Preprints, *15th Conf. Severe Local Storms*, Baltimore, Amer. Meteor. Soc., 529–532.

Hart, J. A., and W. D. Korotky, 1991: The SHARP Workstation— v1.50. A skew T/hodograph analysis and research program for the IBM and compatible PC. User's Manual. NOAA/NWS Forecast Office, Charleston, WV, 62 pp.

Johns, R. H., 1982: A synoptic climatology of northwest flow severe weather outbreaks. Part I: Nature and significance. *Mon. Wea. Rev.*, 110, 1653–1663.

____________, 1984: A synoptic climatology of northwest flow severe weather outbreaks. Part II: Meteorological parameters and synoptic patterns. *Mon. Wea. Rev.*, 112, 449–464.

____________, 1993: Meteorological conditions associated with bow echo development in convective storms. *Wea. Forecasting*, 8, 294–299.

____________, and W. D. Hirt, 1987: Derechos: widespread convectively induced windstorms. *Wea. Forecasting*, 2, 32–49.

____________, J. M. Davies, and P. W. Leftwich, 1990: An examination of the relationship of 0–2 km AGL "positive" wind shear to potential buoyant energy in strong and violent tornado situation. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 593–598.

____________, J. M. Davies, and P. W. Leftwich, 1993: Some wind and instability parameters associated with strong and violent tornadoes, 2. Variations in the combinations of wind and instability parameters. *The Tornado: its Structure, Dynamics, Prediction, and Hazards. Geophysical Monograph 79*, C. Church, Ed., Amer. Geophys. Union, 583–590.

Kelly, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell III, and R. F. Abbey, Jr., 1978: An augmented tornado climatology. *Mon. Wea. Rev.*, 106, 1172–1183.

Lanicci, J. M., and T. T. Warner, 1991: A synoptic climatology of the elevated mixed-layer inversion over the southern Great Plains. Part I: Structure, dynamics, and seasonal evolution. *Wea. Forecasting*, 6, 181–197.

LaPenta, K. D., 1992: Preliminary guidelines for using helicity, buoyancy, and the energy-helicity index from the SHARP workstation. Preprints, *Symposium on Weather Forecasting*, Atlanta, Amer. Meteor. Soc., 160–165.

______________, 1995: Forecasting tornadic versus non-tornadic severe thunderstorms in New York State. *Eastern Region Tech. Attachment*, No. 95–4A. National Weather Service, NOAA, U.S. Dept. of Commerce, 15 pp.

______________, R. J. Kane, and J. S. Waldstreicher, 1990: A multiscale examination of the 10 July 1989 northeast tornado outbreak. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 548–553.

Ludlum, D. M., 1970: *Early American Tornadoes 1586–1870.* Amer. Meteor. Soc., Boston, Massachusetts, 219 pp.

Mogil, H. M., and J. L. Campbell, 1980: The Windsor Locks tornado of October 3, 1979. Preprints, *8th Conf. Wea. Forecasting and Analysis*, Denver, Amer. Meteor. Soc., 74–80.

Penn, S., C. Pierce, and J. K. McGuire, 1955: The squall line and Massachusetts tornadoes of June 9, 1953. *Bull. Amer. Meteor. Soc.*, 36, 109–122.

Riley, G. T., and L. F. Bosart, 1987: The Windsor Locks, Connecticut tornado of 3 October 1979: An analysis of an intermittent severe weather event. *Mon. Wea. Rev.*, 115, 1655–1677.

Segal, M., W. E. Schreiber, G. Kallos, J. R. Garratt, A. Rodi, J. Weaver, and R. A. Pielke, 1989: The impact of crop areas in northeast Colorado on midsummer mesoscale thermal circulations. *Mon. Wea. Rev.*, 117, 809–825.

Uccellini, L. W., and D. R. Johnson, 1979: The coupling of upper and lower tropospheric jet streaks and implications for the development of severe convective storms. *Mon. Wea. Rev.*, 107, 682–703.