Some Meteorological Characteristics of Significant Tornado Events Occurring in Proximity to Flash Flooding

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ABSTRACT

A study was performed to determine meteorological aspects of environments in which thunderstorms produced both strong or violent tornadoes and flash floods within a limited temporal and spatial domain. It was found that the overwhelming majority of these episodes occurred in the spring and summer months and during the afternoon and evening hours. In most instances, at least some of the tornadoes were present when flash flooding was in progress. The ambient environment usually included an air mass that exhibited both relatively high convective instability and abundant lower-tropospheric moisture, including an average most-unstable CAPE of 3200 J kg^{-1} and mean surface dewpoint and precipitable water values of 70°F (21°C) and 41 mm (1.6 in.), respectively. Storm-relative helicity magnitudes indicated that the vertical wind shear ranged from marginally to moderately favorable for supercell formation in all cases. Surface patterns for each episode were generally similar to patterns earlier studies determined to be frequently attendant with flash flooding, in which preexisting surface boundaries acted to focus deep convection. Most events also occurred east of an approaching and well-defined upper-tropospheric trough and in the left-front or right-rear quadrant of an upper-level jet streak in which upward vertical motion is usually present.

1. Introduction

Deep convection and associated weather phenomena remain a forecasting challenge for operational meteorologists because of both the complexity of the atmospheric processes involved and the hazards posed to the community. In addition to lightning, flash flooding and tornadoes account for nearly all fatalities and a major proportion of property damage associated with thunderstorms across the United States. Statistics show that for the period 1955–95, an annual average of 136 fatalities were attributable to flood events and 73 fatalities were attributable to tornadoes (National Climatic Data Center 1995). Therefore, thunderstorm complexes that produce significant tornadoes with flash floods (hereinafter referred to as STF) within a limited time and area represent an extremely dangerous situation (Corfidi et al. 1990; Rogash and Smith 2000).

Because convective systems conducive for both strong and violent tornadoes and excessive rain pose an exceptional hazard to both life and property, the ability to anticipate and identify such multiphenomena events is critical to the mission of operational meteorologists. Thus, this paper will investigate aspects of significant tornado events (defined here as two or more F2 tornadoes or at least one tornado of F3 strength or stronger) that occur in relatively close spatial and temporal proximity to flash flooding or excessive rainfall. The meteorological characteristics of environments favorable for such incidents, including convective instability, atmospheric moisture content, and surface and upper-air patterns, will be examined and discussed.

2. Methodology and data analyses

Using the National Oceanic and Atmospheric Administration publication *Storm Data*, supplemented by available hydrological and cooperative observer information, convective events from 1992 through 1998 were examined for all of the continental United States east of 100° latitude. [For studies concerning the unique problems in forecasting deep convection over the west-

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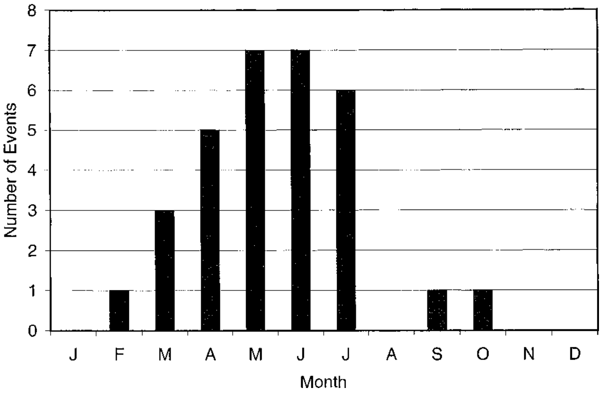

FIG. 1. Monthly frequency distribution for all 31 significant tornadoes occurring with flash flood (STF) events between 1992 and 1998.

ern United States, see Maddox et al. (1980) and Doswell (1980).] Selected cases include those with at least two F2 tornadoes or at least one F3 or stronger tornado and significant flash flood reports with flooding usually occurring over a minimum of three counties. In addition, for each event chosen, the tornadoes must exist within 3 h (either before or after) and within a distance of 250 km (160 mi) of the heavy rain events. For cases selected with only F2 tornadoes, there must be at least two F2 tornadoes that 1) must occur within 250 km and 3 h of the same flash flood reports and 2) must occur within 250 km of one another. Events associated with tropical disturbances were not investigated.

There was some subjectivity in selecting the flash flood cases because of the difficulty in evaluating the quality of information (Maddox et al. 1979, henceforth referred to as M79; Giordano and Frisch 1991). For this particular study, significant flash flood reports included water damage to homes and businesses, widespread flooding and closures of roads and highways, river and stream overflows that caused major disruptions, and rainfall amounts of at least 75 mm (3 in.) in less than 6 h. In addition, to be selected for this study flash flood events had to include significant reports in at least three counties. Because county size varies within different regions, another spatial requirement was at least two of the flood reports must have a distance separation of at least 75 km.

For each case selected, surface, upper-air, and rawinsonde data were examined and analyzed to determine antecedent conditions within 3 h of the evolution of the STF events occurring within the temporal and spatial proximity of flash flooding that meets the requirements noted earlier. For cases involving multiple tornadoes, data closest to the most intense tornado(es) were considered. The construction of proximity soundings first involved an examination of regularly scheduled or special radiosondes released nearest to the tornadoes and within the air mass considered to be most representative of the convective environment. Six-hourly Eta and Rapid Update Cycle (RUC II) model forecasts of wind, temperature, and moisture were subsequently analyzed through the upper troposphere for the area and times of interest. By combining the model information with data obtained from the soundings and hourly surface observations, a vertical profile of wind velocity, temperature, and moisture was interpolated for each point at which F2 or stronger tornadoes ensued. In applying this methodology, it is believed a more representative tornado proximity sounding is derived in comparison with that obtained from using unmodified soundings alone. In most instances, however, regularly or specially launched soundings required only slight modification. Each proximity sounding was further analyzed in detail using an advanced version of the SHARP workstation (Hart and Korotky 1991), with parameters related to instability and wind shear closely examined. In the calculation of instability parameters, a virtual temperature correction was applied.

TABLE 1. Temporal aspects of STF events including times of occurrence and relative time of tornado development with respect to initial flash flood reports.

Time of occurrence (LST)	No. of events
0000–0600	3
0600–1200	4
1200–1800	14
1800–2400	13
Tornadoes developing and ending before flash floods	9 (29%)
Tornadoes developing before and continuing during flash floods	11 (35%)
Tornadoes developing after flash floods	11 (35%)

With respect to the surface and upper troposphere, special attention was directed toward locating such features as surface thermal–moisture boundaries, extratropical cyclone centers, low-level jets, and middle- and upper-tropospheric troughs and jet streaks. As discussed below, lower-tropospheric patterns associated with each episode were generally similar to patterns M79 found attendant with flash flooding. Thus, patterns associated with STF events in this study are categorized in a manner consistent with M79, although important variations from their paradigm are also described and discussed.

3. Environmental conditions and features

a. Temporal aspects

For the period 1992–98, there were 31 STF episodes that meet met the time and space criteria defined above. The monthly distribution plot (Fig. 1) shows 25, or 81%, of these episodes evolved from April through July when significant tornado activity is normally at its peak. An examination of actual time of occurrences (Table 1) indicates the overwhelming number of cases occurred between 1200 and 0000 LST, with several cases beginning during the afternoon and continuing into the evening. The order of occurrence of tornadoes relative to flash flood reports is also explored. As presented in Table 1, for 11 cases (35%) strong or violent tornadoes ensued before but continued after the first flash flood reports.

TABLE 2. Mean environmental conditions and selected forecast parameters for all STF events.

Parameter	
Wind (°/m s^{-1})	
Surface	170/08
850 mb	210/18
700 mb	240/20
500 mb	240/25
250 mb	250/30
Surface dewpoint (°F)	70 (21°C)
850-mb dewpoint (°C)	14
Precipitable water (mm)	41 (1.6 in.)
Most unstable CAPE (J kg^{-1})	3200
Most unstable LI	−9
K index	34
0–3-km storm relative helicity (m^2 s^{-2})	280
BRN shear (m^2 s^{-2})	60
0–6-km total shear (m s^{-1})	23

However, for an equal number of cases, initial flash flooding apparently preceded strong or violent tornado development. There are nine cases (29%) in which all strong and violent tornadoes began and ended prior to the onset of flash flooding.

b. Thermodynamic and vertical wind profiles

From the constructed proximity soundings, critical wind and moisture data are presented in Table 2. Mean values of the most unstable convective available potential energy (CAPE) and the surface-based lifted index (LI) are 3200 J kg^{-1} and −9, respectively, providing evidence of significant convective instability within the precursor environment. The minimum CAPE for all events was 1400 J kg^{-1}, but CAPE values exceeded 3000 J kg^{-1} for 19, or 61%, of the cases. In fact, mean CAPE and LI values determined in this study are conventionally considered indicative of a ''very unstable'' atmosphere among operational meteorologists.

Table 2 also shows abundant moisture being present within the prestorm environment, with an average precipitable water content of 41 mm (1.6 in.), a result consistent with values M79 determined for numerous flash flood events. Similarly, a mean *K* index of 34 indicates ample moisture availability for excessive rainfall in the majority of cases (Funk 1991). In particular, moisture in the lower troposphere is very pronounced, with average dewpoints of 70°F (21°C) at the surface and 14°C at 850 mb. These values are considerably higher than those determined in previous investigations of general tornadic environments. For example, in studies of antecedent conditions for tornadic storms with or without excessive rainfall, Beebe (1956) and Williams (1976) found respective mean surface dewpoints of 61°F (16°C) and 62°F (17°C), and David's (1976) study revealed a mean 850-mb dewpoint of 10°C.

Selected mandatory-level wind data are also presented in Table 2. One important feature is a mean southerly flow of 18 m s^{-1} (35 kt) at 850 mb, which, in conjunction with the high water vapor content in the lower troposphere, suggests substantial lower-tropospheric moisture flux. Also significant is the mean westerly wind of 25 m s^{-1} at 500 mb, which contributes to a composite antecedent vertical wind profile consisting of surface to midtropospheric wind speeds increasing and wind directions veering with height.

From a storm-scale perspective, such a wind shear profile is considered to be conductive for updraft rotation and subsequent thunderstorm intensification and tornadogenesis (Maddox 1976; Weisman and Klemp 1984). This assessment is confirmed by the 0–3-km storm relative helicity [SRH; Davies and Johns (1993), assuming a storm motion vector with a direction 30° to the right and a speed 75% of the 0–6-km environmental wind] calculations, which determined a mean SRH of 280 m^2 s^{-2}, with values in all cases exceeding 100 m^2 s^{-2}. Perhaps of equal importance is that the SRH is greater than 400 m^2 s^{-2} for only 5 of the 31 cases, with values no greater than 450 m^2 s^{-2} for all events. This result suggests STF events may be considerably less likely in areas of stronger 0–3-km wind shear. When considering the lower- to midtropospheric wind shear, the bulk Richardson number (BRN) shear (Weisman and Klemp 1984) was also evaluated, with both the mean and median value of the BRN shear being 60 m^2 s^{-2}. This result is consistent with Stensrud et al. (1997), who determined that tornadic supercells have a relatively high probability of occurrence when the SRH exceeds 100 m^2 s^{-2} and the BRN shear ranges from 40 to 100 m^2 s^{-2}. These results indicate that, for typical STF events, the combination of wind shear and instability was favorable for tornadic supercells.

4. STF meteorological patterns

It was also found for this study that STF events develop within lower-tropospheric meteorological patterns similar to those M79 associated with flash flooding over the central and eastern United States. Thus, STF patterns are classified as either frontal, mesohigh, or synoptic, consistent with the categories established by M79. However, as will be discussed below, mid- and upper-tropospheric features attendant with STF events can differ significantly from those M79 associated with general flash flood occurrences.

a. Frontal events

Ten cases, or 32%, of the STF events occurred in conjunction with the frontal pattern. As illustrated in Fig. 2 the primary features of this pattern include a cold front (or a dryline in several cases) extending south or southwest of a surface low pressure center with a warm or stationary front aligned to the east or southeast. A band of moderate to strong southerly or southwesterly winds at 850 mb usually intrudes northward through the warm sector and across the warm or stationary front at which mesoscale lifting is enhanced. In the mid- and

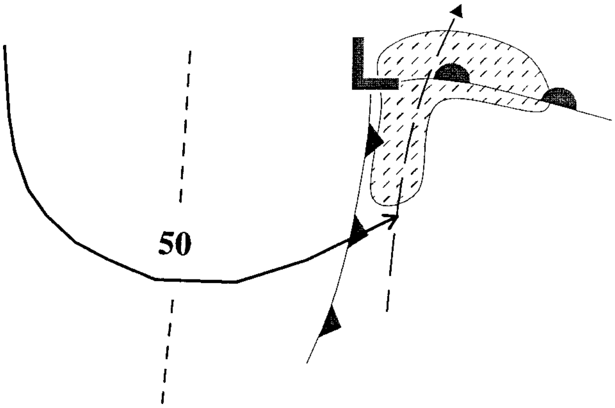

FIG. 2. Composite diagram showing significant features associated with the frontal-type STF pattern. Surface low center is indicated by an L, with conventional symbols used for surface boundaries. Heavy dashed line shows position of 500-mb trough axis. Dashed arrow indicates axis of maximum 850-mb winds, with solid arrow denoting maximum winds above at 500 mb. Numerical value indicates approximate position and speed of upper-tropospheric jet maxima in meters per second. Hatched region indicates area of potential tornadoes and excessive rainfall. See text for further details.

upper troposphere, a height trough is to the west and most frequently is within 800 km of the event. All but one of the cases also occurred within the left-front or right-rear quadrants of upper-tropospheric jet streaks with average maximum wind speeds near 50 m s^{-1}. Synoptic- and mesoalpha-scale vertical velocity analyses (not shown) detected upward motion between 700 and 500 mb for a large majority of STF cases, providing evidence that the mid- and upper-tropospheric upward vertical motion associated with the trough dynamics or jet streak circulations is collocated with the lower-tropospheric forcing along the surface boundaries (Uccellini and Johnson 1979).

During frontal events investigated in this study, most tornadoes develop along or slightly east or southeast of the cold front (or dryline), but several cases also included strong tornado formation along the warm front extending to the east. In all cases, at least some of the flash floods are reported along the warm or stationary front, in proximity to the low-level jet axis. However, there are also instances in which flooding or heavy rain is reported along both the warm and cold fronts or dryline (slightly east of the cold front), further complicating the short-range forecasting and warning processes.

b. Mesohigh events

There are 10 mesohigh (32%) STF events for this study. As depicted in Fig. 3, the primary focusing mechanism is an outflow boundary, located within the warm sector of a surface extratropical cyclone and originating from the evaporative cooling associated with previous or ongoing rainfall. Deepest convection aligns along the outflow boundary and usually along or slightly west of the axis of strongest flow at 850 mb, at which lower-tropospheric wind shear and forcing will be optimal for both tornadoes and flash flooding. In the mid- and upper troposphere, a short- or medium-wave trough approaches from the west with the trough axis within 500 km of the event in the majority of situations. As in the case of the frontal pattern, upper troughs associated with STF mesohigh events have higher amplitude and better definition in comparison with the short waves that M79 found concurrent with mesohigh heavy rain events. In addition, all tornadoes develop within the left-front and/or right-rear quadrants of well-defined (60 m s^{-1} mean wind speed) upper-level jet streaks.

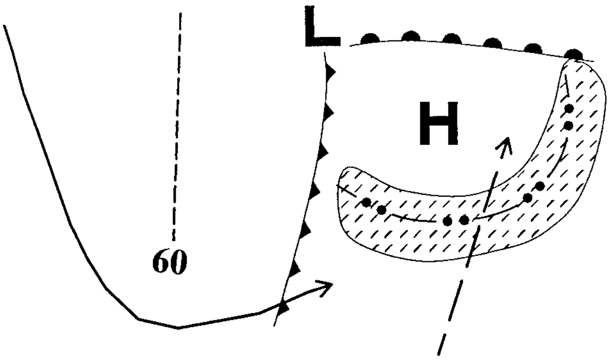

FIG. 3. Composite diagram showing significant features associated with the mesohigh-type STF pattern. An H indicates location of surface high. Other features are similar to Fig. 2.

c. Synoptic events

There are 11 STF events (35%) associated with the synoptic pattern, which is represented in Fig. 4. In typical cases, thunderstorms develop along a slow-moving cold front and subsequently advance north or northeastward nearly parallel to the boundary. Storms consequently may move repeatedly or "train" across a localized area with tornadic supercells sometimes contributing to greatest rain

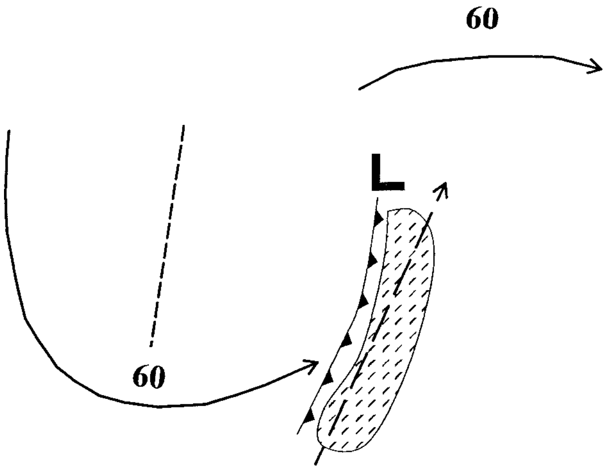

FIG. 4. Composite diagram showing features associated with the synoptic-type STF events. Details are the same as in Fig. 2.

accumulations (Rogash and Smith 2000). The close proximity of the low-level jet both augments the low-level wind shear and helicity required for mesocyclogenesis and maintains the high levels of moisture flux usually necessary for heavy rainfall. In addition, as demonstrated by Corfidi et al. (1996), the presence of a low-level jet is conducive for the upstream propagation or ''backbuilding'' of thunderstorms, another process favorable for heavy rainfall. For the STF synoptic pattern, upstream propagation is especially likely.

For all synoptic cases, a mid- or upper-tropospheric trough approaches the region with the trough usually 800 km or more to the west of the tornadic thunderstorms. However, troughs attendant with the synoptic pattern usually have greater amplitudes and wavelengths in comparison with troughs attendant with the frontal and mesohigh patterns. The majority of synoptic STF events also occur within the left-front and/or right-rear quadrants of upper-tropospheric jet streaks.

5. Summary and conclusions

This study demonstrates that there are both important similarities and differences with respect to environmental conditions favorable for the near concurrence of both significant tornadoes and flash flooding within a limited area. Some common ingredients include an air mass at least moderately but usually very unstable and with relatively high moisture content, especially in the lower troposphere. Environmental wind and moisture characteristics also indicate vertical wind shears favorable for tornadic supercells and lower-tropospheric moisture flux of sufficient magnitude to support heavy rainfall. The overwhelming majority of STF events also occur to the east of and in proximity to an approaching and well-defined midtropospheric trough while simultaneously developing in the left-front or right-rear quadrant of an upper-tropospheric jet streak.

Surface patterns conducive for STF were similar to those M79 determined to be associated with flash flooding or excessive rainfall. For almost all STF cases, tornadic- and flash flood–producing convection developed near or along preexisting surface boundaries along which lower-tropospheric upward forcing and moisture convergence are likely focused. However, depending on the situation, tornadic thunderstorms may either occur along the same boundary, focusing flash flooding, or on a separate boundary.

There were some instances in which thunderstorms that produced tornadoes also contributed directly to excessive rainfall; there conversely were also occasions on which tornadic storms were distinct or separate from convection that contributed to flash flooding. Thus, although data suggest strong and violent tornado formation usually precedes flash flooding, in about one-third of the cases initial flash flooding was reported before the occurrence of tornadoes, further indicating the variability and complexity of STF environments.

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