TORNADOES IN THE EASTERN MID-ATLANTIC STATES REGION: MESOSCALE SURFACE ANALYSES

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Abstract

For many years, there has been evidence of a minor tornado frequency maximum in the eastern mid-Atlantic region of the United States. Previous studies have shown that the maximum is not generated by the large human population there. Thus, there must be some meteorological process(es) at work generating an anomalous number of tornado occurrences in that area. To identify atmospheric conditions at the surface precursor to tornado development in this region 38° to 42° North and 74° to 78° West, fourteen tornado days were examined from the summer months (June-August) between 1975 and 1993. Analyses of hourly surface data (as would be available to operational forecasters) were employed, with emphasis on individual parameter fields (temperature, dew point, etc.) These parameters were evaluated on a case-by-case basis and were also composited. Composites are averages of gridded values, where the grids are centered on the event location at the time of the event. The most striking findings were that tornadoes in the region nearly always formed on or very near a surface thermal axis; also, a large number of events were found to occur very near or in an isolated moisture (dew point) convergence maximum. Composites of the various parameters and one case study are provided for review. The ultimate goal of this work is to augment severe weather nowcasting in the heavily populated eastern mid-Atlantic States region.

1. Introduction

a. Purpose

For at least 45 years, tornado climatologies have identified a minor tornado frequency maximum in the eastern mid-Atlantic States region. Numerous analyses of the United States tornado climatology (e.g., Flora 1958; Kelly et al. 1978; National Weather Service [NWS] 1982; Tecson and Fujita 1982) have consistently shown the existence of this maximum. Though older analyses bore many inaccuracies (Court 1970), more recent efforts have eliminated many of those older biases as in the NWS effort (Fig. 1). The region in question changes location slightly with each analysis but generally lies along a broad swath from Washington, D.C. , to the north and east through Baltimore, and on to Philadelphia. That area is home to over nine million people, a number exceeding the combined populations of Kansas and Oklahoma. This elevated rate of occurrence affecting such high human population densities lends as much relevance to the study of this maximum as those for regions with high tornado occurrence and relatively sparse human populations.

Prior studies (Market and Clark 1992) have shown that this maximum is not artificially generated by the large human population present in the same area. Using 14 years of tornado reports from *Storm Data* and population figures from the 1980 census, they attempted to correlate tornado events to human population on a county-by-county basis to no avail; they found a correlation co-efficient of 0.19 at a confidence interval of 0.95. At the same time they successfully demonstrated that these tornadoes formed a significant secondary maximum as opposed to a random fluctuation in tornado occurrence using the Mann-Whitney-Wilcoxon Rank Sum Test. Here the region of highest tornado frequency (over northeast Maryland, northern Delaware, and extreme southeastern Pennsylvania) was tested against the rest of the region bounded by 38° to 42° North and 74° to 78° West. Thus, a real maximum in tornado frequency had been positively identified over one of the most densely populated sections of the United States.

Having confirmed the reality and significance of the maximum, the task became one of identifying those surface atmospheric conditions which best foster tornado generation in this area. There are a number of papers that focus on the upper air conditions that generate severe weather in the Northeast (Giordano 1987; Harnack and Quinlan 1988) and even focus on the eastern mid-Atlantic States region (Giordano and Fritsch 1991; Iovino 1993). Yet, few studies have addressed the surface scenario leading to severe weather in the Northeast. A study by Williams (1976) examining surface parameters attending tornado occurrences was broken down by season and geographic region. That study provided average surface parameter values for the whole Northeast for the months of June through August, the seasonal period considered in this study. Further consideration of Williams' findings will be given later.

A preliminary study by the author sought to identify a dominant synoptic pattern for tornado generation in the eastern mid-Atlantic States region (38° to 42° North and 74° to 78° West). Examination of 33 tornado days in the region of interest failed to yield a clearly defined surface synoptic setting in which tornadoes are generated. However, more than half of the tornadoes studied developed near warm or cold frontal boundaries or non-frontal troughs of the like described by Weisman (1990a, b). Fortunately, in an anticipated tornadic atmosphere, any such boundary would be monitored and viewed with suspicion. Ultimately, it was necessary to search for signatures on a finer spatial and temporal scale than the synoptic.

In examining the sub-synoptic atmosphere, standard surface observations were of greatest interest, as they are the most easily and frequently monitored. Evaluation of atmospheric parameters and recognizing patterns therein are two primary

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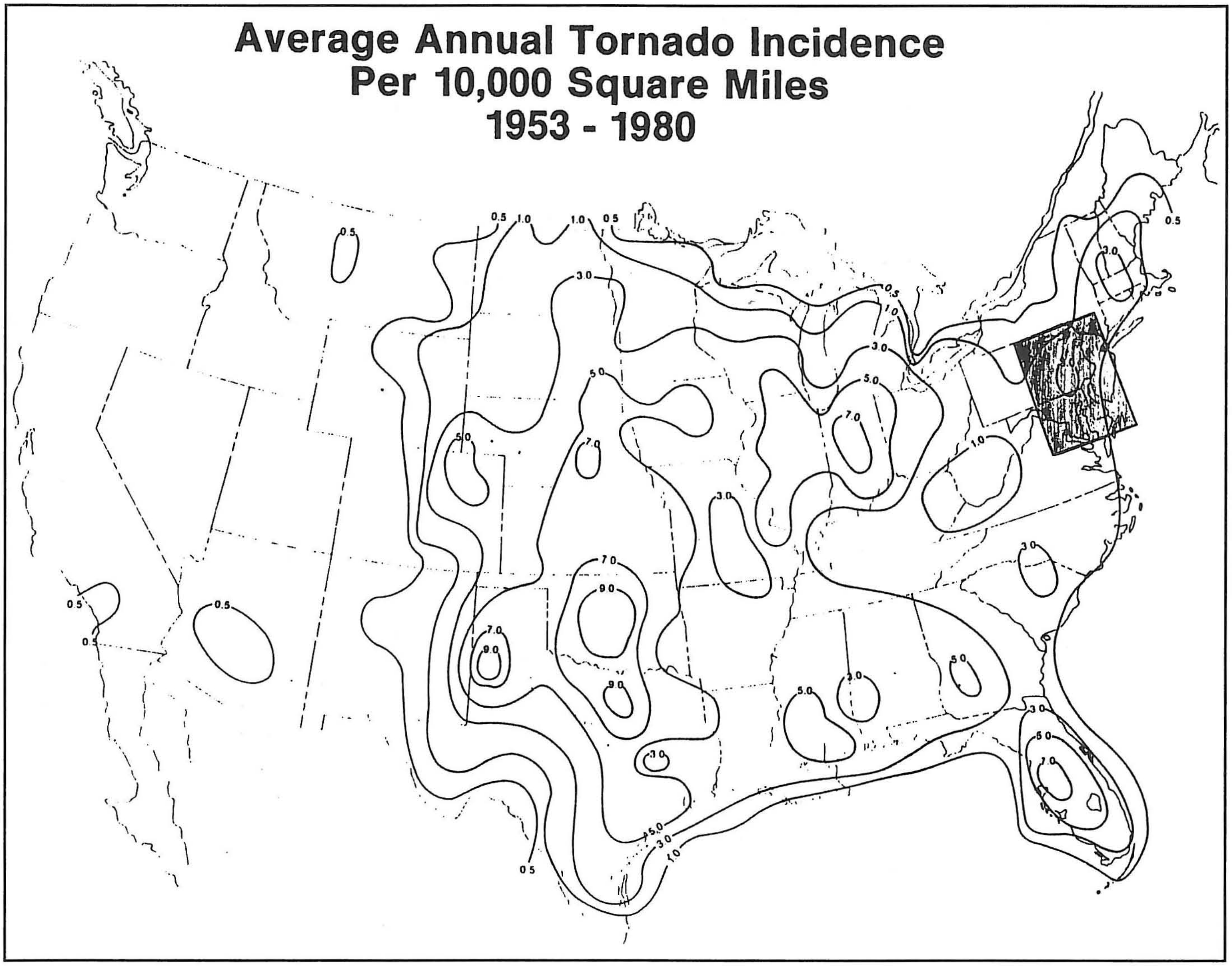


Fig. 1. National tornado incidence map reproduced from the National Weather Service (1982). Boxed, shaded region is the area of concern for this study, enclosing 38° to 42° North and 74° to 78° West.

keys to the severe weather forecasting process (Johns and Doswell 1992). This work aims to provide those keys as they apply in the eastern mid-Atlantic States region. Those surface parameters which seem most important will be scrutinized as will the patterns that attend them.

b. Data

Of the 33 tornado days mentioned above, 14 days were examined from the period 1975 through 1993 (Table I) including events near both warm and cold frontal boundaries. These 14 events provided a representative sample of the tornadic activity in the region while allowing the study to be completed in a timely fashion. Only events in the warm season (June through August) were considered. All events were chosen from the region enclosed by 38° to 42° North and 74° to 78° West. In addition, no preference was given to stronger tornadoes that occurred there, as they are relatively rare.

At least 38 tornadoes were reported in the eastern mid-Atlantic States region on the 14 days mentioned before based on reports from the University of Chicago's DAPPL tape and *Storm Data*. For dates prior to 1992, surface data for those days were obtained from the NOAA National Climatic Data Center (NCDC) on microfiche and manually digitized. In the years 1992–93, data were automatically archived onto disk. Temperature, dew point, equivalent potential temperature Theta-e, dew point flux divergence (DPFD), and 2-hour altimeter change fields (not presented here) were examined for three hours preceding each tornado. Emphasis was placed on data from the hour immediately preceding the event, although the evolution of those fields was also important.

c. Method

Composite analyses are for the hour directly before the tornado and are centered on the event site. Compositing was chosen to arrive at representative parameter fields in a typical surface tornadic environment in this particular region. Values for the composites were taken from GEMPAK objective analysis grid-point output and subjected to a simple average. The spacing of the grid-points was every third of a degree of latitude and longitude. Given the small area examined, no consideration

Table 1. Tornadic events studied and used to derive the composite analyses.

Date	Time *UTC*	Location	F-scale
From *DAPPL Tape:*			
06-20-75*	0000	39.6°N, 77.1°W	F 1
06-28-76	2200	40.6°N, 77.1°W	F 1
06-30-76*	1800	40.6°N, 75.8°W	F 1
06-02-77*	0000	40.6°N, 75.3°W	F 1
06-09-77	1500	39.1°N, 75.3°W	F 2
08-17-77*	1800	39.6°N, 75.8°W	F 1
06-08-80*	0000	39.8°N, 76.8°W	F 3
08-11-83*	2000	40.6°N, 75.3°W	F 1
07-05-84*	2300	40.3°N, 75.6°W	F 2
08-30-85*	1900	39.8°N, 76.1°W	F 1
From *Storm Data:*			
06-19-92*	1720	St. Thomas, PA	F 0
07-17-92*	2212	2 N Hummelstown, PA**	F 1
	2234	2 N Palmyra, PA	F 1
	2244	3 N Annville, PA	Funnel Cloud
	2245	2 W Washingtonville, PA	F 1
07-31-92	1947	2 NE Tullytown, PA	F 0
06-09-93*	2020	Near Coatesville, PA	F 1

*Events used to prepare the parameter composites.
**Location from city in statute miles and compass directions (e.g., 2 N is two statute miles north of ⟨*location*⟩).

was made for map factors. These data were then re-analyzed for the final contour analyses which follow.

Of the fourteen days analyzed, eleven included tornadoes sufficiently inside the data area to yield robust gridded values. Events close to the coast lacked data over the ocean for any sort of meaningful analysis. Thus, three of the fourteen cases were not included in the grid averages for each composite.

One case study is provided for an F3 tornado occurrence near Philadelphia, Pennsylvania, on 27 July 1994. Hourly surface meso-analyses will be shown, depicting the evolution of surface parameter fields in a tornadic environment. This case study illustrates useful parallels with the composite analyses.

2. Composite Parameter Analyses

a. Temperature

Initially, temperature was of prime consideration, as regions of higher surface temperatures in a tornadic atmosphere typically imply greater buoyancy. However, the composite thermal field is shown (Fig. 2) with a poorly-defined temperature axis lying just east of the event site (approx. 50 km), oriented southwest-northeast. West of the event, the isotherm pattern troughs somewhat, defining the presence of colder air in the post-convective atmosphere.

It should be noted that some detail may have been lost in these analyses due to the compositing process. In the temperature field, individual cases often exhibit a thermal axis that is more pronounced. The cold air to the west is usually better defined in each separate case also. Regardless, this arrangement places the tornado on a temperature gradient with cold air to the west generated by such mechanisms as reduced insolation due to the approaching cloud mass, cold downdraft outflow, or simply post-cold frontal flow. In some cases used for the composites cold frontal boundaries had already pushed into the northwestern portion of the grid, resulting in appreciably lower temperatures.

Nevertheless, the composite places the average tornado about 50 km west of the thermal axis. The temperature at the event site averages 28°C (from the four grid points forming a box around the event location), with a sample standard deviation of 2.2°C.

b. Dew point

Moisture was examined using the dew point field which is more poorly defined than that of temperature (Fig. 3). While a gradient does exist west of the event site, the pattern becomes diffuse in the eastern half of the grid. As with temperature, individual cases often have axes that are better defined than indicated here. Still, we can see the presence of drier (colder) air in the northwestern portion of the grid. Composite dew point temperatures average 21°C over the event site (using the above method applied to temperature), with a sample standard deviation of 1.4°C.

c. Equivalent potential temperature

The Theta-e field is better defined than that for dew point, but less so than that of temperature. This is not surprising, as Theta-e can be thought of as a parameter for combining the thermal and moisture fields. Figure 4 shows that the Theta-e field does exhibit a vague axis feature to the east of the event site, thus mirroring the temperature field.

The composite event occurs on the leading edge of an appreciable Theta-e gradient, which is known to be a favored area for severe weather development (Ruthi and Kimple 1977; Brady et al. 1982). However, the composite indicates the tornado developing just west of the axis of the warmest, most humid, and perhaps, most buoyant surface atmosphere.

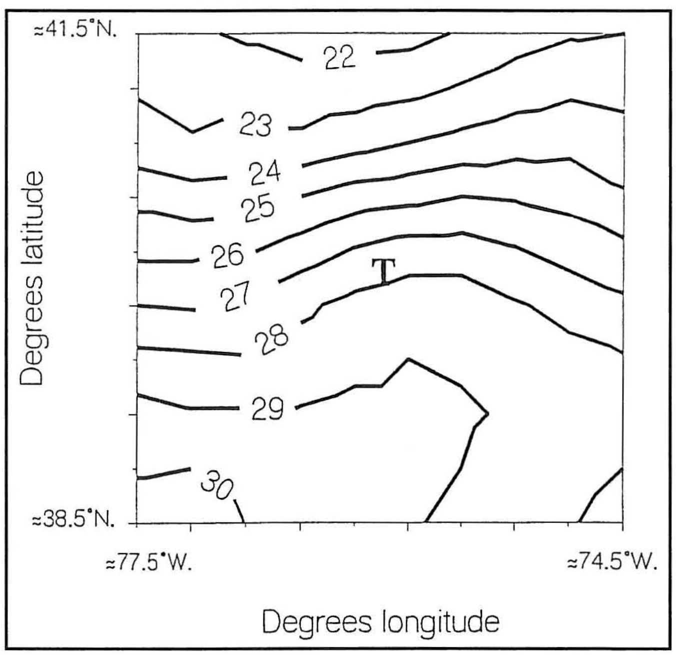


Fig. 2. Composite temperature analysis (°C) for the hour prior to tornado occurrence. The bold T at the center represents the tornado location and will be so in Figs. 3–5 also.

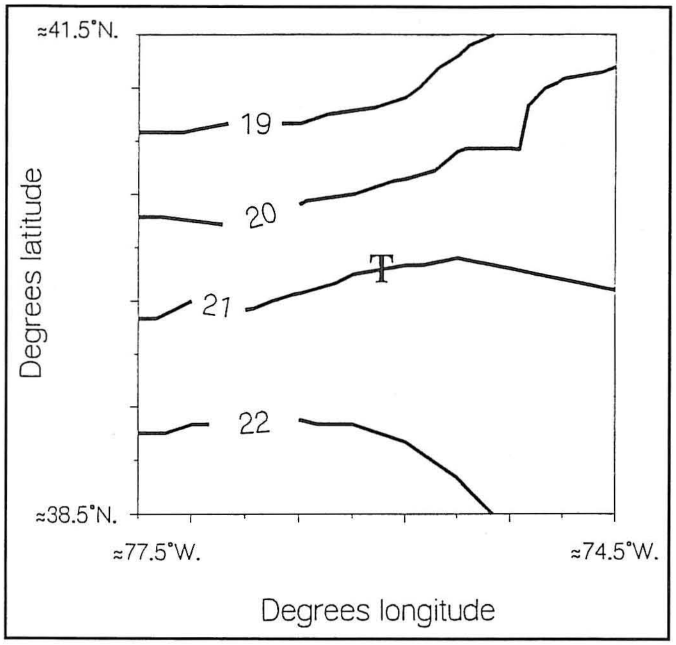


Fig. 3. Composite dew point analysis (°C) for the hour prior to tornado occurrence.

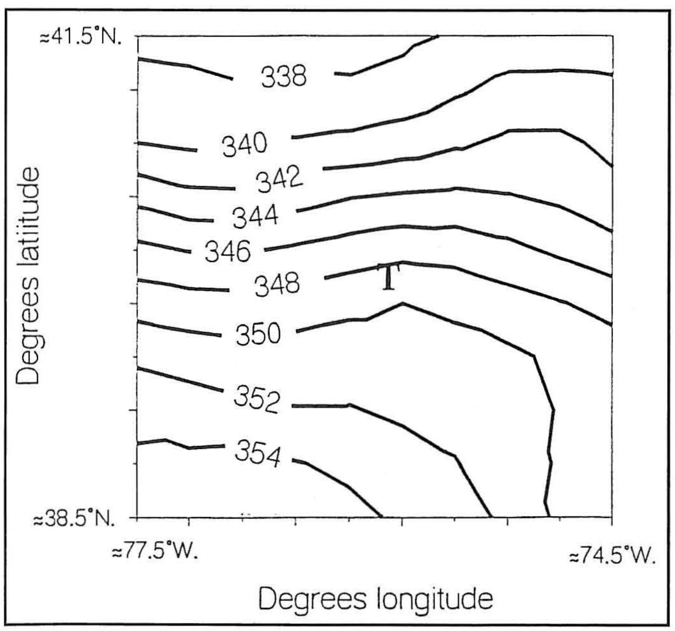


Fig. 4. Composite Theta-e analysis (°K) for the hour prior to tornado occurrence.

d. Dew point flux divergence

While the dew point field alone may not yield much information, transports in that field do, and dew point flux divergence, given by:

$$\text{DPFD} = T_d(\nabla \cdot \vec{V}) + \vec{V} \cdot \nabla T_d$$

is the most revealing of all the parameters considered. Here:

- T_d is the surface dew point
- ∇ is the del operator, and
- $\vec{V}$ is the observed wind.

Surface moisture convergence is a well-known parameter for defining areas of severe weather generation (Newman 1972; Waldstreicher 1989). Dew point flux divergence (DPFD) was focused on after work by Hirt (1982), as it provided useful values and patterns for comparison. Hirt expected to find the strongest severe weather on the gradient of a dew point flux divergence-convergence couplet and less severe weather in or east of an isolated convergence center.

However, Fig. 5 shows the typical tornado occurring just east of an extremely well-defined DPFD convergence center and without a divergence center to the east to form a couplet; quite similar to the findings of Livingston and Darkow (1979) for the Midwest. It should be noted here that many of the individual cases used to make the composite analysis included tornadoes that occurred in the center of a convergence maximum (six of the eleven). Moreover, the evolution of the maxima used to form the composite events was usually characterized by quasi-stationary motion. Of the parameters examined, DPFD appears to be the best parameter to use in locating those regions most prone to tornado development, as its signature is best defined. Typical values for DPFD in the tornado vicinity were -8×10^{-4} °C s^{-1} indicating moisture convergence, although individual cases exhibited values that were much higher (from -2 to -23×10^{-4} °C s^{-1}, the weakest and strongest cases in the composite group).

e. Summary

These composites were created for the hour directly prior to tornado occurrences during the months of June-August. Williams (1976) determined surface parameter values in tornadic

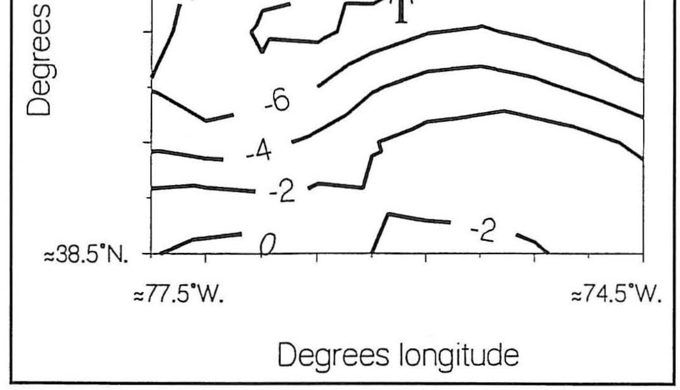


Fig. 5. Composite dew point convergence analysis (values $\times 10^{-4}$ °C s^{-1}) for the hour prior to tornado occurrence.

atmospheres for those same summer months in the Northeast. Williams found that the average surface temperature 0-3 hours prior to tornado occurrence in the Northeast was 77°F (25.0°C), while the dew point average was 66°F (18.9°C). This compares well with the above values of temperature (28°C) and dew point (21°C) determined for this study. The values presented here are higher, as they are from the southern extreme of Williams' Northeast area and were calculated only from the hour prior to the tornado occurrence. Values for DPFD and Theta-e were unavailable for comparison.

3. Case Study—27 July 1994

On the night of 27 July 1994, approximately 10 tornadoes occurred in Virginia, Maryland, and Pennsylvania ranging up to F3 in intensity. These events took place on the warm side of a quasi-stationary front that paralleled the coast (Fig. 6). At 0000 UTC 28 July 1994, upper air analyses (not shown) depicted a broad trough present in the Midwest over Illinois and Wisconsin. Weak isentropic upslope flow was present in the lower troposphere over the mid-Atlantic States region, while farther aloft, at 250 mb, the right entrance region of a linear jet streak existed over the same region. Both features favor synoptic-scale rising motion.

Near the end of this mini-outbreak, an F3 tornado occurred in Limerick Township in eastern Pennsylvania, killing three people and injuring at least 25 more. This particular event was unusually strong, especially for the time of day when it occurred, and will be the focus of the case study.

Examination of the thermal field (Fig. 7) clearly shows the thermal gradient attending the quasi-stationary front. The Limerick tornado occurred at 0350 UTC on 28 July 1994. While the event did not take place on a thermal axis *per se,* it did develop in the warmest surface air in the region. This parameter's surface pattern evolved little over the prior 3 hours (not shown). Much like temperature, the dew point pattern (Fig. 8) also evolved little.

In contrast, a Theta-e axis takes form and propagates north and east, arriving over the event site at the time of occurrence (Figs. 9a-d). As we saw before, the warmest, most humid air resided along the coast in the vicinity of the Limerick tornado. Theta-e being a useful tool for combining thermal and moisture

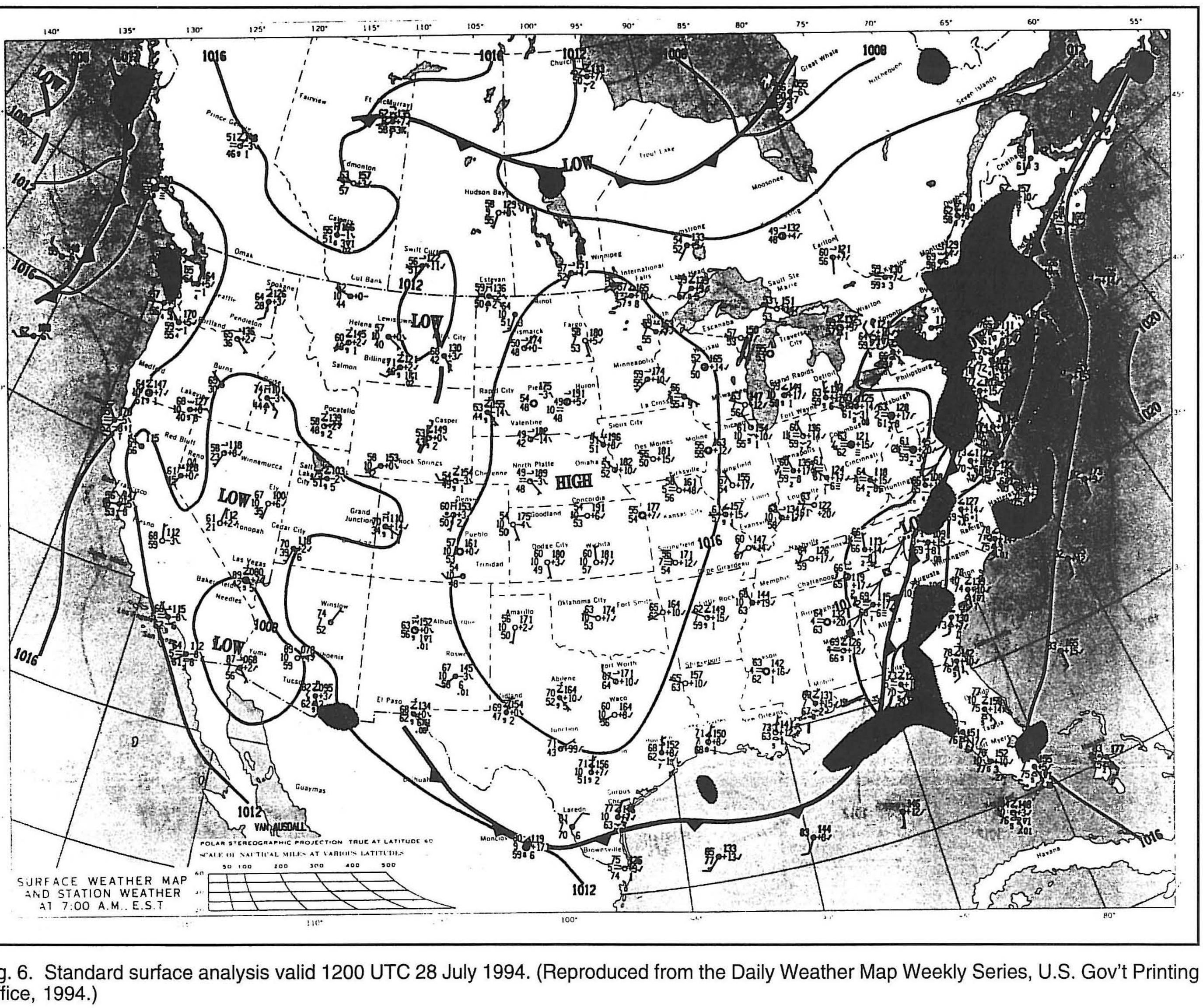


Fig. 6. Standard surface analysis valid 1200 UTC 28 July 1994. (Reproduced from the Daily Weather Map Weekly Series, U.S. Gov't Printing Office, 1994.)

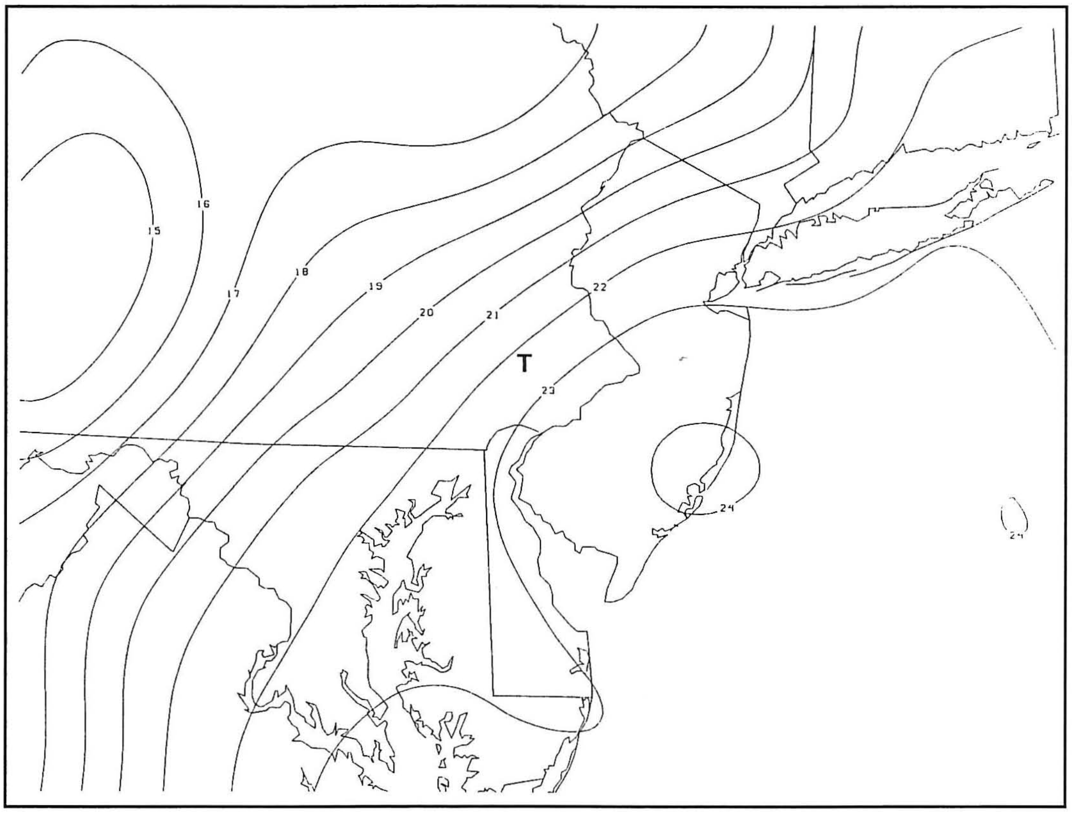


Fig. 7. Temperature analysis (°C) valid at 0400 UTC 28 July 1994. The bold T highlights the tornado location in this figure, and also in Figs. 8, 9d, and 10d.

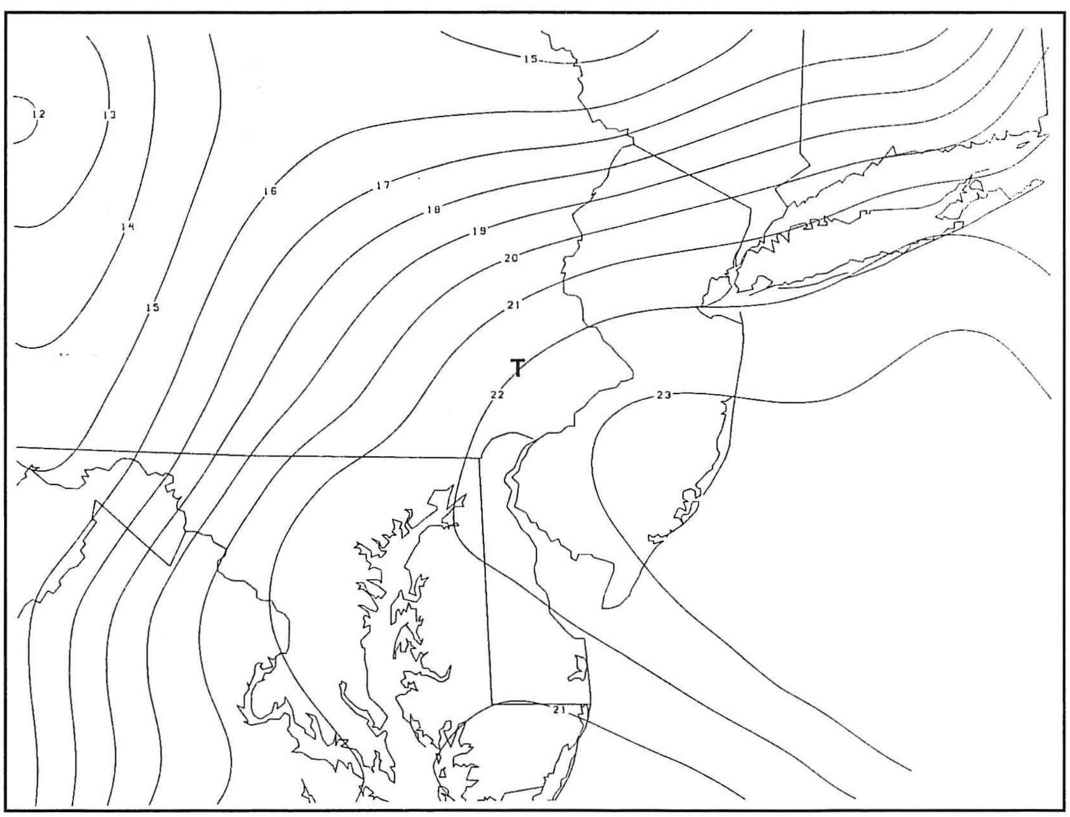
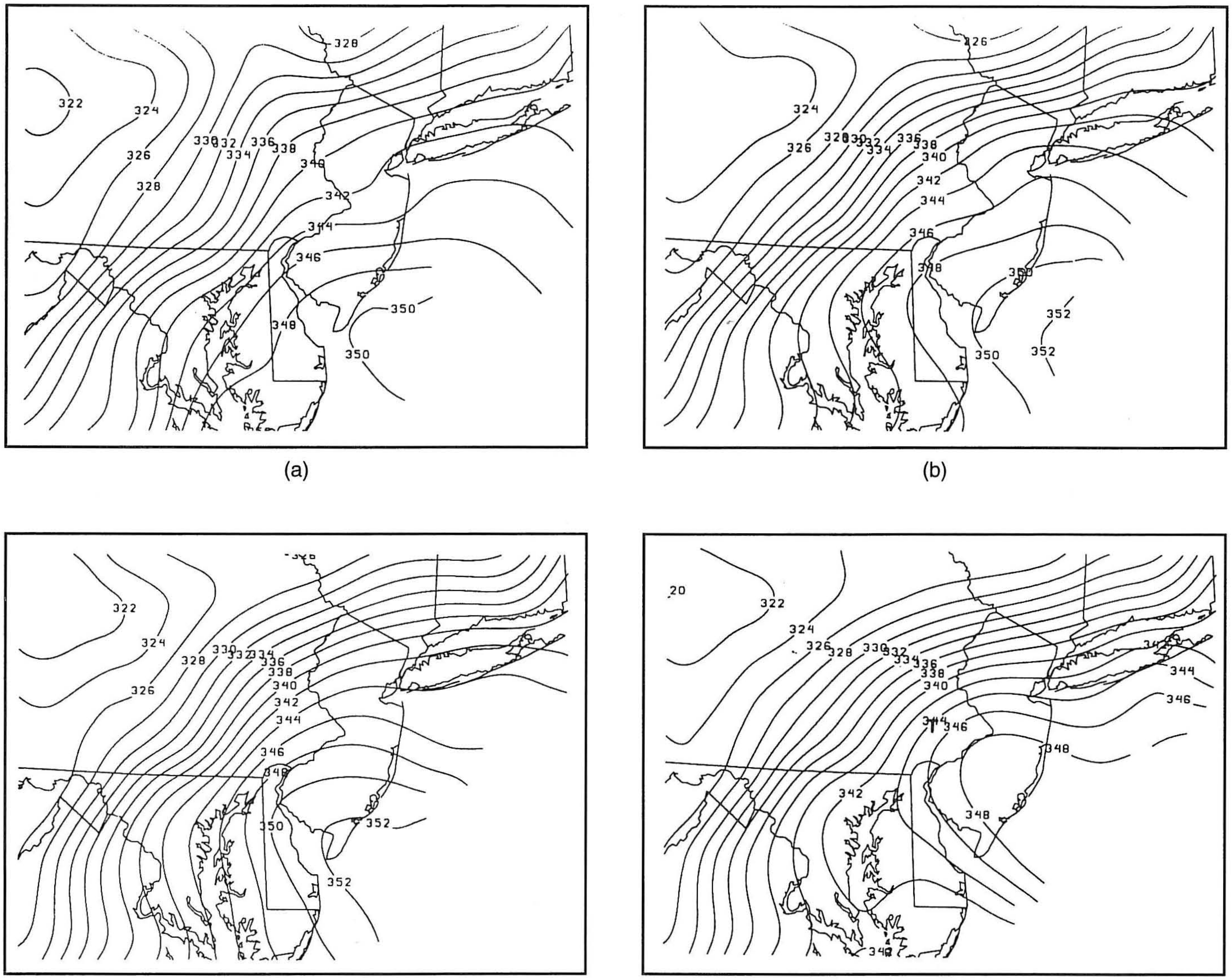


Fig. 8. Dew point analysis (°C) valid at 0400 UTC 28 July 1994.



(a) (b) (c) (d)

Fig. 9. Theta-e analyses (°K) valid at: (a) 0100 UTC; (b) 0200 UTC; (c) 0300 UTC; and (d) 0400 UTC 28 July 1994.

measurements, the evolution of this pattern suggests that the most potentially buoyant surface air was indeed progressing northeastward. This would coincide with the progression of tornadic activity from northern Virginia into eastern Pennsylvania.

Indeed, convection that spawned the severe weather occurred east of a meso-low that was propagating to the northeast along the quasi-stationary front. DPFD analyses (Figs. 10a-d) track the motion of the low, with an important convergence center residing east of the low center.

The convergence center of interest resides over the northern Chesapeake Bay at 0100 UTC and moves very slowly northeastward retaining its signature as it does so. By 0400 UTC (at the time of the event) the convergence maximum resides over the event site, without a divergence center to the east to form a couplet. Here we see an event that typifies the majority of cases examined in detail when forming the composite analyses. The Limerick event occurred in the warmest surface air near the center of a DPFD convergence maximum.

In spite of its F3 intensity, this event resembled many of the weaker events used to compile the composites. Their common bond is a tendency to form tornadic convection in or near a convergent quasi-stationary surface DPFD maximum, whereas Hirt (1982) expected more severe weather to be associated with a convergence-divergence couplet in the DPFD field. Moreover, this strong Limerick event also occurred in the center of a convergence maximum without an accompanying divergence center.

4. The Non-Event

A brief comment on the nature of non-events would seem appropriate at this juncture. In cases where tornadic activity does not occur, the DPFD pattern in particular is typically less

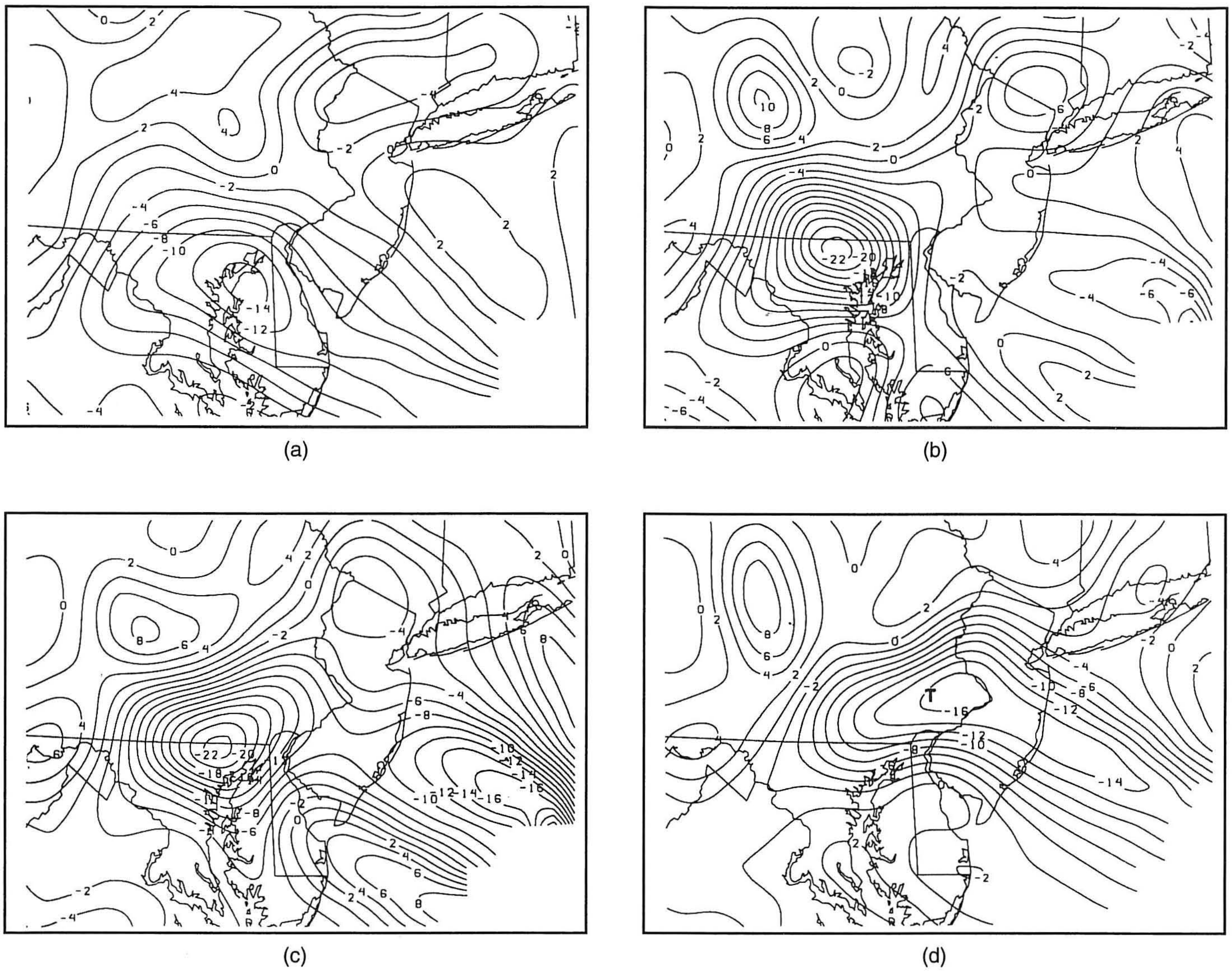


Fig. 10. Dew point flux divergence analyses (values × 10^{-4} °C s^{-1}) valid at: (a) 0100 UTC; (b) 0200 UTC; (c) 0300 UTC; and (d) 0400 UTC 28 July 1994. Negative values denote regions of convergence.

well-defined, with centers (if they form) being short-lived and generally lacking continuity from hour to hour. Both the experience of the author and cases examined in detail bear this out. This is likely due to the lack of organization in the surface flow regime observed with general convection to the degree observed accompanying tornadic convection.

5. Conclusions

The presence of a real and significant (though minor) tornado maximum in the eastern mid-Atlantic States region has been shown and draws attention to the problem of forecasting such activity in that area. Aside from a preference for a frontal boundary as a focus for tornadic convective initiation, no synoptic pattern was identified which clearly signaled the likelihood of tornadic activity. Well-known forecasting techniques (Miller 1972; Johns and Doswell 1992) work well for general synoptic diagnosis of severe weather, although more detailed work could certainly be performed for the eastern mid-Atlantic States region as done for the Great Plains (Doswell 1980; Weaver and Doesken 1991).

This study has demonstrated the usefulness of sub-synoptic patterns of DPFD in particular for identifying likely areas of tornadic activity. In the work of Hirt (1982), stronger severe weather is expected on the gradient between a couplet of dew point convergence and divergence maxima. Over the mid-Atlantic States region, the preferred region appears to be in or very near a dew point flux convergence center. In fact, only two of the eleven composite events examined in this study clearly showed a dew point flux divergence maximum east of a convergence maximum, and tornadic activity on the gradient between them. However, six of the eleven composite events depicted tornadic activity very near or just east of a convergence maximum, without a divergent center to the east to form a couplet. The other three events resolved no clear pattern.

For tornadic events, the model in Fig. 11 is suggested based on the composite studies. This model places tornadic activity on a broad thermal axis. More importantly, tornadic activity

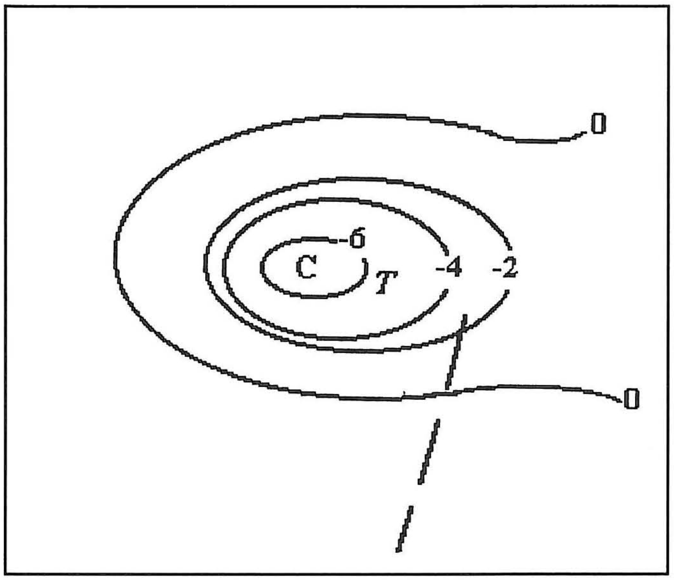


Fig. 11. A model depicting the typical surface dew point flux divergence (solid; values and magnitudes same as Fig. 10) and thermal axis (dashed) present at the time of tornado activity in the eastern mid-Atlantic States region. C is the convergence center, while T is the suspected tornado location.

will likely occur in or just east of a dew point flux convergence maximum, whether or not a divergence maximum is present to the east. This model is conceptually sound, as it depicts tornadic activity in relatively warm surface air with a high and increasing moisture content.

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