An Examination of Jet Stream Configurations, 500 mb Vorticity Advection and Low-Level Thermal Advection Patterns During Extended Periods of Intense Convection

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ABSTRACT

Three cases of widespread and persistent intense convective storms are examined. It is shown that synoptic-scale meteorological settings attending these events did not fit classic severe storm patterns that have been extensively documented in the literature. The analyses suggest that lower-tropospheric warm advection dominated mid-tropospheric differential vorticity advection in forcing upward vertical motion that triggered and organized the convective events. It is hypothesized that by shifting attention from the 500 mb level to observed and forecast low-level warm advection, the operational forecaster might better anticipate organized, intense convective outbreaks that develop within relatively benign synoptic-scale settings.

1. Introduction

The occurrence of severe thunderstorms and tornadoes has often been related to upward vertical motion fields associated with speed maxima in upper- and lower-level jet streams (ULJ and LLJ, respectively). Riehl *et al.* (1952) asserted that divergence fields associated with speed maxima (i.e., jet streaks) in the ULJ produce upward motion in the left-front (left exit zone) and right-rear (right entrance zone) quadrants of the streak. Beebe and Bates (1955) emphasized the interaction of streaks in the ULJ (defined by 500 mb data) and LLJ in the development of severe thunderstorms. They indicated that two regions (illustrated in Fig. 1) are favored for intense convection. Lee and Galway (1956, 1958), using Beebe and Bates' findings, related speed maxima observed in upper-tropospheric winds to tornado occurrence in papers that were directly oriented toward operational severe storm forecasting. Miller (1967) did likewise in his descriptions of empirical severe storm forecast procedures.

A decade later Whitney (1977) related satellite depictions of severe thunderstorms to the positions of the polar and subtropical jet streams. He found that severe storms tend to occur north of the subtropical jet and south of the polar jet. Intense convection and severe storms associated with the subtropical jet were shown to occur most often within the left exit zone, or abreast of, a speed maximum. McNulty (1978), emphasizing 300 mb instead of the often considered 500 mb level, suggested that the divergence patterns associated with upper-level wind maxima can be used in combination with low-level moisture, instability and convergence to define areas where severe thunderstorm and tornado activity might occur. Uccellini and Johnson (1979) reexamined the model of Beebe and Bates (1955) and showed that the ULJ and LLJ are often coupled by mass adjustments associated with the propagation of streaks in the ULJ. Southerly momentum generation in the lower troposphere helps create an environment favorable for severe thunderstorm development, especially when the intersection of the jet axes occurs within the exit region of the upper-tropospheric jet streak.

Kloth and Davies-Jones (1980) studied tornado occurrences during May 1977 in relation to the position and intensity of the 300 mb jet stream. They found that tornadoes generally occur beneath 300 mb wind speeds of 15–35 m s^{-1} and within 1250 km of a jet streak whose maximum winds range from 35 to 55 m s^{-1}. In their study the 300 mb level in the vicinity of tornadic storms was usually characterized by positive vorticity advection and divergence. Further, tornadoes were seen to occur generally in the left-front or right-rear quadrants of the jet streak, as suggested by Riehl *et al.* (1952). They noted a tendency for weak tornadoes to be associated with anticyclonic shear (at 300 mb) and for intense tornadoes to be associated with cyclonic shear.

Another synoptic feature considered favorable for

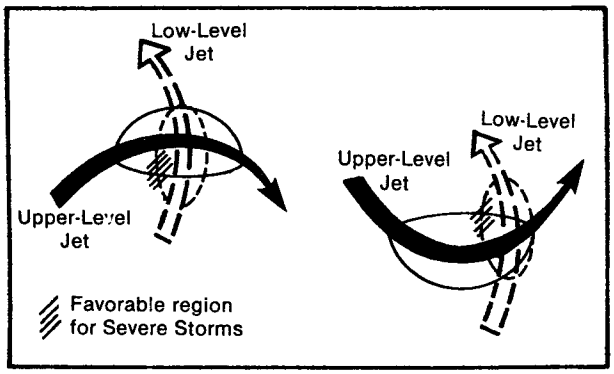


FIG. 1. Configurations of upper-level and lower-level jet streams favorable for severe thunderstorm development (after Beebe and Bates, 1955).

severe thunderstorms is strong positive vorticity advection at 500 mb. For example, Koscielski (1965) found it inadvisable to forecast tornadoes if 500 mb positive vorticity advection is not expected. In a similar vein, Miller (1967) listed strong positive vorticity advection at 500 mb as *the most important* parameter for severe weather forecasting.

However, Hales (1979) noted that if vorticity advection is considered the dominant forcing function for vertical motion [considering the quasi-geostrophic omega equation (e.g., Holton, 1972, p. 112)] then 500 mb vorticity advection patterns might be misleading to the operational forecaster. Indeed, Doswell (1976) had noted previously that strong positive vorticity advection at 500 mb is not clearly associated with many tornado events over the Great Plains. Hales suggested that consideration of 250 mb vorticity advection in conjunction with horizontal wind shear at 250 mb (shear naturally being most significant in the vicinity of jet streaks or streams) might help delineate regions with a potential for significant severe weather.

All of the studies referenced above, however, have tended to consider springtime severe storm situations, i.e., those characterized by strongly baroclinic weather systems and intense, well-defined jet streams. The purpose of this paper is to illustrate, qualitatively, that classical ULJ/LLJ and 500 mb vorticity advection relationships considered supportive of severe local storms are not always present or clearly defined. This is accomplished for three specific cases by relating satellite depictions of the evolution of intense, long-lived convective storm systems with the concurrent evolution of 850 and 200 mb jet streams, and with LFM forecasted 500 mb vorticity advection and barotropic vorticity analyses. The role of lower tropospheric warm advection in these severe storm cases is then considered.

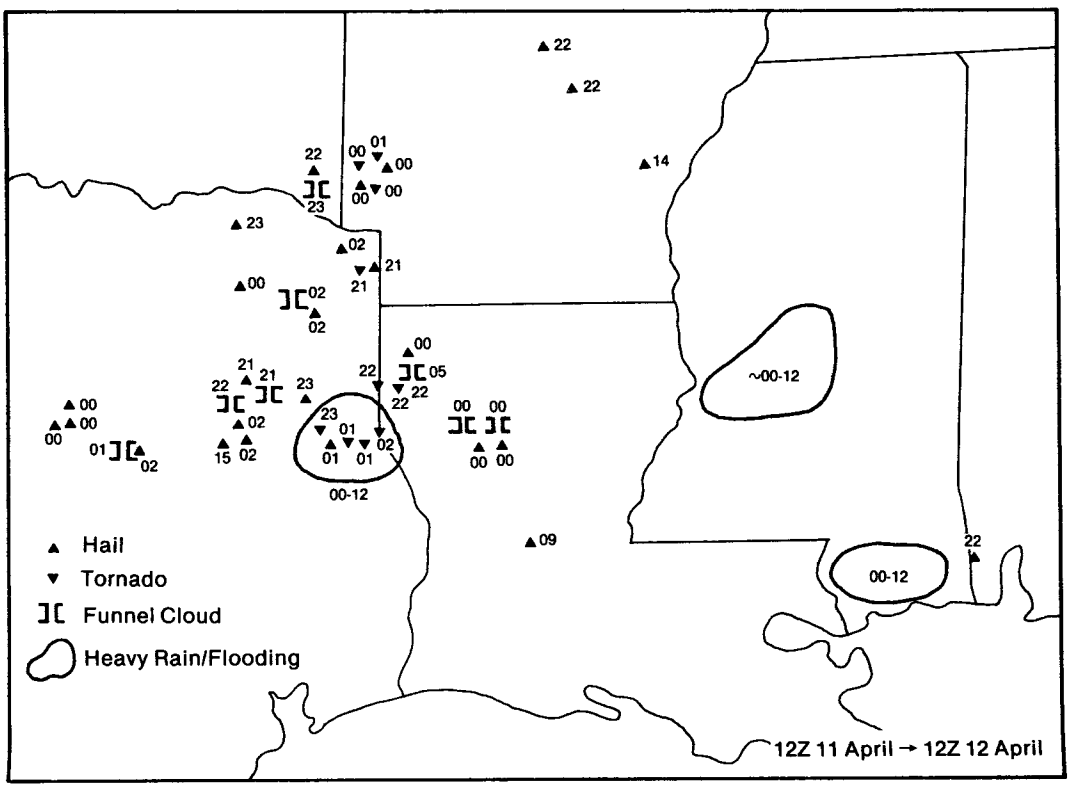


FIG. 2. Locations of severe storm reports on 11 and 12 April 1980.

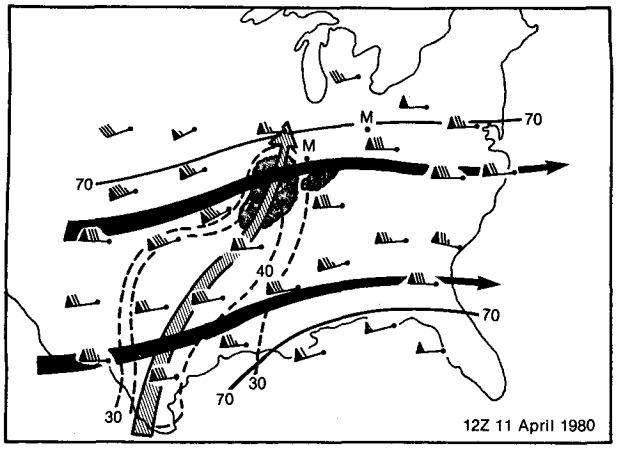


FIG. 3. Upper-level and lower-level jet stream analyses for 1200 GMT 11 April 1980. Plotted winds, solid isotachs and shaded arrows (denoting axes of maximum winds) are for 200 mb [winds are in kt with full barb = 10 kt (~5 m s^{-1}) and flag = 50 kt (~25 m s^{-1})]. Axis of 850 mb maximum winds is cross-hatched with 850 mb speeds indicated by the dashed isotachs (again in knots). Shaded region indicates area of thunderstorms as depicted by the concurrent enhanced IR satellite image (IR temperatures ≤ -52°C in this region).

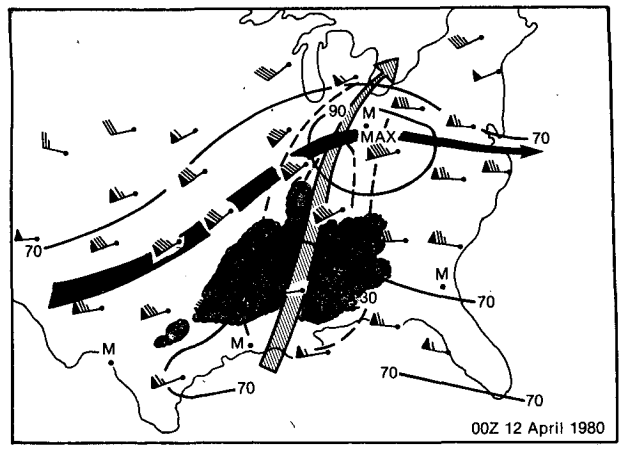


FIG. 5. Jet stream analyses for 0000 GMT 12 April 1980. Details are similar to Fig. 3.

2. Three case studies

a. The case of 11–12 April 1980

During the late afternoon and early night hours of 11 and 12 April 1980 severe thunderstorms produced tornadoes, hail and locally heavy rains over a region from northeastern Texas and southern Arkansas eastward into Mississippi. The severe weather events listed in *Storm Data* (a NOAA EDIS publication) are plotted, along with their approximate time of occurrence, in Fig. 2.

At 1200 (all times GMT) on the 11th, jet stream analyses (Fig. 3) indicated that the 200 mb flow was basically westerly and that a broad zone exhibited speeds of 70–85 kt (~35–42 m s^{-1}). Thunderstorms were occurring (Fig. 4) in the region of intersection of the northern ULJ and LLJ, much like the Beebe and Bates (1955) model. The activity was at the nose of the LLJ and in a region characterized by strong vertical wind shear. Observe that there was no pro-

FIG. 4. Enhanced IR satellite image for 1230 GMT 11 April 1980. Interior gray, black, gray and white shading indicates colder IR temperatures and higher cloud tops.

FIG. 6. Enhanced IR satellite image for 0030 GMT 12 April 1980.

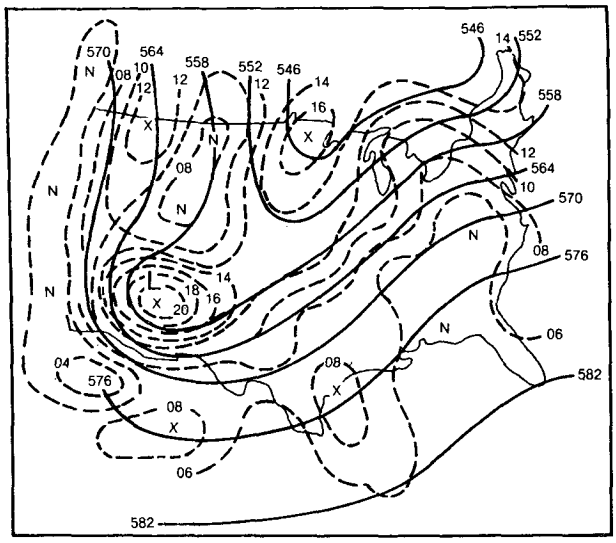


FIG. 7. Twelve-hour Limited Fine Mesh (LFM) forecast of 500 mb heights (solid lines, dam) and vorticity (dashed lines) valid at 0000 GMT 12 April 1980.

nounced upper jet streak associated with either the LLJ or the thunderstorms.

The jet stream analysis for 0000 on 12 April is shown in Fig. 5. Comparison with Fig. 3 indicates that substantial changes occurred during the 12 h separating analyses. Intense convection (Fig. 6) was occurring both east and west of the LLJ axis and to the *rear* of the speed maximum. Although the configurations of the jets and convective areas had changed considerably, the general pattern remained similar to the Beebe and Bates model (see Fig. 1). The most intense storms [southern half of shaded area (refer to Fig. 2)] were 1000–1500 km south and west of the analyzed ULJ streak at 0000. Upper-

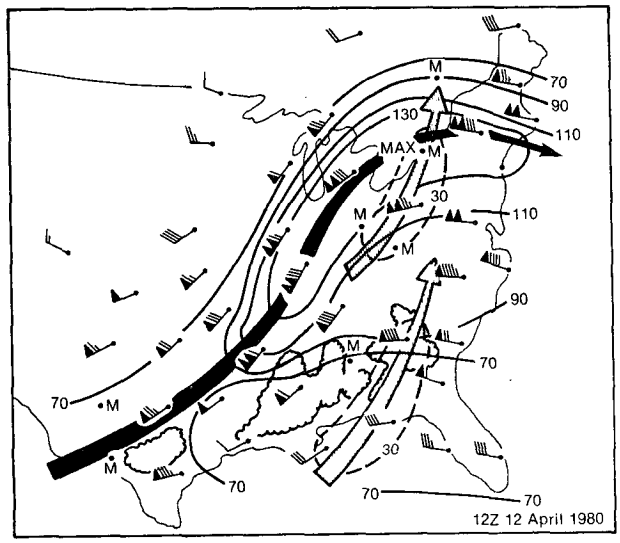


FIG. 8. Jet stream analyses for 1200 GMT 12 April 1980. Details are similar to Fig. 3.

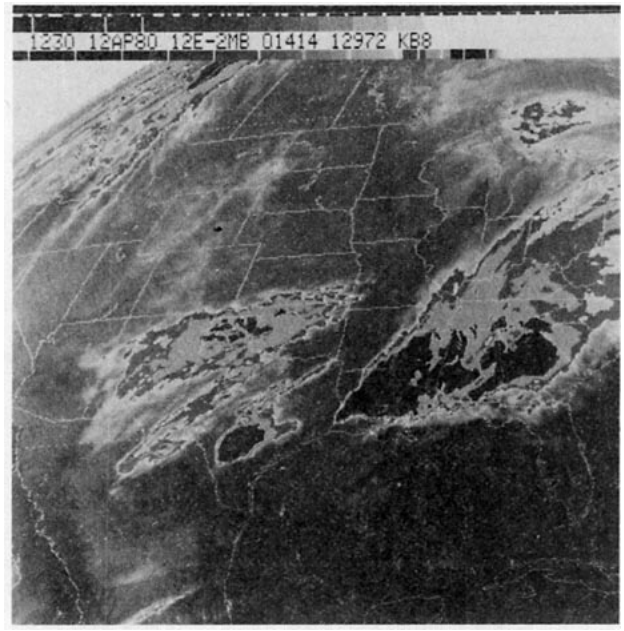


FIG. 9. Enhanced IR satellite image for 1230 GMT 12 April 1980.

level flow over this region had obviously weakened and become quite diffluent. Indeed, qualitative appraisal of Figs. 3 and 5 indicates that the storms were located within a region of weaker vertical wind shear than 12 h earlier.

The Limited-area Fine-mesh Model (LFM) operational 12 h forecast of 500 mb heights and vorticity valid at 0000 is shown in Fig. 7. The most intense short-wave troughs and vorticity centers were forecast far to the west and north of the region of intense storms, which were just ahead of a very weak short-wave trough over the southeastern Texas Gulf of Mexico coast.

The jet stream analysis for 1200 on 12 April is shown in Fig. 8 with a 1230 satellite image presented in Fig. 9. Comparison of Figs. 8 and 5 shows that remarkable changes in the ULJ streak had occurred during the night. The speed maximum within the top of the ridge had remained essentially stationary (only shifting northward as the ridge continued to amplify) but had increased dramatically in extent and intensity. Maximum winds exceeded 130 kt ($\sim$65 m s^{-1}) from the central Mississippi Valley to the East Coast. The LLJ had weakened and split into northern and southern branches. Intense thunderstorms continued over the southern Mississippi Valley, well to the west of the southern LLJ. New storms had also developed far to the west over southern Texas. Upper-tropospheric winds continued to weaken in the immediate vicinity of the persistent storm region (note the observed 200 mb wind of less than 5 m s^{-1} at the upwind edge of the convective system), with strong diffluence in the storm region. It is important to remember that upper-level diffluence became more pronounced *after*

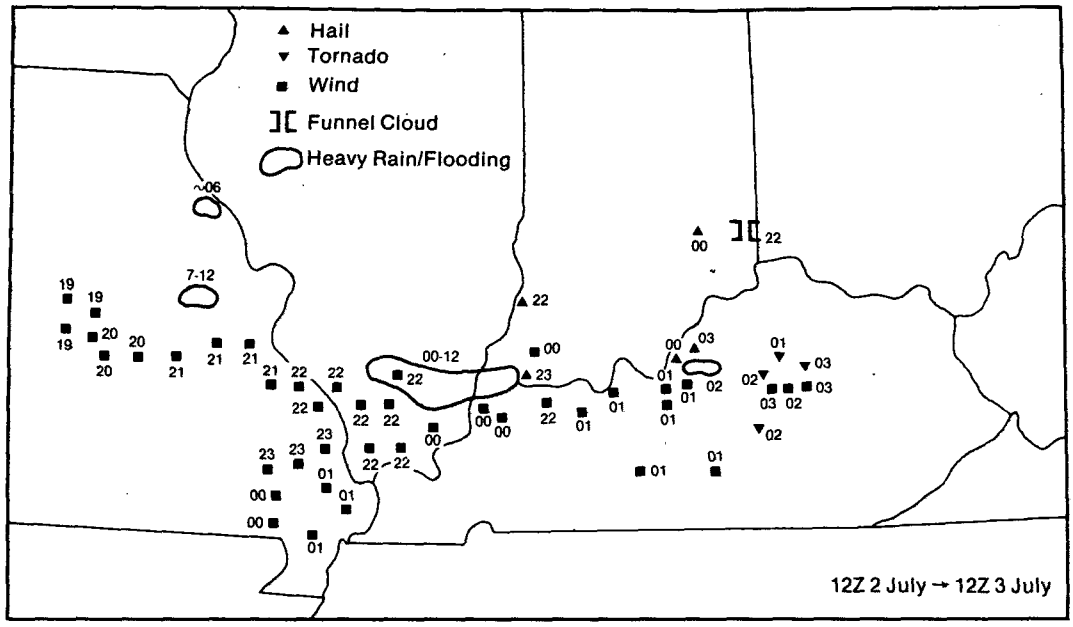


FIG. 10. Locations of severe storm reports on 2 and 3 July 1980.

convection developed and became widespread. Ninomiya (1971) and Fankhauser (1974) also have noted dramatic increases in upper-tropospheric diffluence *after* severe thunderstorms develop. This case was in conflict with forecast rules (such as Miller, 1967) that emphasize pronounced upper-level diffluence as a *prognostic aid* in forecasting the severe thunderstorms occurrence.

b. The case of 2–3 July 1980

During the afternoon and evening of 2 and 3 July 1980 an outbreak of severe thunderstorms, tornadoes, large hail and high winds occurred along a swath from central Missouri eastward across Kentucky. During the night of the 3rd, heavy rains and flash flooding occurred in portions of Indiana, Kentucky, Illinois and Missouri. Severe storm events reported to *Storm Data* for this outbreak are shown in Fig. 10 and indicate that this particular convective system primarily produced damaging surface winds as it swept eastward.

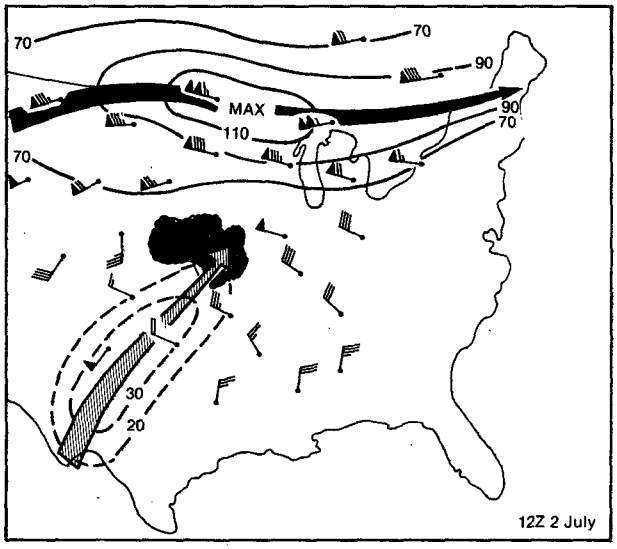


FIG. 11. Jet stream analyses for 1200 GMT 2 July 1980. Details are similar to Fig. 3.

The jet stream analysis for 1200 on the 2nd (Fig. 11) shows intense convective storms occurring at the nose of the LLJ, ~1000 km south of the ULJ streak. The anticyclonic curvature of the 200 mb winds indicates that these storms were beneath the upper-tropospheric ridge, in a region of relatively weak vertical wind shear.

Evolution and eastward movement of this intense convective system is illustrated in Figs. 12a–d. From 1215 to 2200 (Figs. 12a–12c) the system moved steadily southeastward across Missouri and southern Illinois. However, the 2200 image shows a number of thunderstorms developing across southern Indiana and Kentucky, east of the main system. These new storms developed explosively and by 2300 (Fig. 12d) the convective system elongated eastward, merging with the new activity.

The jet stream analysis for 0000 on the 3rd is shown in Fig. 13. Comparison with Fig. 11 shows that the intense storms at 0000 had remained directly beneath an upper-tropospheric anticyclone in a region of apparent weak vertical wind shear. Note that the new storm developments in the Ohio Valley occurred within the *right* exit zone of the ULJ streak, a region usually not considered favorable for severe storm genesis. The 1200 LFM forecast valid at 0000

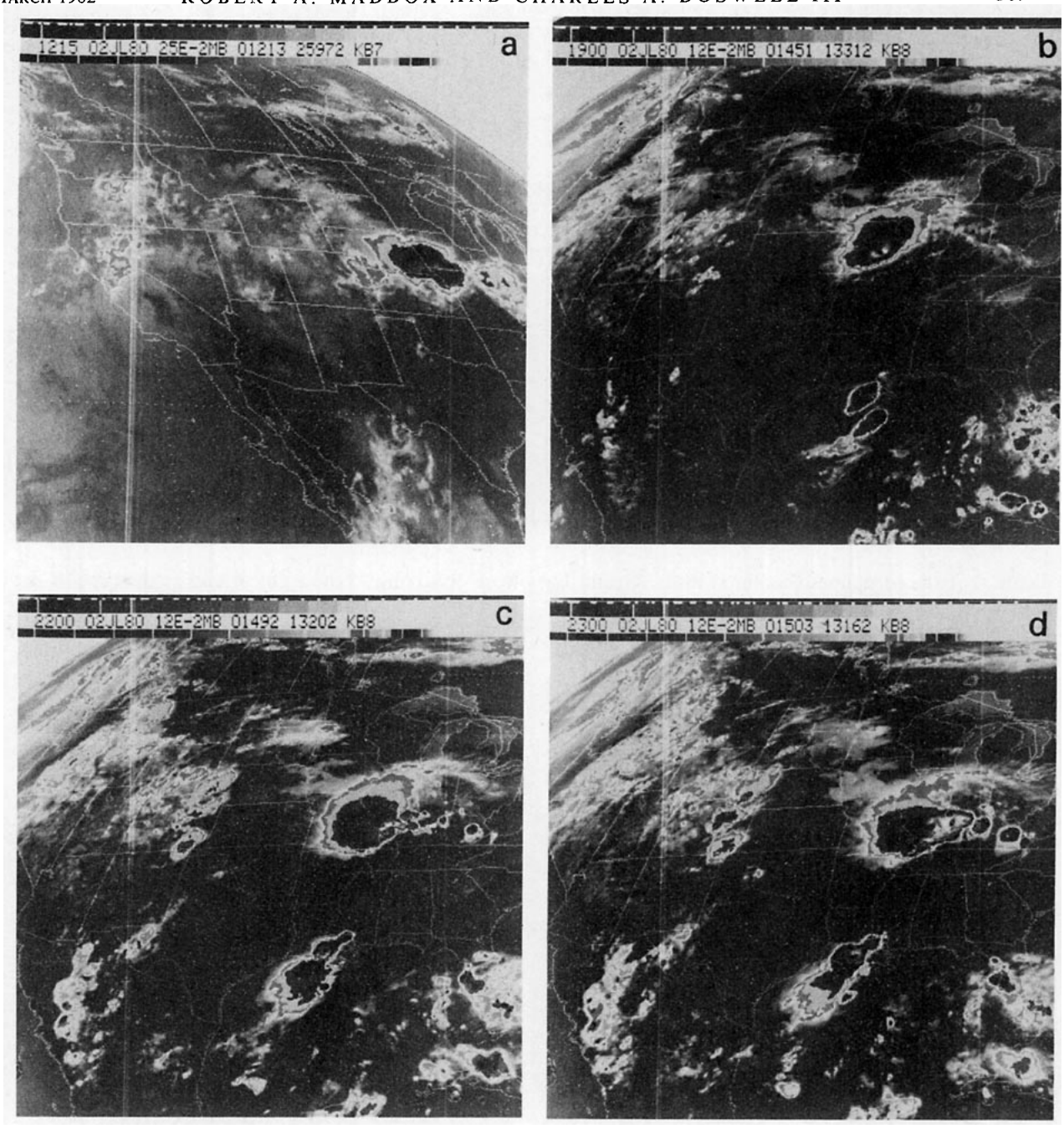


FIG. 12. Enhanced IR satellite images on 2 July 1980 for (a) 1215 GMT, (b) 1900 GMT, (c) 2200 GMT and (d) 2300 GMT.

on the 3rd (Fig. 14) shows that the intense storms were within a region forecast to be characterized by neutral or slightly positive vorticity advection.

Analysis of the jets at 1200 on the 3rd (Fig. 15) shows that significant storms (Fig. 16) were occurring at the nose of the LLJ 30 kt isotach ($\sim$15 m s^{-1}), very near the upper-tropospheric ridge and well south of the ULJ. The spatial relationship of these storms to speed maxima in the ULJ was not well-defined. Once again, vertical wind shear in the storm region appeared to be quite weak. This case, like that discussed before, revealed considerable differences from conventional forecast rules.

c. The case of 3 and 4 June 1980

Severe thunderstorms struck portions of North Dakota and eastern Nebraska during the afternoon and evening of 3 and 4 June 1980 (see Fig. 17). The storms in eastern Nebraska were most significant, producing hail, high winds, heavy rains, flash flooding and seven tornadoes. *Storm Data* statistics in-

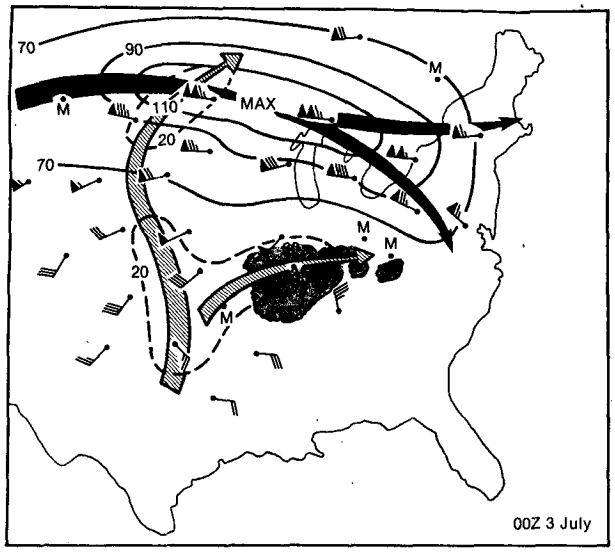


FIG. 13. Jet stream analyses for 0000 GMT 3 July 1980. Details are similar to Fig. 3.

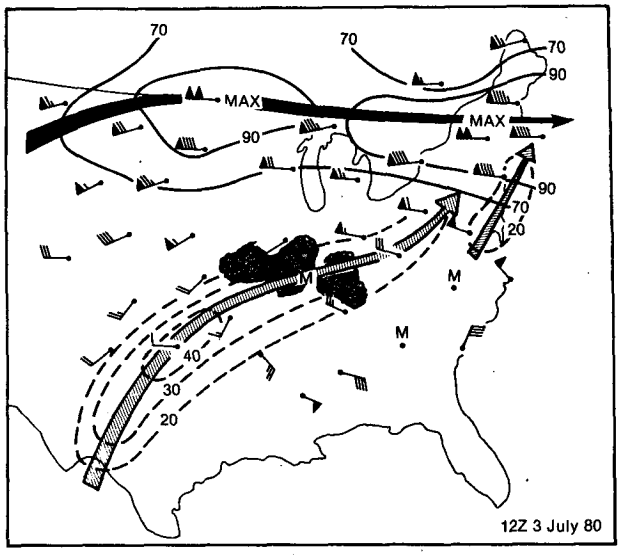


FIG. 15. Jet stream analyses for 1200 GMT 3 July 1980. Details are similar to Fig. 3.

dicate that the tornadoes (confined to the Grand Island area) killed 5 and injured 200 persons while inflicting tremendous property damage (see Fig. 17).

Jet stream analyses for 0000 on the 4th are presented in Fig. 18. Observe that upper and lower jets clearly intersected and the subjective model of Beebe and Bates (1955) would indicate that the storm located within the 40 kt LLJ isotach (also see satellite images of Fig. 20) was situated in an ideal location for intensification. Severe storms over North Dakota were occurring to the right of and at the nose of the LLJ, far removed from the ULJ. The storm in the Omaha/Grand Island area was located at the nose of the LLJ 30 kt isotach but was also apparently beneath the unfavorable left entrance zone of the ULJ streak. The barotropic 500 mb height/vorticity analysis for 0000 on the 4th (Fig. 19) shows that all of the central United States thunderstorms were occurring within the large-scale ridge and in a region of neutral or slightly positive vorticity advection.

Satellite depiction of the nocturnal evolution of the

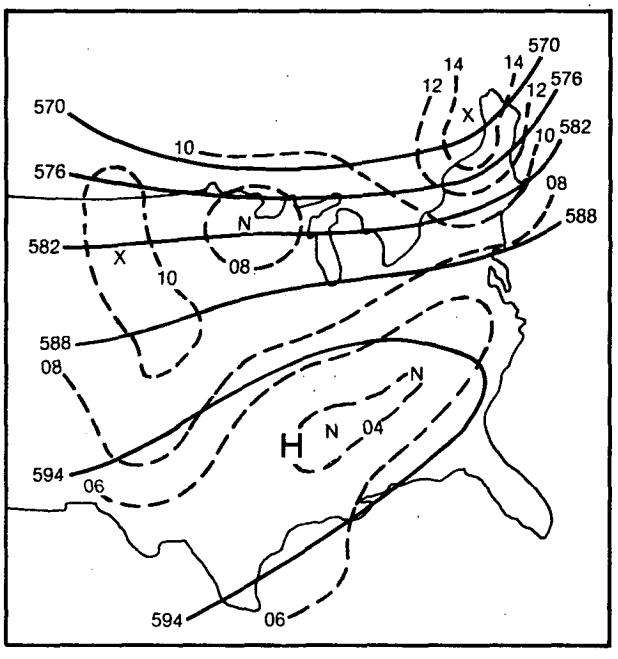


FIG. 14. Twelve-hour LFM 500 mb forecast valid at 0000 GMT 3 July 1980.

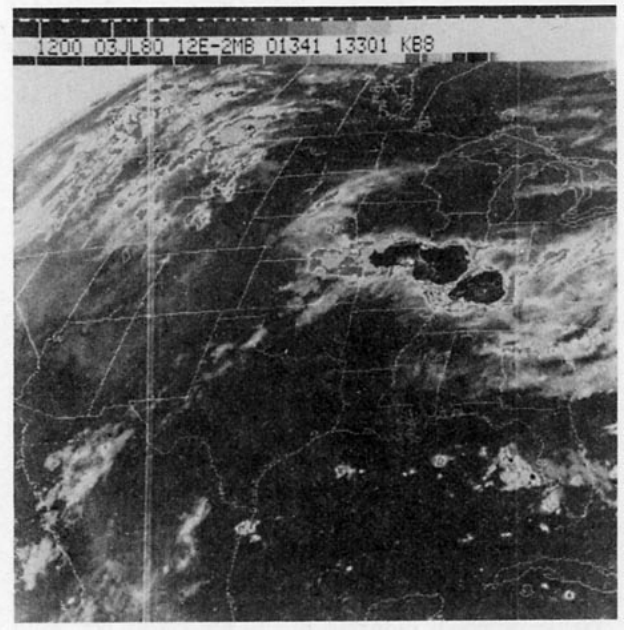


FIG. 16. Enhanced IR satellite image for 1200 GMT 3 July 1980.

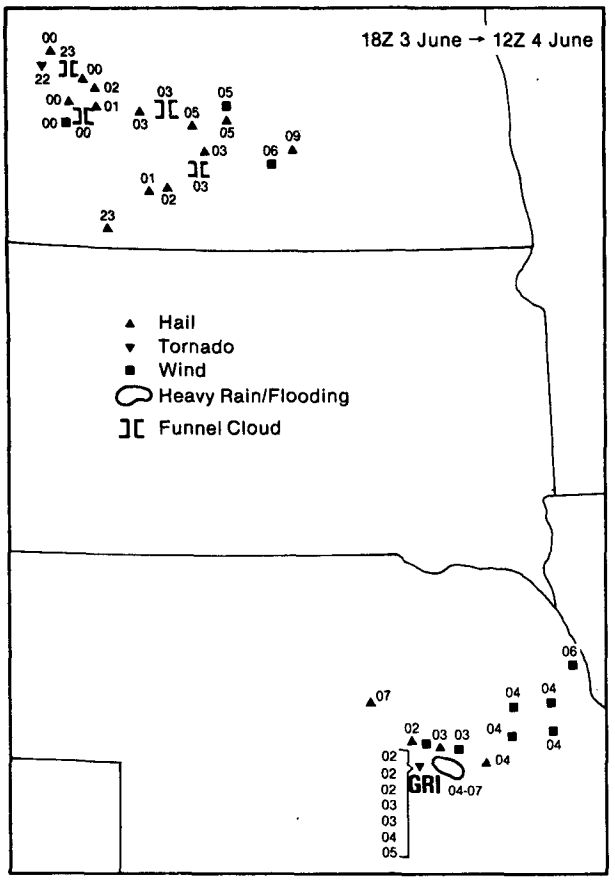


FIG. 17. Locations of severe storm reports on 3 and 4 June 1980. GRI indicates location of Grand Island, Nebraska.

convective storms is illustrated in Fig. 20. At 0115 (Fig. 20a) the storms over North Dakota were the most impressive. By 0645 (Fig. 20b) the storms over both North Dakota and Nebraska/Iowa had grown into large nocturnal complexes, while the cluster of activity over the southern plains had weakened. By 1330 (Fig. 20c) the complex which originated near Grand Island had moved eastward over northern Illinois and was about to weaken rapidly. To the north, a large area of intense convection persisted over Minnesota and eastern North Dakota.

The jet stream analysis for 1200 on the 4th (Fig. 21) indicates little change in the character and intensity of the LLJ, but considerable changes in the ULJ structure. A new, anticyclonically curved ULJ branch was present around the northern and eastern periphery of the convective complex which had devastated Grand Island. Note the observed northwesterly winds in excess of 50 m s^{-1} directly east of the convective system.

Objective analyses of subsynoptic divergence at 250 mb are presented in Figs. 22a and 22b for 0000 and 1200 on the 4th of June. The subsynoptic winds were extracted from the upper-air data utilizing a

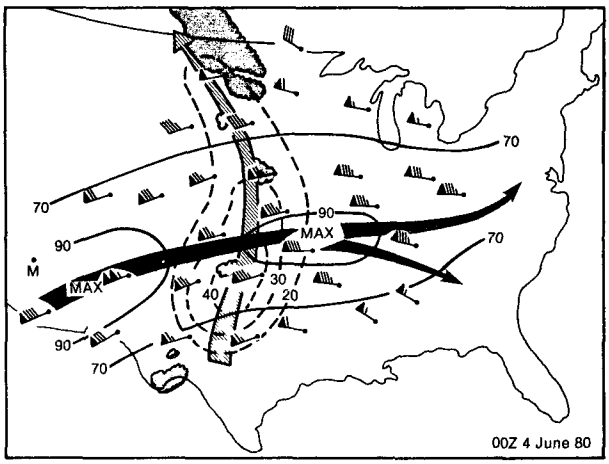


FIG. 18. Jet stream analyses for 0000 GMT 4 June 1980. Details are similar to Fig. 3.

bandpass filter centered at 1900 wavelength km [see Doswell (1977) for a detailed description of the objective analysis technique]. Comparison of Figs. 22a and 20a shows that initial storm developments in eastern Nebraska occurred beneath a region of weak *upper-tropospheric convergence.* However, by 1200 (Fig. 22b) the active storm complexes were associated with a well-defined region of upper-level divergence. There is no apparent continuity between the divergence analyses of Figs. 22a and 22b. The observed evolution of upper-tropospheric winds and divergence is quite similar to that documented in the vicinity of other long-lived convective complexes by Maddox (1980), Fritsch and Maddox (1981) and Maddox *et al.* (1981). Note again that both the difluence and computed divergence of the upper-tropospheric flow increased markedly over the persistent convective systems.

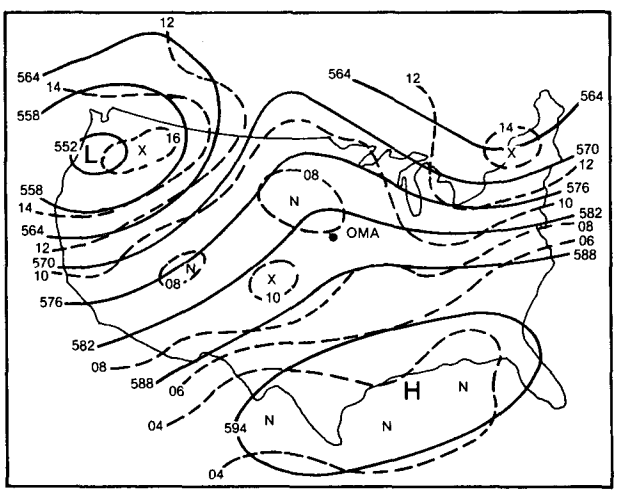


FIG. 19. Barotropic 500 mb height and vorticity analysis for 0000 GMT 4 June 1980.

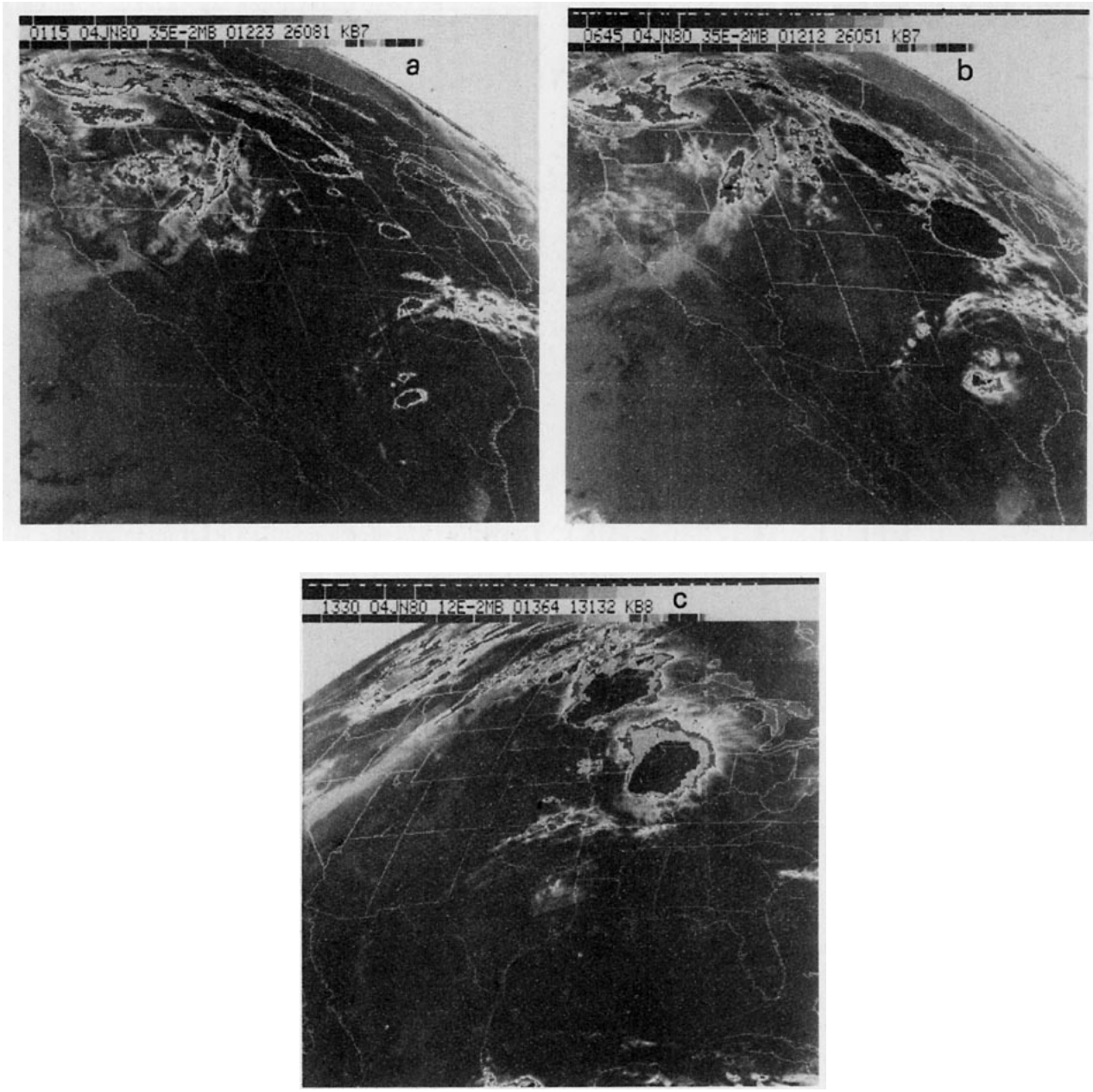


FIG. 20. Enhanced IR satellite images on 4 June 1980 for (a) 0115 GMT, (b) 0645 GMT and (c) 1330 GMT.

The barotropic 500 mb height and vorticity analysis for 1200 on the 4th (Fig. 23) shows that both regions of convection were located directly within the 500 mb ridge. The Grand Island system had actually moved just to the east of the ridge, within a region of neutral or slightly positive vorticity advection. The northern system was within a region of neutral or slightly *negative* vorticity advection! Consideration of the 500 mb flow fields and/or ULJ and LLJ structure lends little insight into the physical mechanisms that might have acted to trigger and organize the intense, large and long-lived convective systems actually observed.

d. Discussion

Although these convective events produced widespread severe weather, the temporal evolution and spatial relationships of the convective storms to ULJ and LLJ features were, at best, ill-defined by the synoptic rawinsonde data. The LFM forecasts (and analyses) for these situations indicated that the most

intense thunderstorm activity occurred in regions characterized by neutral or weak 500 mb positive vorticity advection. In addition, the storms tended to occur near the upper-tropospheric ridge in regions of weak vertical wind shear. Therefore, it appears that these cases did not fit either the classical model of large-scale features favorable for severe convection (e.g., Newton, 1950) or familiar empirical forecast rules (e.g., Miller, 1967). However, it should be emphasized that the classical models were constructed from severe storm cases associated with strongly sheared, intensely baroclinic large-scale meteorological settings (i.e., conditions that produce the severe pre-frontal "squall line"). Meteorological settings of the events presented in *this* study appear to be more typical of those associated with heavy convective precipitation and flash floods (see Maddox *et al.*, 1979). In fact, all three events produced heavy rains and localized flash flooding, in addition to severe storms. Logical questions from the operational forecaster's point of view include: what are the predominant large-scale mechanisms forcing this type of intense convective event and what types of analyses/products might help the forecaster anticipate similar developments? These questions provide the motivation for examining the role that lower-tropospheric warm advection might have played in these three cases.

3. The role of warm advection

Hoskins *et al.* (1978) and Trenberth (1978) have recently discussed some of the difficulties inherent in subjectively appraising the quasi-geostrophic omega equation's forcing functions. They have pointed out [as did Hales (1979)] the dangers of inferring the vertical motion via vorticity advection at a single level (usually 500 mb) and have developed

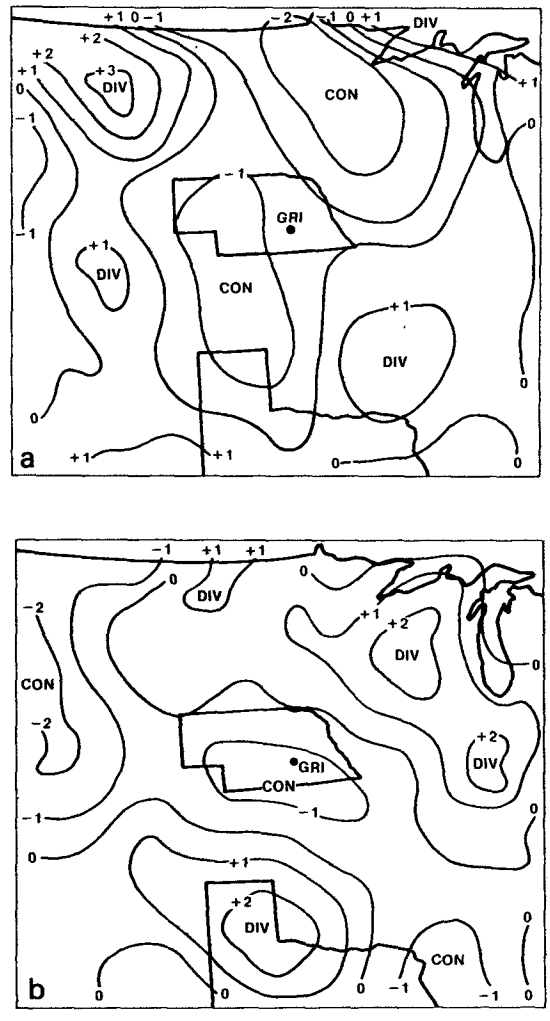


FIG. 22. Subsynoptic divergence ($\times 10^{-5}$ s^{-1}) at 250 mb for (a) 0000 GMT 4 June 1980 and (b) 1200 GMT 4 June 1980.

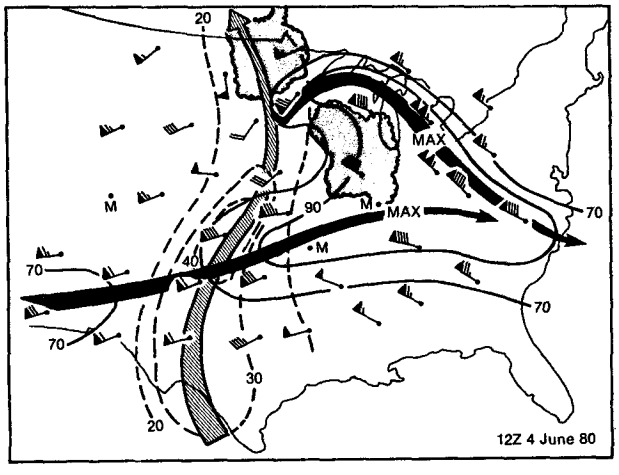


FIG. 21. Jet stream analyses for 1200 GMT 4 June 1980. Details are similar to Fig. 3.

ways of combining the vorticity and thermal advection terms to simplify qualitative assessment. It is suggested that, for situations in which mid-level vorticity and vorticity advection patterns are weak, the operational forecaster might better subjectively diagnose significant upward motion areas (and thereby better anticipate convective development) *by placing much less emphasis on the 500 mb height/vorticity analyses and prognoses and examining instead the low-level thermal advection fields.* The meteorological logic supporting this approach is that convective development often depends upon lifting within the *lowest several kilometers* to release conditional instability and that one's attention should therefore be directed to these lower levels. This approach certainly deserves examination for the cases presented here, since they do not seem to be very clearly related to 500 mb positive vorticity advection.

The literature abounds with direct and indirect

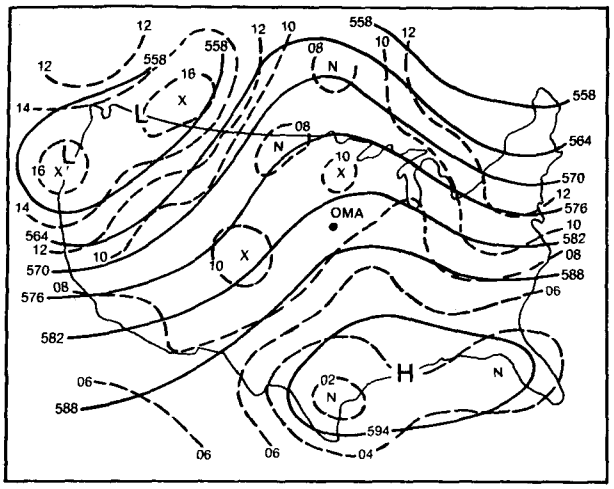
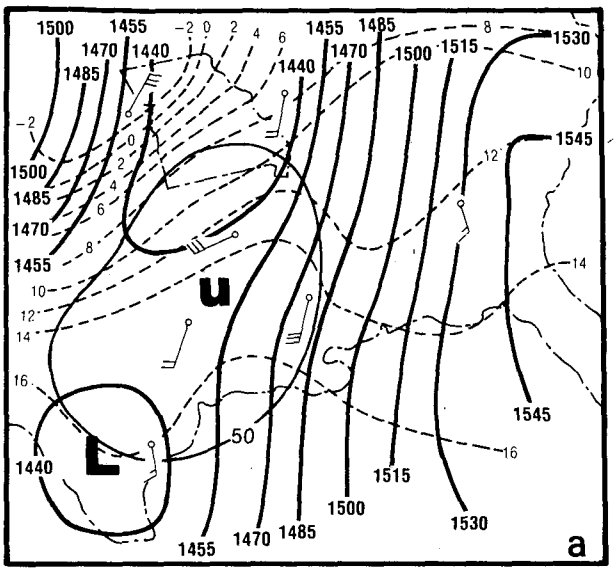


FIG. 23. Barotropic 500 mb height and vorticity analysis for 1200 GMT 4 June 1980.



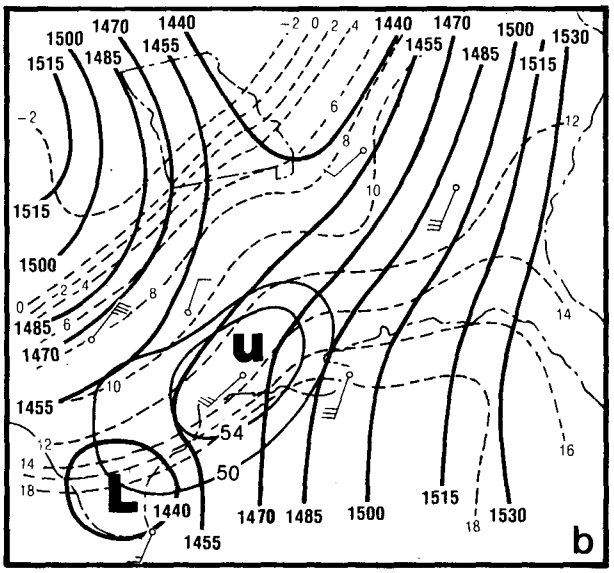


FIG. 24. 850 mb analyses for 12 April 1980. Heights (m) are heavy solid contours; Totals index is analyzed in light solid contours; isotherms (°C) are dashed; and selected wind observations (full barb = 5 m s^{-1}) are shown for (a) 0000 GMT and (b) 1200 GMT.

evidence supporting this contention. Means (1944, 1952, 1954) found that nocturnal thunderstorms in the midwestern United States were usually associated with apparent warm advection at about the 700 mb level. Whiting (1957) and Darkow *et al.* (1958) showed that tornadoes often occurred northeast of the tongue of warmest surface temperatures, while Whiting and Bailey (1957), Tegtmeier (1974) and Moller (1980) all found a tendency for tornadic storms to develop within the northeast quadrant of sub-synoptic surface lows. Both of these favored regions are characterized by strong low-level warm advection. Heavy precipitation situations are also often characterized by low-level warm advection (e.g., Matsumoto *et al.*, 1971; Bosart and Carr, 1978; Ninomiya, 1978). The generalized physical models of meteorological patterns that produce both tornadic storms and flash floods along thermal boundaries presented in Maddox *et al.* (1980 and 1979, respectively) delineate threat regions that again may be presumed to be characterized by strong low-level warm advection. Indeed, a number of Miller's (1967) empirical forecast rules lead the forecaster indirectly to key upon regions of pronounced low-level warm advection; for example, his stipulation that conditions are most favorable for severe storms if the axis of warmest 850 mb temperatures lies to the west of the 850 mb moisture axis. It appears this concept remains valid *even in strongly baroclinic situations*, such as the 3 April 1974 tornado outbreak. Hoxit and Chappell (1975) computed vertical motion kinematically for that case, and the significant upward motion occurred in areas of strong low-level warm advection (see, for example, their Figs. 44 and 46).

With these considerations in mind, low-level thermal advection patterns were examined for all three severe thunderstorm cases discussed in Section 2. Height and temperature analyses for the 850 mb level are shown in Figs. 24a and 24b for 0000 and 1200 on the 12th of April 1980. Regions of conditional instability [Totals index $\geqslant$ 50 (see Miller, 1967)] are also indicated. Comparison of these analyses with the figures of Section 2a shows that the significant thunderstorms were occurring in regions of pronounced warm advection where unstable air was either located or available just upstream. Similarly, comparison of the 850 mb analyses for 3 July 1980 (Figs. 25a and 25b) with the figures of Section 2b illustrates similar relationships between the re-

gions of pronounced warm advection, the severe thunderstorms and the unstable air.

The low-level thermal advection patterns were examined for the Grand Island case in slightly more detail. Objective quantitative analyses of temperature advection by the geostrophic wind at 850 and 700 mb are presented in Fig. 26a for 0000. [In this case a low-pass filter objective analysis technique as described by Barnes (1964) was used.] Significant warm advection was indicated at both levels (stippling denotes the region in which warm advection exceeds 0.2°C h^{-1} at *both* 850 and 700 mb) over the central and northern Plains. Twelve h later (Fig. 26b) the warm advection region shifted northward and eastward, with a secondary pocket remaining over the Plains south of Nebraska. Comparison of Fig. 26b with the satellite image of Fig. 20c indicates that the storm complex which originated near Grand Island moved to the southeastern edge of the warm advection region. Additional imagery (not presented) revealed that the system over Illinois (see Fig. 20c) dissipated rapidly after 1200. However, the convection within the warm advection region over the northern Plains *persisted through the day*, while new thunderstorms developed in the region of warm advection over eastern Kansas.

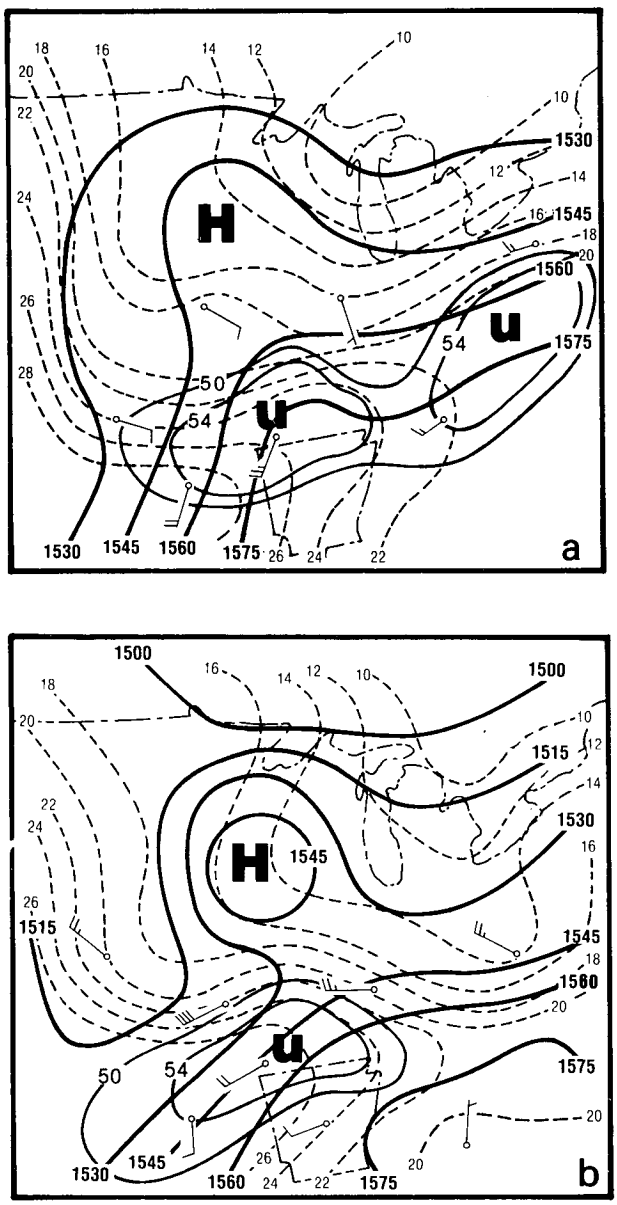


FIG. 25. 850 mb analyses for 3 July 1980. Details as in Fig. 24 for (a) 0000 GMT and (b) 1200 GMT.

The analyses presented in this section indicate that the intense thunderstorms, for all three cases considered, were associated with very weak midtropospheric vorticity advection patterns and unusual LLJ/ULJ configurations. However, these storm systems all developed within regions characterized by strong and persistent lower-tropospheric warm advection and significant conditional instability.

4. Summary

The case studies in Sections 2 and 3 illustrate that synoptic-scale meteorological settings attending some outbreaks of severe convective storms do not fit classic patterns that have been extensively documented in the literature. In particular, the locations of intense thunderstorms relative to the orientations of the upper and lower tropospheric jet streams demonstrated considerable variability. At times the patterns were much like those documented as favorable, while at other times storms developed and/or occurred within regions not usually considered favorable. In addition, mid-tropospheric vorticity and vorticity advection patterns associated with these events were ill-defined and quite weak.

The Grand Island, Nebraska case further demonstrates that not only can such convective events produce widespread and persistent thunderstorms but that such storms can, on occasion, be extremely severe. The Grand Island storms occurred within a region of significant lower-tropospheric warm advection and it is suggested that when mid-tropospheric vorticity patterns are weak, the lower-tropospheric thermal advection patterns should be closely monitored by operational forecasters. The physical basis, in such situations, is that thermal advection fields likely dominate differential vorticity advection in forcing vertical motion. Thus, *when pronounced low-level warm advection occurs in regions of strong conditional instability*, the resultant lifting may produce important convective events such as those considered in this paper.

Unfortunately, convective events of this type, especially flash flood situations, often catch the operational forecaster by surprise, since working proce-

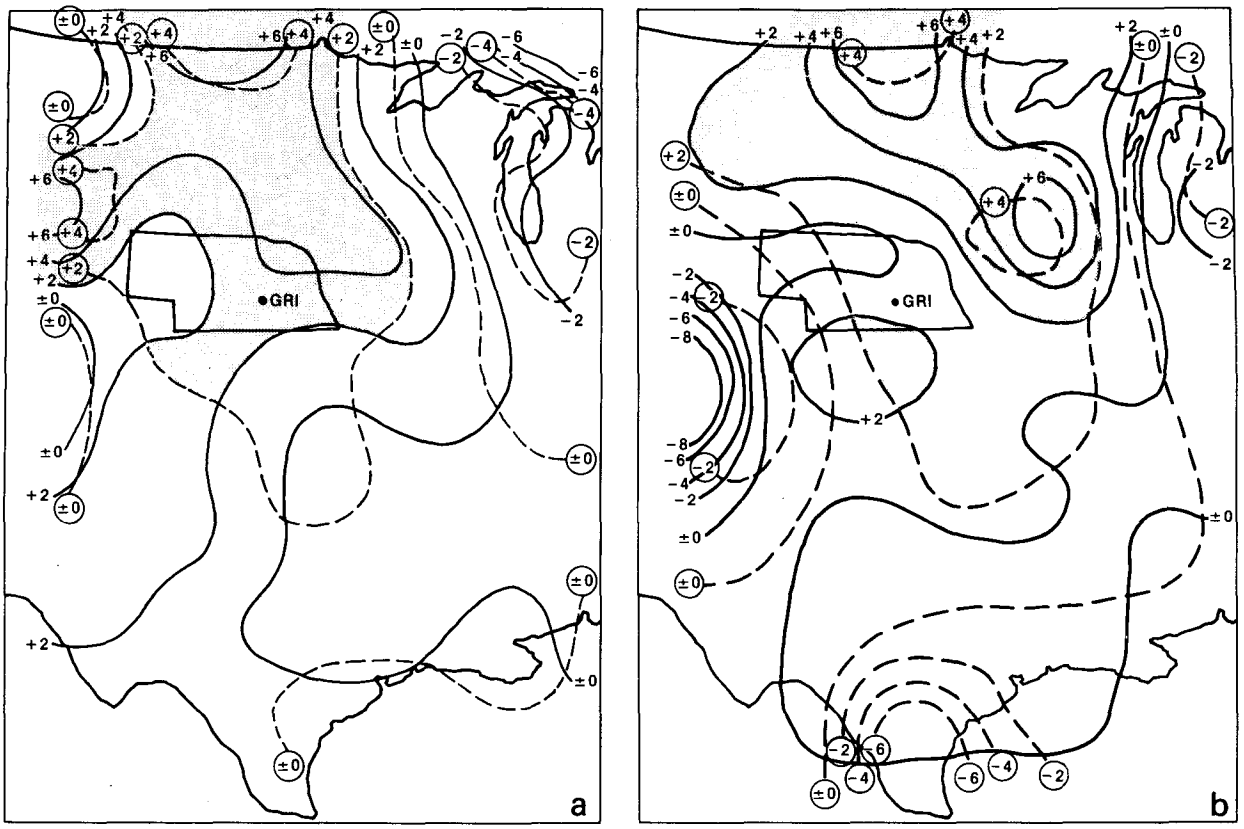


FIG. 26. Temperature advection (°C $h^{-1} \times 10^1$) by the geostrophic wind at 850 mb (solid contours) and at 700 mb (dashed contours) for (a) 0000 GMT 4 June 1980 and (b) 1200 GMT 4 June 1980. Regions in which warm advection exceeds 0.2°C h^{-1} at both 850 and 700 mb are shaded.

dures are typically built around analyses and forecasts of vorticity and vorticity advection at 500 mb (the barotropic chart, the LFM analysis and forecasts, etc.). It would be a rather simple procedure to produce operational analyses (and LFM forecasts) of low-level warm advection. Such products could be produced nationally, or at the local level when needed. It is felt that by shifting the emphasis away from mid-tropospheric vorticity advection, the operational meteorologist might be better able to anticipate one of the most difficult forecast problems: organized, intense convective storms occurring within relatively benign synoptic-scale settings.

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