THE IMPORTANCE OF PARCEL CHOICE IN ELEVATED CAPE COMPUTATIONS

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Abstract

It has been suggested that one choose the most unstable parcel in the lowest 300 hPa layer of a sounding when calculating convective available potential energy (CAPE). This approach is especially useful for cases where instability is found aloft, and is also applicable when lifting a surface- or low-level-based parcel or layer as appropriate. Raising a (near) surface parcel to evaluate CAPE is not always illustrative of the true nature of the convectively unstable environment. An example of such a case exists when elevated CAPE is released from parcels lifted along and/or north of a frontal boundary. Two brief case studies of heavy rainfall [>100 mm (24 h)$^{-1}$*] episodes in the midwestern United States are presented, in which thunderstorms resulted from the release of elevated CAPE. In both cases the CAPE computed from lifting the most unstable parcel (the parcel with the highest* θ_e *in the lowest 300 hPa layer) was much greater than the CAPE computed by lifting the parcel based on the average thermal and moisture characteristics of the lowest 100 hPa layer; in one case the latter "mean-parcel" CAPE was zero.*

1. Introduction

Choosing the most suitable parcel to evaluate CAPE has been a somewhat contentious issue, as actual CAPE values depend on the particular lifted parcel (Williams and Renno 1993; Doswell and Brooks 1993; Doswell and Rasmussen 1994). There are at least three approaches to this problem: 1) lifting a surface-based parcel (Hales and Doswell 1982); 2) lifting a parcel representative of the lowest 100-hPa layer (Prosser and Foster 1966; Miller 1972; Hart and Korotky 1991); and 3) lifting the most unstable parcel in the lowest 300 hPa (Doswell and Rasmussen 1994). The third method is more applicable for evaluating the convective potential of the environment when a surface-based parcel or layer is not appropriate (Doswell and Rasmussen 1994).

During our investigation of heavy rainfall-producing mesoscale convective systems (MCSs) in the midwestern United States, we found numerous episodes in which the convection was not rooted in the atmospheric boundary layer (as is usually the case with deep convection). These storms, known as *elevated thunderstorms* (defined in Colman 1990a, b), occur in response to lifting above a cool, stable boundary layer ahead of a surface thermal boundary. The environmental wind profile in the vicinity of the thermal boundary is typically distinguished by sharp veering in the lower and middle troposphere. This type of wind profile results in differential thermal/moisture advection. The cool, stable layer beneath the front is characterized typically by flow with an easterly component. Warm, moist air is transported northward and upward above/within the frontal zone, while slightly cooler and much drier air is advected by westerly flow in the middle troposphere. The resultant stratification of the lower troposphere is characterized by elevated convective instability (and elevated CAPE), with a layer of convectively unstable air $(\partial\theta_e/\partial p > 0)$ above the frontal zone (often found at or around 850 hPa) and convectively stable air $(\partial\theta_e/\partial p < 0)$ below.

The large-scale lift associated with the approach of a short-wave trough and strengthening low-level jet (LLJ) are instrumental in lifting this convectively unstable layer to saturation, thereby realizing the latent instability. Meso-α lifting at or near the frontal zone due to localized moisture convergence could then lift air parcels to their level of free convection (LFC), thereby leading to strong convection over a limited area. This area is generally found in the exit region of the LLJ where moisture convergence is maximized.

Elevated thunderstorms can produce copious rainfall (Rochette and Moore 1996) or severe weather (Grant 1995), with large hail being the primary severe weather threat. The following is an excerpt from a forecast discussion from the National Weather Service Forecast Office (NWSFO) in Twin Cities/Chanhassen, Minnesota, which illustrates the conditions associated with a particular episode of elevated thunderstorms that occurred on 14 October 1998:

> WSR-88D radar reflectivity returns lighting up across much of far southwest and south-central [*sic*] Minnesota with a number of 3/4 inch hail reports with some of the activity. Convection is elevated but the mixing ratios showing up at 850 mb on LAPS generated soundings is [*sic*] incredible for so late in the season. At 19Z near KMKT [Mankato, Minnesota]...the 850 mb mixing ratio was 9 gm/kg with elevated [*sic*] CAPE of 575 J/kg.

The purpose of this paper is to discuss the importance of selecting the most unstable parcel in the lowest 300 hPa when computing CAPE. Toward this end, brief diagnostic analyses of two heavy rainfall episodes in the midwestern United States in which lifting the most unstable parcel resulted in a significant increase in CAPE will be presented. As such, data from these two cases are provided only to serve as background to the problem, not to stand alone as exhaustive case studies. The reader is directed to the original sources for further insight.

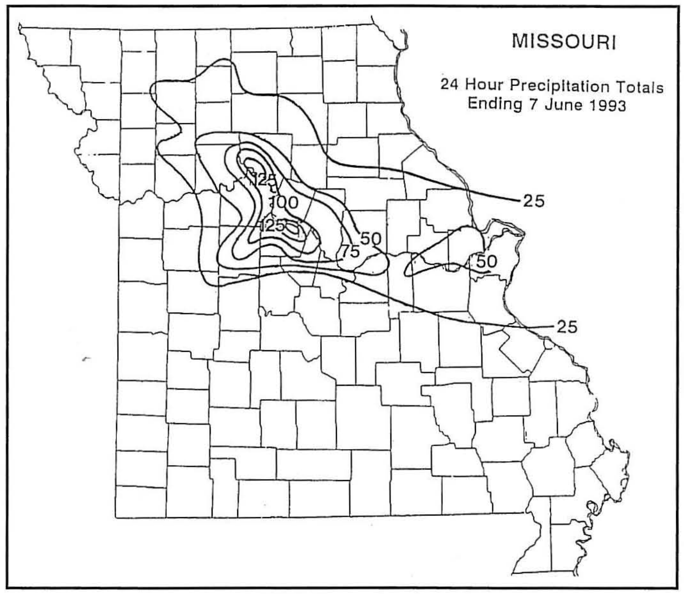

Fig. 1. 24-hour total rainfall (mm) ending at 1200 UTC 7 June 1993 for Missouri, as measured by NWS cooperative network rain gauges (after Rochette and Moore 1996).

2. Illustrative Cases

a. 6 June 1993

During the morning and early afternoon hours of 6 June 1993, an MCS developed over west-central Missouri and traveled southeastward, resulting in a narrow swath of heavy precipitation as it traversed central and eastern portions of the state. Rainfall amounts in excess of 150 mm (6 in.) fell in localized areas of central Missouri (Fig. 1). The operational community was caught off guard by this event, as there was little mention of rain in the national guidance or local forecasts. The heavy rainfall-producing thunderstorms developed well north of a quasi-stationary surface boundary extending from the lower Mississippi Valley across north-central Oklahoma into western Kansas. Figure 2 reveals that surface temperatures over Missouri ranged from 11 to 16 °C (52 to 62 °F), indicative of a cool, stable boundary layer, an environment not usually associated with the potential for deep

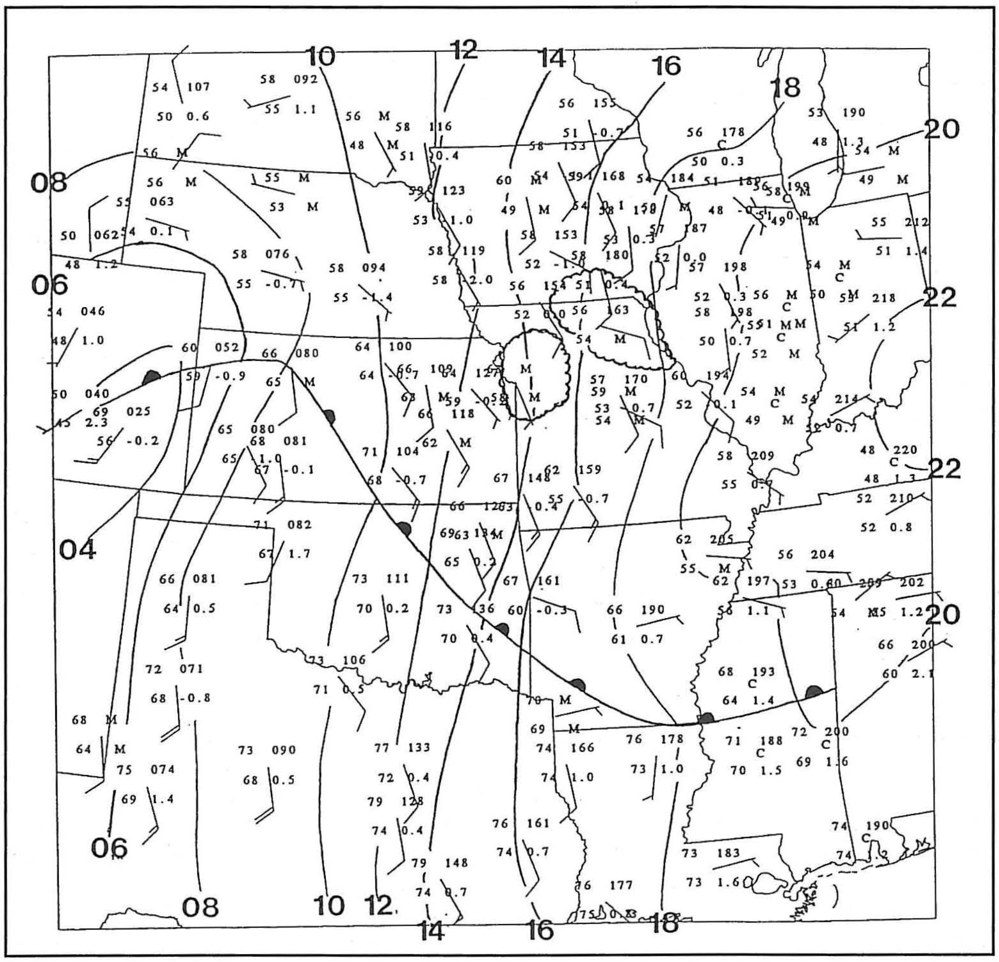

Fig. 2. Surface analysis for 1200 UTC 6 June 1993. Solid lines are isobars in 2 hPa increments (1012 = 12). Station model as follows: upper left, temperature in °F; bottom left, dewpoint in °F; upper right, surface pressure in hPa (1020.4 = 204); lower right, 3-h pressure tendency in hPa. Wind reported as follows: full feather and half feather denote 5.0 and 2.5 ms^{-1} respectively. C indicates calm, M signifies missing data. Scalloped region signifies area of initial storm development (adapted from Rochette and Moore 1996).

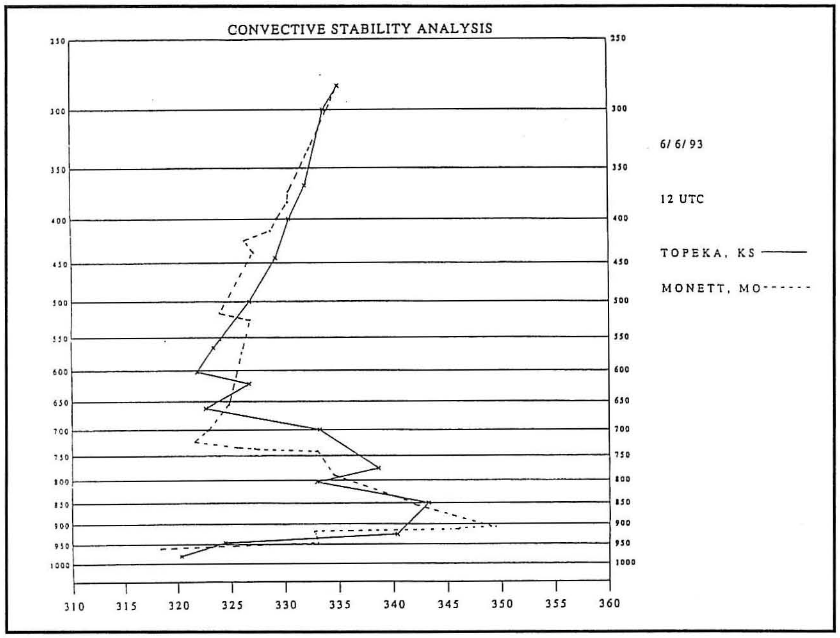

Fig. 3. 1200 UTC 6 June 1993 convective stability analysis for Topeka, Kansas (solid) and Monett, Missouri (dashed). Abscissa is θ_e (K), ordinate is pressure (hPa) (after Rochette and Moore 1996).

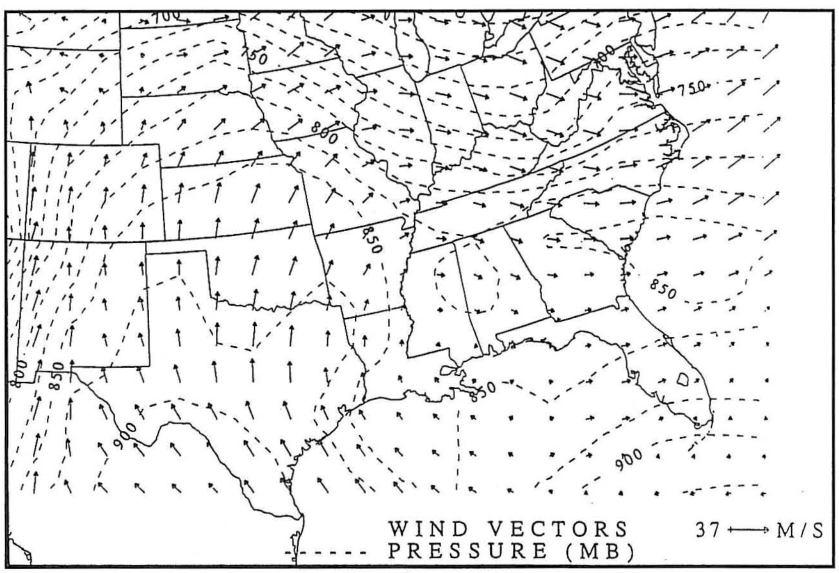

Fig. 4. 1200 UTC 6 June 1993 306 K isentropic surface. Arrows represent wind vectors, dashed lines are isobars (hPa).

convection. Further details of this episode may be found in Rochette and Moore (1996).

A simple method of evaluating the convective instability of a local environment (and the potential for elevated convection) is to examine the vertical profile of equivalent potential temperature (θ_e). Figure 3 is the distribution of θ_e with respect to pressure at Topeka, Kansas (solid) and Monett, Missouri (dashed) for 1200 UTC 6 June 1993. Given the location of MCS initiation, the Topeka profile most closely approximated the ambient environment in the cool sector, while the Monett profile was representative of the inflow air. The Topeka profile is characterized by a potentially convectively unstable thermal stratification from 850 to 660 hPa (with the exception of a shallow stable layer around 800 hPa) superimposed on a stable frontal zone layer (surface to 850 hPa). The Monett profile reveals a similar pattern, with a higher maximum θ_e value lower along the frontal boundary. As a result, the environment associated with the MCS in question is characterized by elevated potential convective instability.

Elevated thunderstorms require the release of convective instability via lifting at or above the frontal zone. In the case of elevated convection, lifting is not surface-based but takes place along or ahead of the frontal boundary, often best diagnosed utilizing an isentropic perspective. In order to illustrate the elevated nature of the lifting in this case, the 306 K isentropic surface at 1200 UTC 6 June 1993 (Fig. 4) is presented. The isentropic perspective is presented to show how rising air parcels from Texas and Oklahoma were part of the large-scale lifting process. Vertical motion on an isentropic surface can be expressed via the following:

$$\omega_\theta = \underbrace{\frac{\partial P}{\partial t}}_{A} + \underbrace{\vec{V} \cdot \nabla P}_{B} + \underbrace{\frac{d\theta}{dt}\frac{\partial P}{\partial \theta}}_{C} \qquad (1)$$

Note that the strongest lifting is present over central and northern Missouri, which is characterized by winds oriented normal to the closely spaced isobars, blowing from higher to lower pressure; this is the contribution of term B of (1), the pressure advection term. In this case, rising motion is indicated in the vicinity of 850 hPa, within the layer of elevated convective instability. It should be noted that diabatic heating associated with the convection [term C of (1)] will generally increase the upward vertical motion, while the local pressure tendency on the isentropic surface [term A of (1)] will detract from the upward motion (Moore 1993). Examination of the surface divergence field at 1200 UTC (not shown) indicates generally weak convergence (> -1.0 x 10^{-5} s^{-1}) to weak divergence (< +1.0 x 10^{-5} s^{-1}) over Missouri, further corroborating the elevated nature of the large-scale lift.

High moisture content is also essential for the release of convective instability. Examination of the relative humidity (RH) field on the 306 K surface at 1200 UTC 6 June 1993 (not shown) reveals that the majority of Missouri is characterized by RHs in excess of 70%, while the 80% isohume encloses the northern third of Missouri, most of Iowa, and a north-south sliver through the central portion of Minnesota. This verifies that the initial thunderstorms developed in a region characterized by high values of relative humidity (~80%).

The effect of parcel choice in CAPE computation is demonstrated in Fig. 5, a skew T-log P diagram for Monett, Missouri, at 1200 UTC 6 June 1993. The cross-hatched region represents the CAPE based upon the

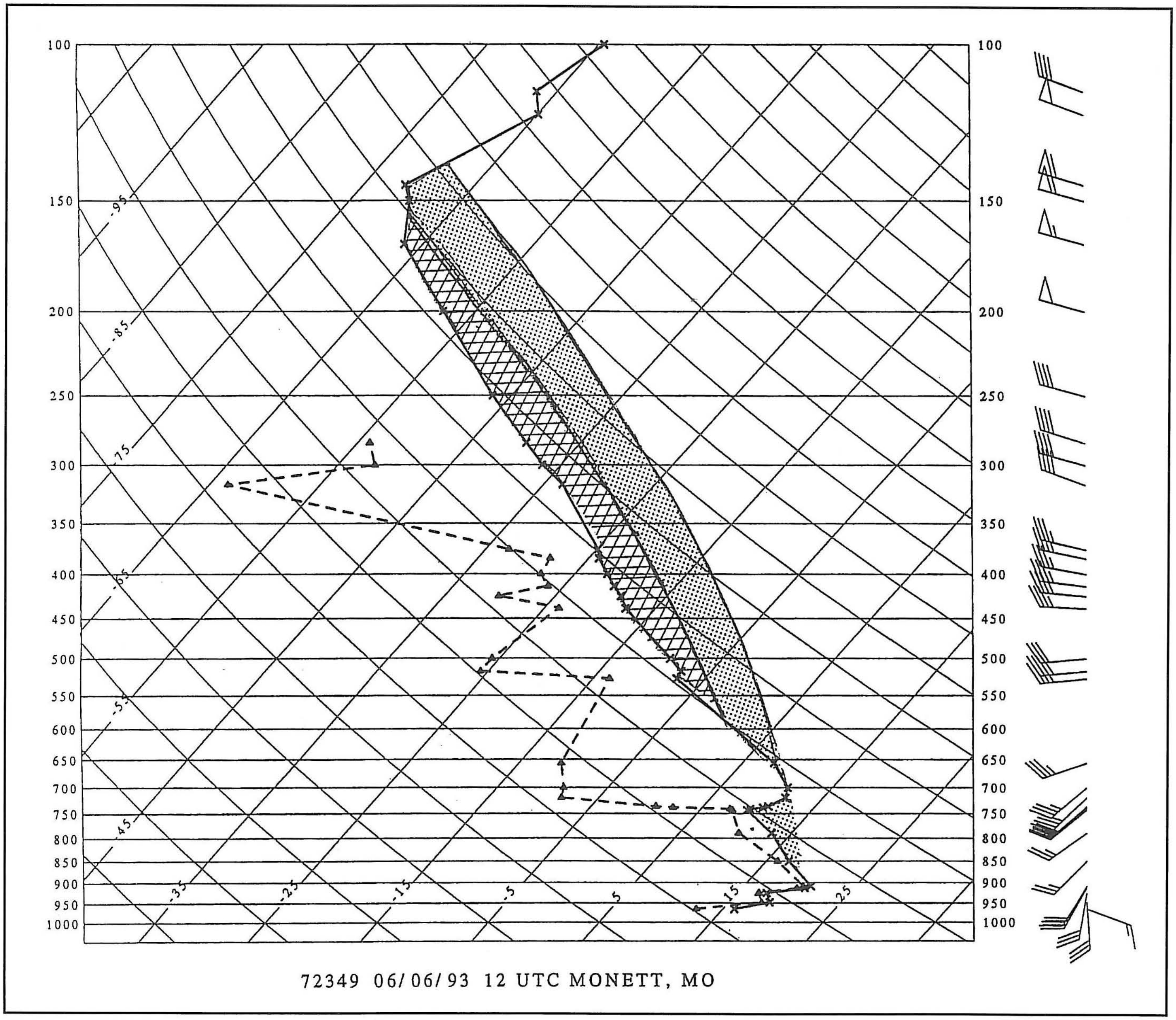

Fig. 5. 1200 UTC 6 June 1993 skew T-log P diagram for Monett, Missouri. Horizontal lines depict pressure (hPa), straight slanting (lower left to upper right) lines are isotherms (°C), and slightly curved sloping (lower right to upper left) lines are dry adiabats (K). Winds follow standard notation, with full and half feathers representing 5.0 and 2.5 ms^{-1}, respectively, and pennants representing 25.0 ms^{-1}. Cross-hatched region indicates convective available potential energy (CAPE) based upon lifting the mean 100-hPa parcel, stippled region represents additional CAPE based on lifting the parcel with the highest θ_e value in the lowest 300 hPa (after Rochette and Moore 1996).

lifting of a parcel based on the average thermal and moisture characteristics of the lowest 100-hPa layer (hereafter referred to as mean-parcel CAPE), while the stippled region represents the additional CAPE realized by lifting the most unstable parcel (i.e., the parcel with the highest θ_e, located around 910 hPa) in the lowest 300-hPa layer (hereafter referred to as 'best CAPE'). The Monett sounding revealed a mean-parcel CAPE of 2258 J kg^{-1}, suggestive of a moderately unstable environment. However, by lifting the most unstable parcel, the best CAPE was 4256 J kg^{-1}, an increase of more than 88%. The Topeka sounding for the same time (Fig. 6) was even more dramatic; the mean-parcel CAPE was 699 J kg^{-1}, while the best CAPE was 2814 J kg^{-1}, an increase of more than 300%. It is noteworthy that both soundings exhibited virtually no convective inhibition (CIN), and that both represent weakly sheared environments.

Further corroboration of this difference is unveiled by the comparison of plan views of mean-parcel CAPE (Fig. 7) and best CAPE (Fig. 8). Note that northern Missouri is only slightly unstable at best, with mean-parcel CAPE values generally less than 500 J kg^{-1}. In contrast, the best CAPE field over the initiation region reveals a much more unstable environment, with values in excess of 1500 J kg^{-1}. Thus, the pre-MCS environment north of the warm front on the morning of 6 June 1993 had the potential for strong convection, and conventional CAPE computations would not disclose this fact.

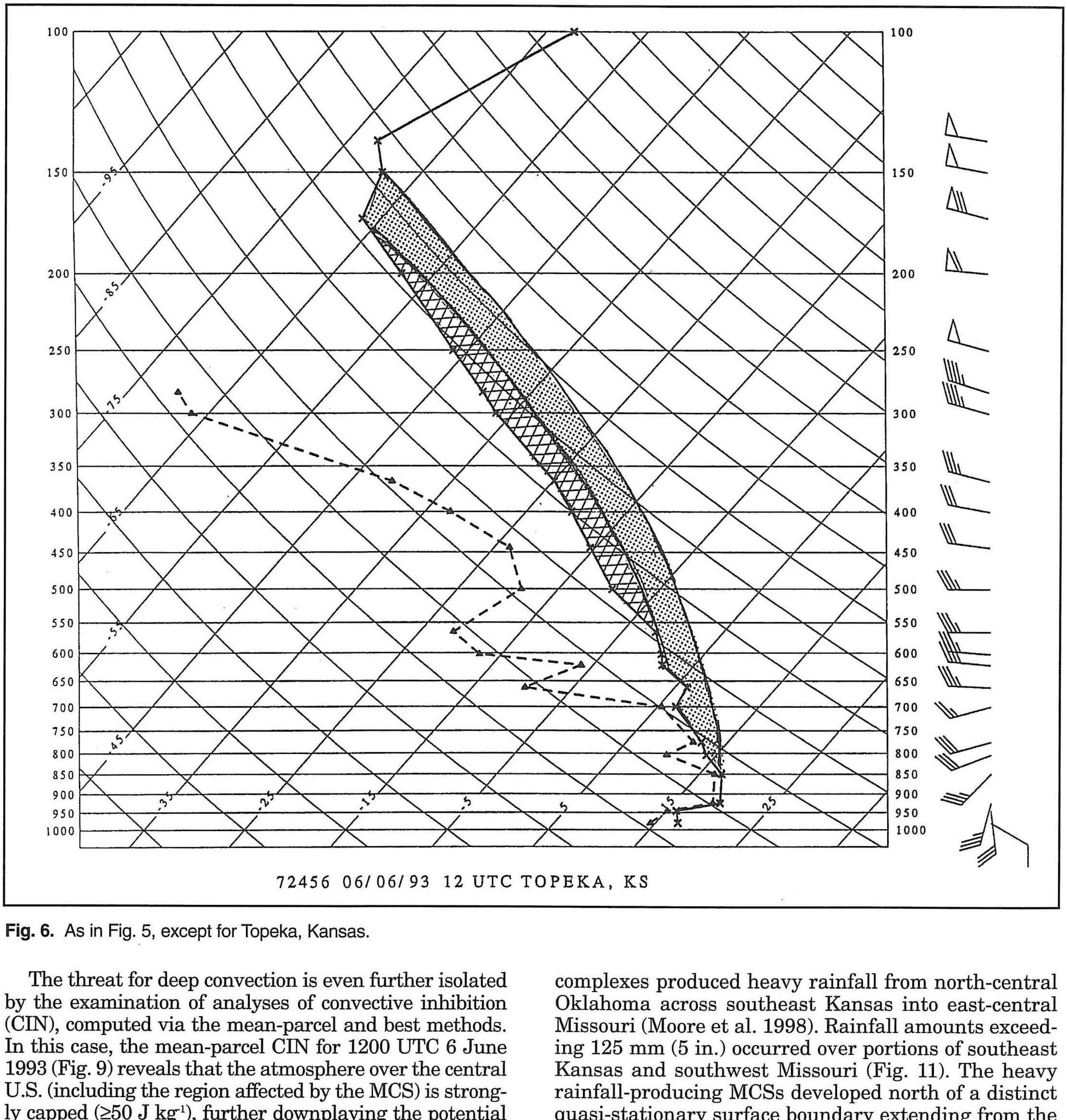

Fig. 6. As in Fig. 5, except for Topeka, Kansas.

The threat for deep convection is even further isolated by the examination of analyses of convective inhibition (CIN), computed via the mean-parcel and best methods. In this case, the mean-parcel CIN for 1200 UTC 6 June 1993 (Fig. 9) reveals that the atmosphere over the central U.S. (including the region affected by the MCS) is strongly capped (≥50 J kg^{-1}), further downplaying the potential for thunderstorm development at this time. However, CIN computed through the lifting of the most unstable parcel (best CIN, Fig. 10) is generally weaker and much smaller in areal extent, with values below 50 J kg^{-1} over northern Missouri, indicating a much more conducive environment for the elevated thunderstorms and excessive precipitation that occurred in this region.

b. 27-28 April 1994

From the late afternoon of 27 April 1994 into the morning of 28 April 1994, a series of thunderstorm complexes produced heavy rainfall from north-central Oklahoma across southeast Kansas into east-central Missouri (Moore et al. 1998). Rainfall amounts exceeding 125 mm (5 in.) occurred over portions of southeast Kansas and southwest Missouri (Fig. 11). The heavy rainfall-producing MCSs developed north of a distinct quasi-stationary surface boundary extending from the Missouri bootheel through southeast Oklahoma into north-central Texas. Figure 12 is the 0000 UTC 28 April 1994 surface analysis, showing a strong baroclinic zone with warm-sector temperatures from 28 to 31 °C (82 to 88 °F) and cool-sector temperatures of 5 to 15 °C (41 to 59 °F). Convective stability profiles at 0000 UTC 28 April 1994 for Monett, Missouri (solid) and Norman, Oklahoma (dashed) are shown in Fig. 13. The profiles from both stations are similar to those shown for 1200 UTC 6 June 1993, with strong stable layers from the surface to 850 hPa (beneath the frontal inversion) and potential convectively unstable layers above to 650-700 hPa (with shallow stable layers in-between). This vertical stratification is indicative of elevated convective instability supporting the MCS over the surface cool-sector environment.

The 304 K isentropic surface at 0000 UTC 28 April 1994 (Fig. 14) is presented to diagnose lifting above the boundary layer within the frontal zone. The strongest lifting on this isentropic surface was present over northeastern Oklahoma, northern Arkansas, extreme southeastern Kansas and southwestern Missouri in the 850-800 hPa layer. An analysis of surface divergence at 0000 UTC (not shown) depicted weak divergence (2.0 to 4.0 x 10^{-5} s^{-1}) over most of Missouri; these findings suggest that the lifting was not surface-based. Isentropic uplift above the frontal zone was responsible for the release of the elevated convective instability, although it should be noted that existing convection could disrupt the continuity of isentropic surfaces through diabatic heating.

As was the case in the previously described episode, high moisture was present in the storms' initial environment at 0000 UTC 28 April 1994. A large swath of high RH values (≥70%) was indicated on the 304 K isentropic surface (not shown), covering eastern Nebraska, the eastern two-thirds of Kansas, southwestern Missouri, central and eastern Oklahoma, and most of Arkansas. The initial thunderstorms developed in an area where RH values were in excess of 70%.

The differences between the mean-parcel CAPE and the best CAPE are rather dramatic, as evidenced by the soundings from Monett, Missouri (Fig. 15) and Norman, Oklahoma (Fig. 16). Lifting a mean parcel in either sounding results in a CAPE value of 0 J kg^{-1}, while the best CAPE values were 1793 J kg^{-1} (Monett) and 2479 J kg^{-1} (Norman). This supports the assertion that the thunderstorms occurring at this time were the result of the release of elevated CAPE. Comparison of the analyses of mean-parcel CAPE (Fig. 17) and best CAPE (Fig. 18) at this time yields further evidence. Mean-parcel CAPE values indicate modestly unstable air in central Oklahoma (≤500 J kg^{-1}), increasing to the south and east, while the best CAPE analysis reveals values in excess of 2000 J kg^{-1} over the same area. It should be noted that any discrepancies in CAPE values between those derived from the soundings and those shown in plan view are most likely attributable to the Barnes (1973) objective analysis scheme.

Analysis of mean-parcel CIN (Fig. 19) reveals that the Southern Plains region (including Oklahoma, Arkansas, and Missouri) is characterized by weak values (<50 J kg^{-1}). Meanwhile, the best CIN field (Fig. 20) illustrates that the

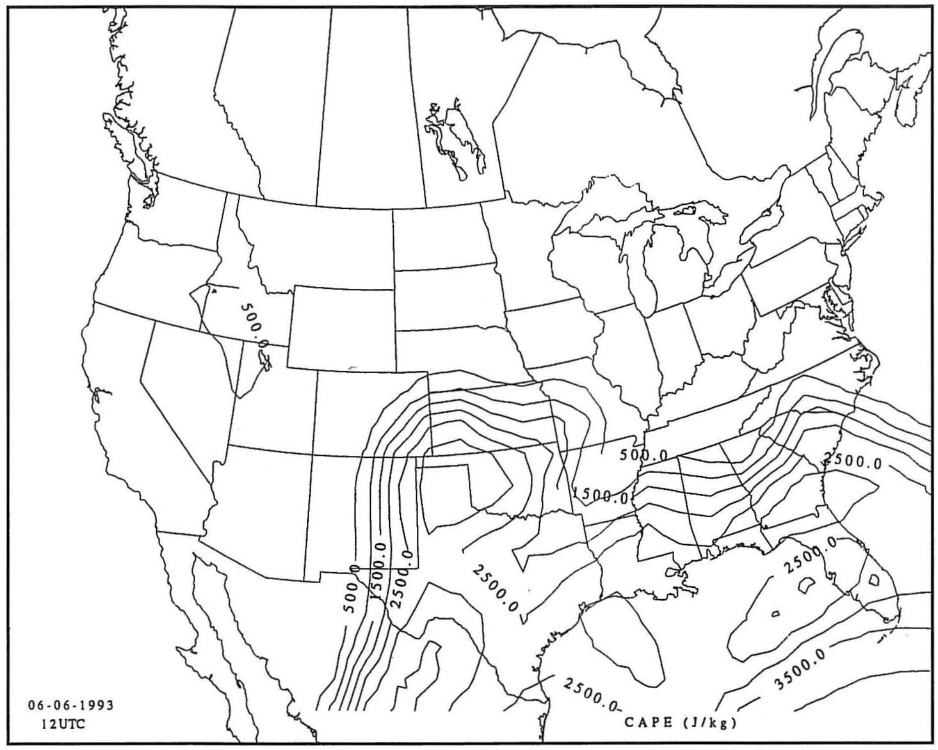

Fig. 7. 1200 UTC 6 June 1993 objective analysis of mean-parcel CAPE (J kg^{-1}).

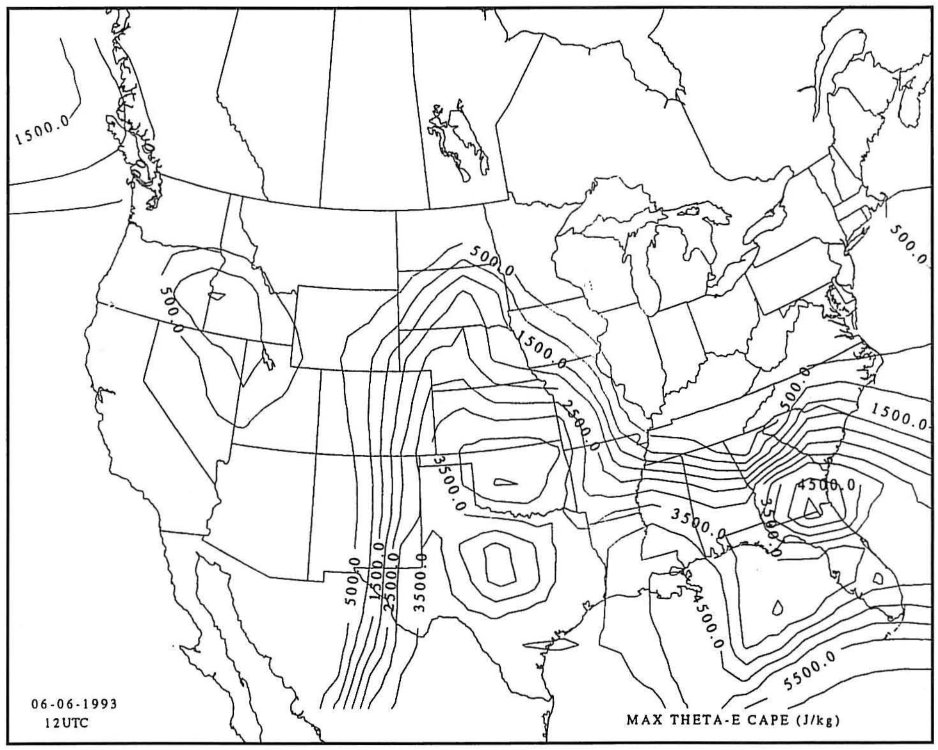

Fig. 8. As in Fig. 7, except for best CAPE (J kg^{-1}).

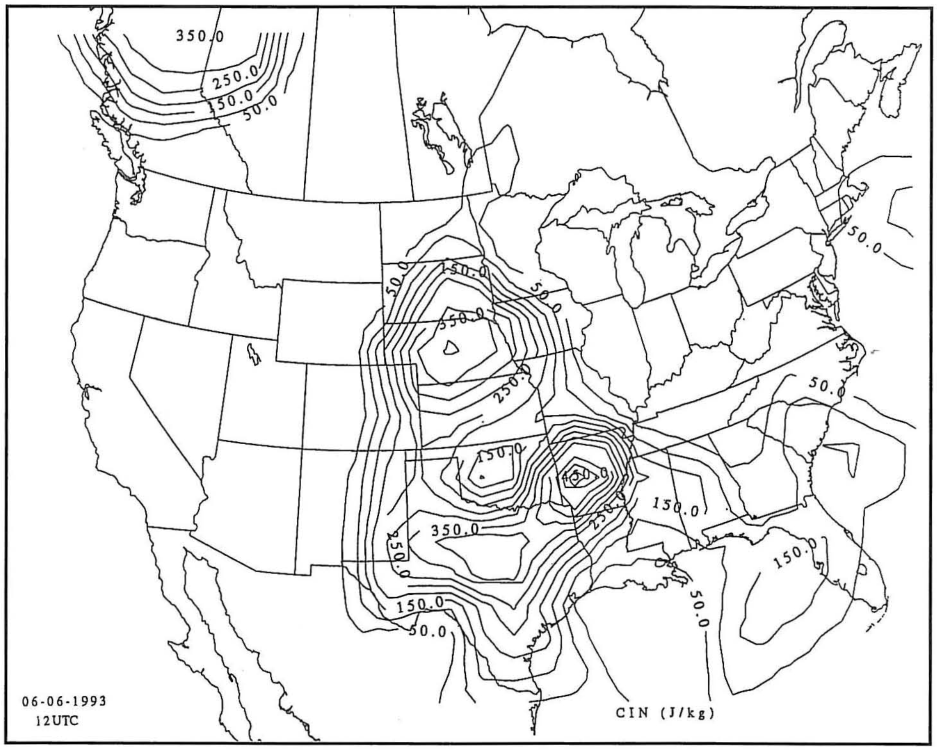

Fig. 9. 1200 UTC 6 June 1993 objective analysis of mean-parcel convective inhibition (CIN; J kg^{-1}).

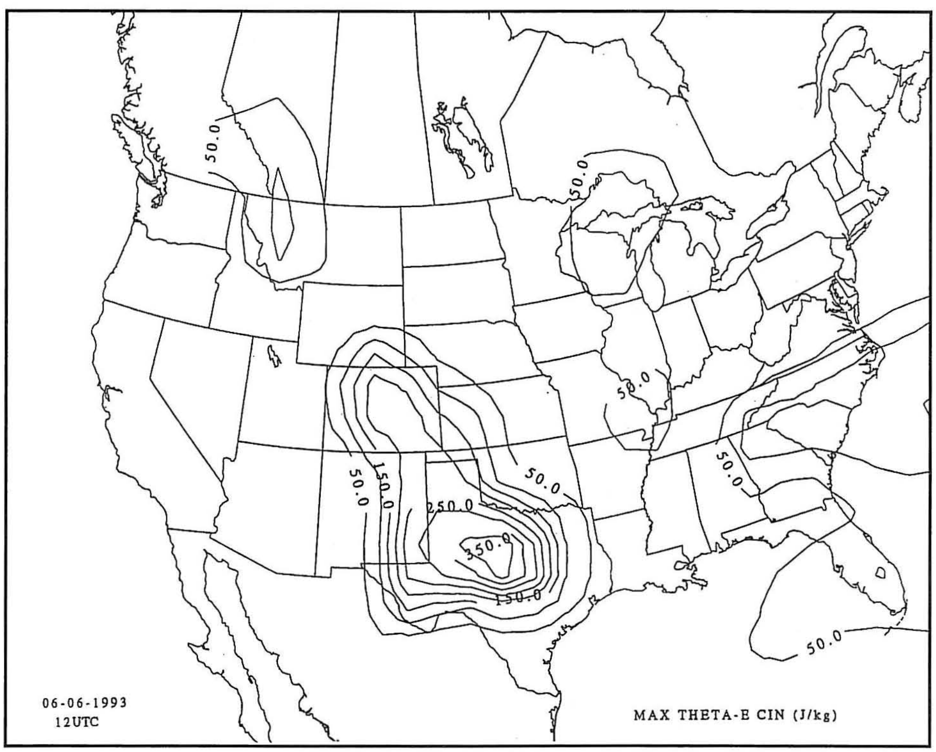

Fig. 10. As in Fig. 9, except for best CIN (J kg^{-1}).

region of elevated convection lies in an area of minimum CIN (<50 J kg^{-1}). However, western Kansas and the Oklahoma Panhandle are experiencing a localized maximum of CIN (~150 J kg^{-1}), further isolating eastern Oklahoma and southwestern Missouri as the region of excessive convective precipitation.

3. Discussion

In two episodes of Midwestern heavy rainfall associated with elevated convective instability, it was shown that the choice of lifted parcel in the computation of CAPE made a distinct difference in evaluating the environmental support of convection. It was illustrated that the CAPE computed by lifting a parcel based on the average thermal and moisture characteristics of the lowest 100-hPa layer (mean-parcel CAPE) was often much less than that computed by lifting the most unstable parcel in the lowest 300 hPa layer (best CAPE). In one of the cases examined the best CAPE was sufficiently large to support strong convection, even though the mean-parcel CAPE was nonexistent. Analyses of best CIN can further isolate regions of potential excessive precipitation via elevated thunderstorms.

Regions of non-zero best CAPE will typically be associated with environments characterized by layers of convective instability, either surface-based or elevated. However, best CAPE quantifies this instability and relates it directly to parcel accelerations in a more-recognized form. The ideal situation would be to examine CAPE and CIN fields in plan view and vertical profiles of θ_e for specific soundings (observed or forecast) to determine the convective potential for a given region.

In summary, there are convective episodes that result in heavy rainfall and severe weather that occur in environments that do not appear to have sufficient instability to support convection. A thorough analysis of the environment that includes examining both mean-parcel CAPE (CIN) and best CAPE (CIN) will highlight situations where elevated thunderstorms may occur, and should result in better prediction of a potentially dangerous situation. In addition, the presence of modest values of best CAPE might indicate regions where convective winter precipitation (e.g., thundersnow) may occur. Modification of existing (and development of future) computer software packages should make such a comparison relatively simple.

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Fig. 11. 24-h total rainfall (mm) ending at 1200 UTC 28 April 1994 as measured by NWS cooperative network rain gauges.

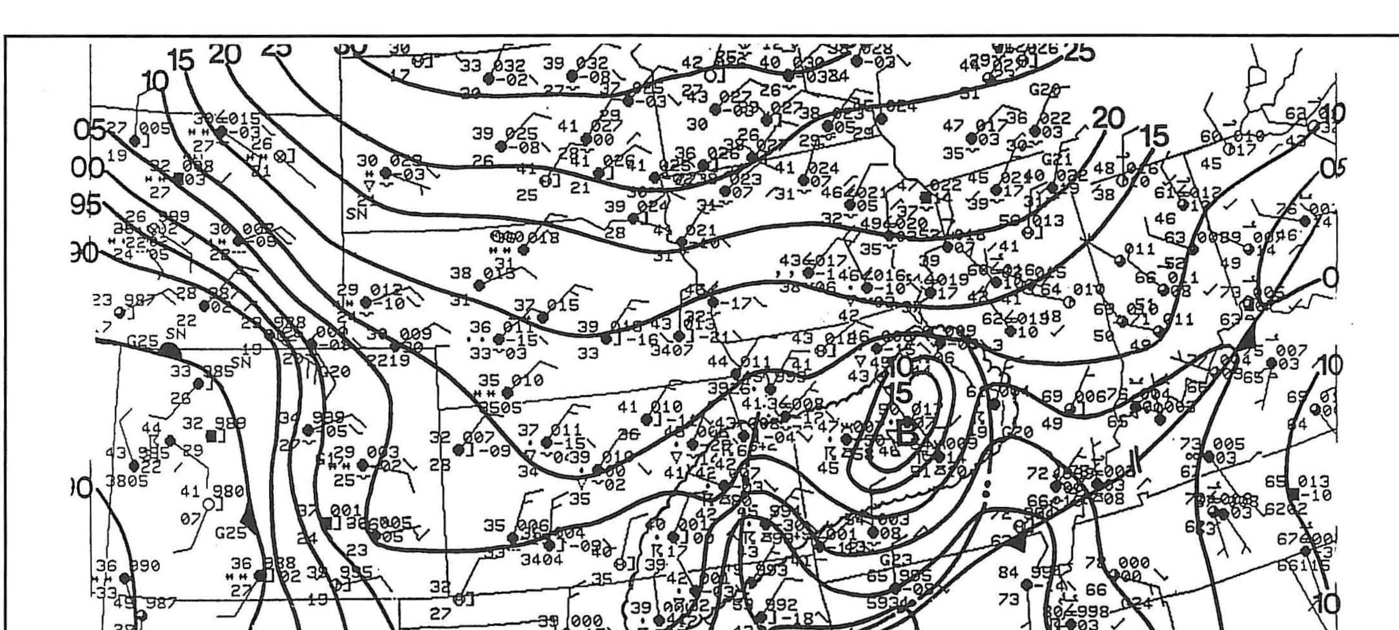

Fig. 12. As in Fig. 2, except for 0000 UTC 28 April 1994. Station model follows that of Fig. 2, with the following exceptions: solid lines are isopleths of altimeter setting (in Hg), cloud cover and genera are included, along with pressure trend symbol. Number preceded by "G" indicates wind gust in knots. Bold 'B' denotes location of bubble high. Dashed-double dotted line indicates outflow boundary. Scalloped region signifies area of initial storm development (adapted from Moore et al. 1998).

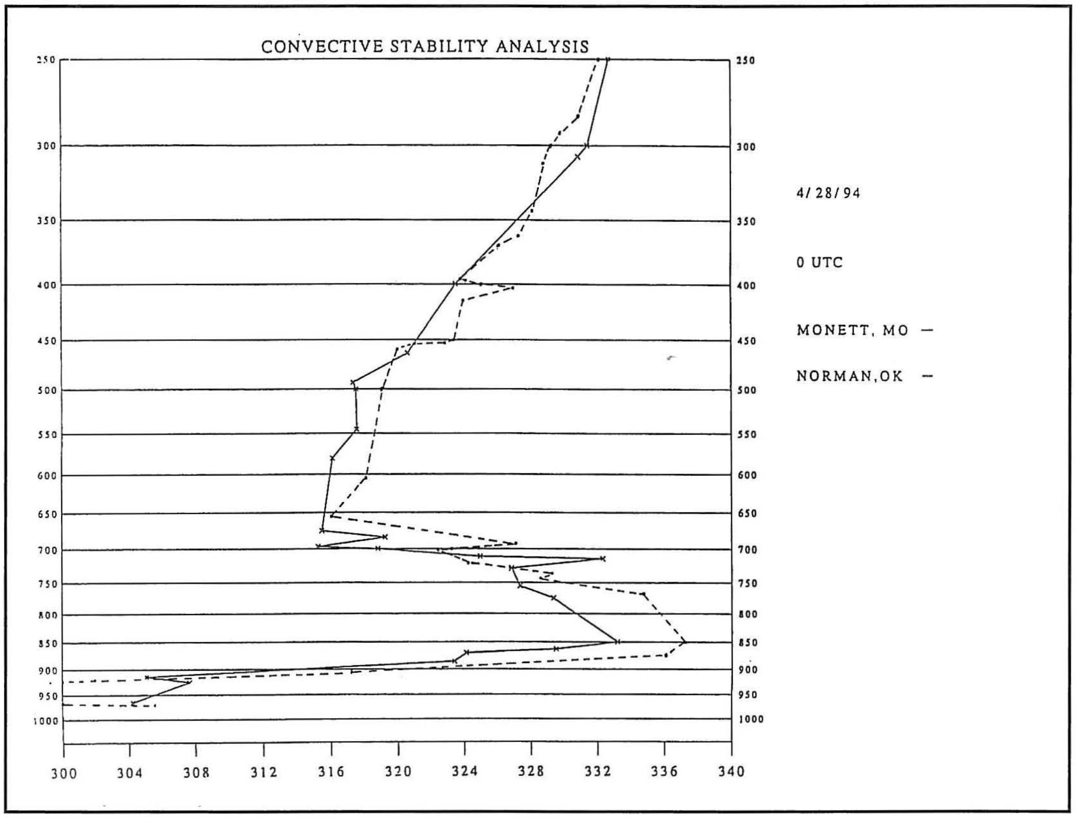

Fig. 13. 0000 UTC 28 April 1994 convective stability analysis for Monett, Missouri (solid) and Norman, Oklahoma (dashed). Abscissa is θ_e (K), ordinate is pressure (hPa).

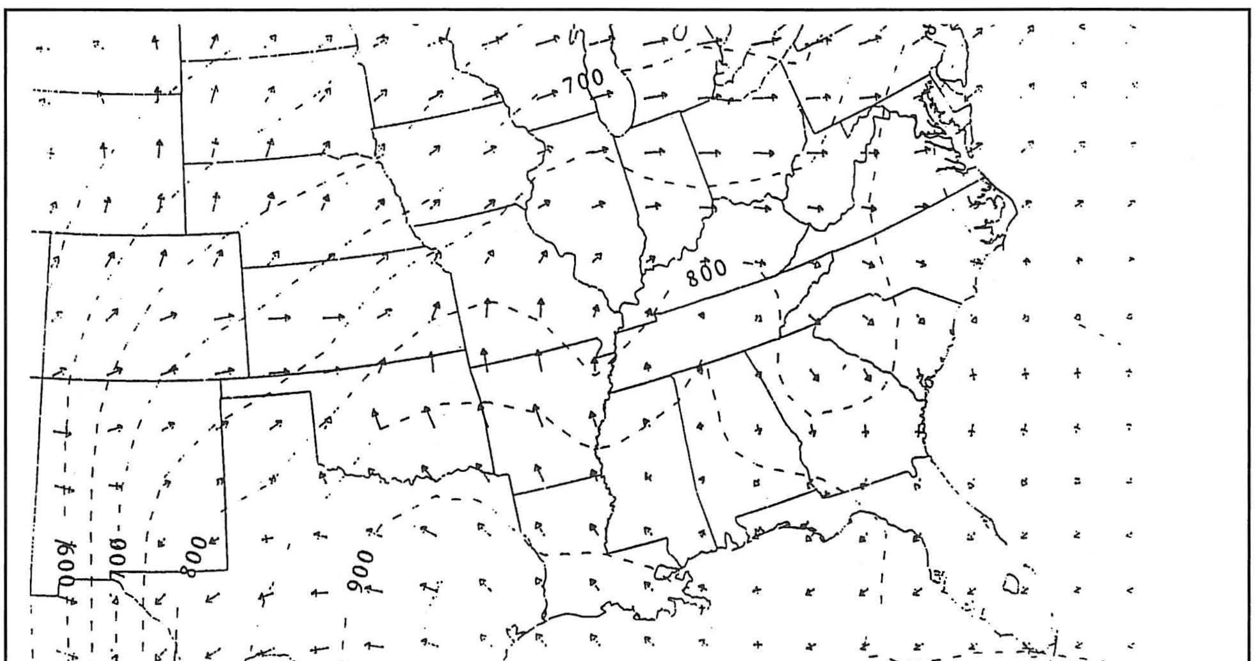

Fig. 14. 0000 UTC 28 April 1994 304 K isentropic surface. Notation follows that of Fig. 4.

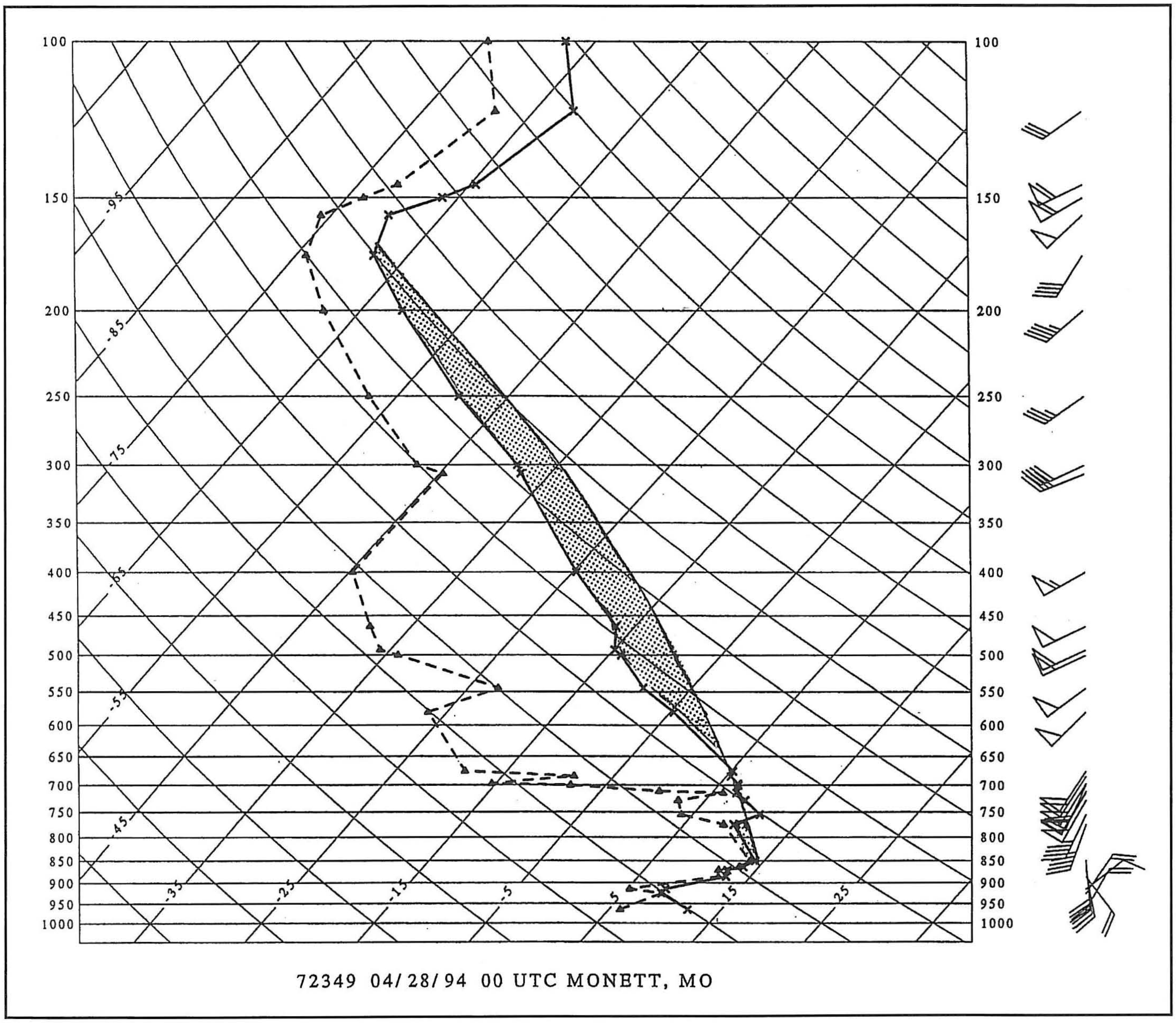

Fig. 15. 0000 UTC 28 April 1994 skew T-log P diagram for Monett, Missouri. Notation follows that of Fig. 5. Stippled region represents CAPE based on lifting the parcel with the highest θ_e value in the lowest 300 hPa.

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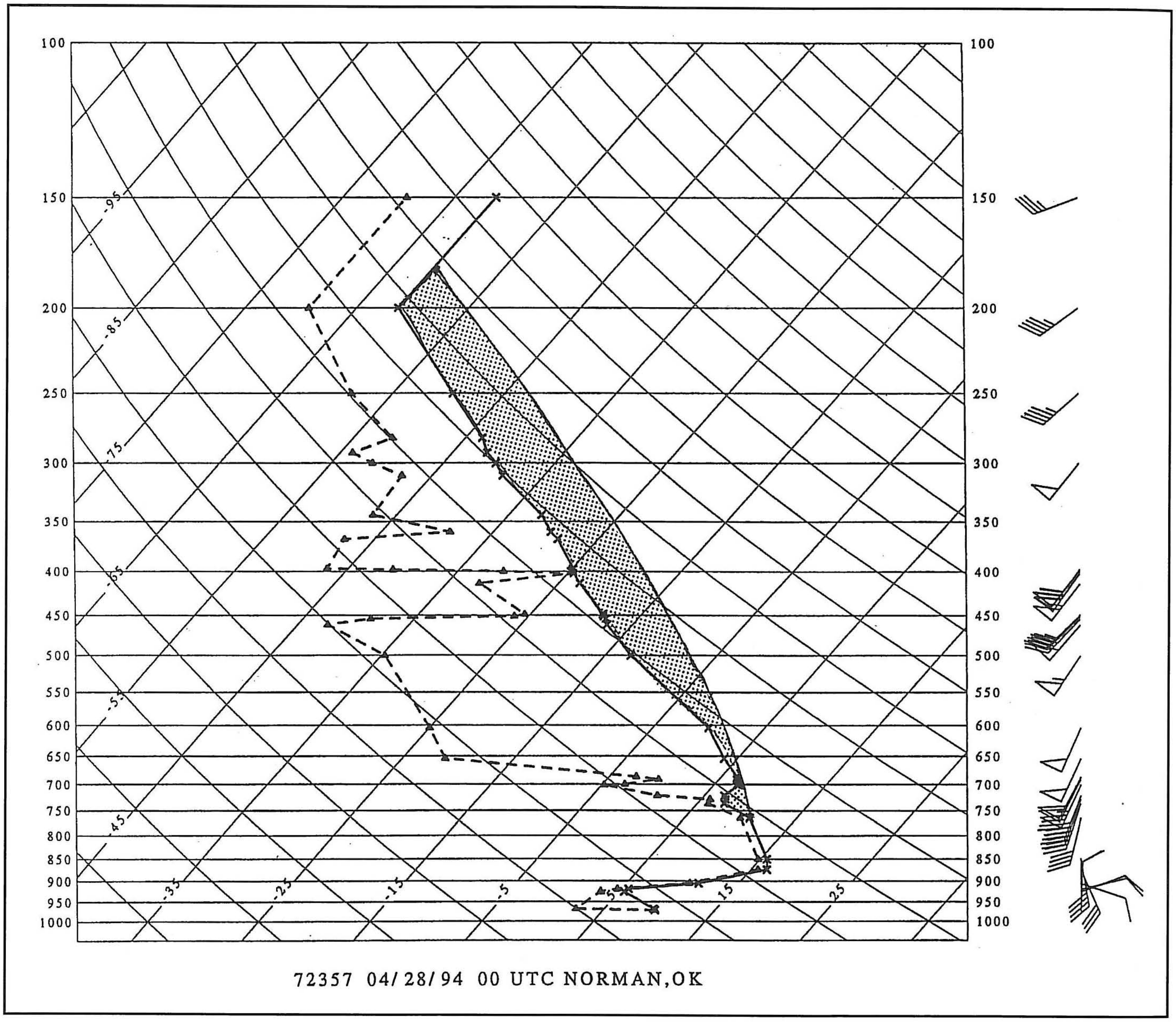

Fig. 16. As in Fig. 15, except for Norman, Oklahoma.

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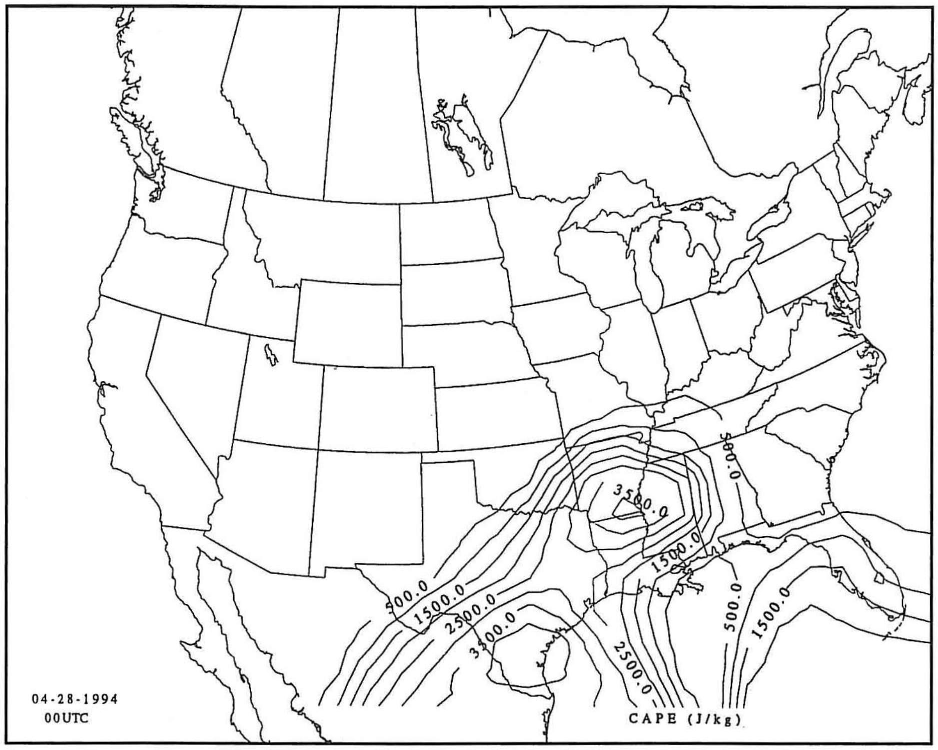

Fig. 17. 0000 UTC 28 April 1994 objective analysis of mean-parcel CAPE (J kg^{-1}).

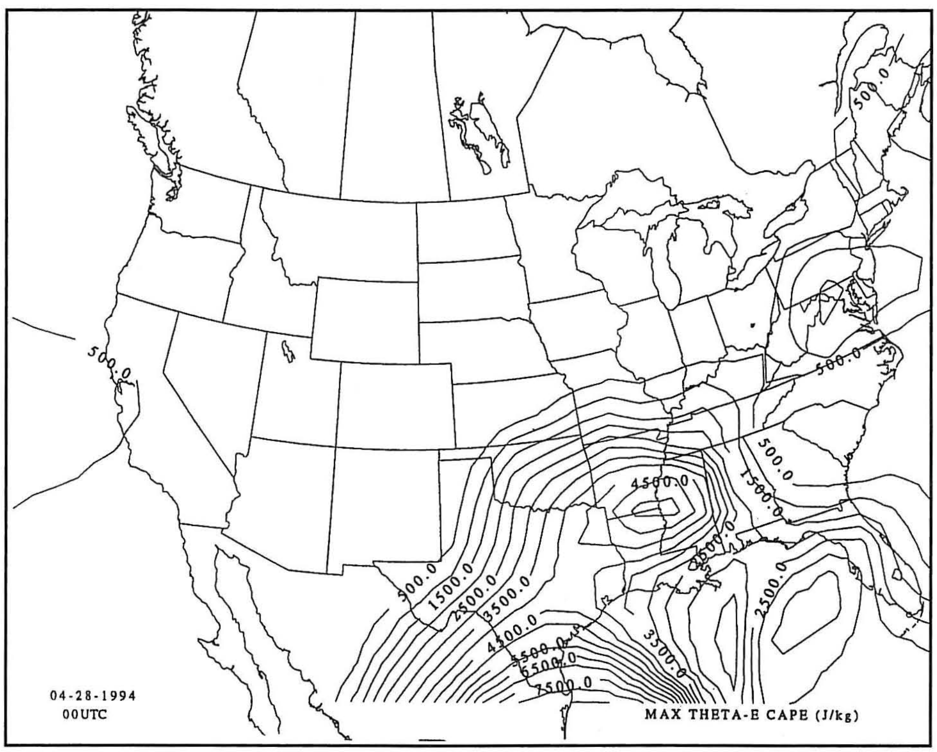

Fig. 18. As in Fig. 17, except for best CAPE (J kg^{-1}).

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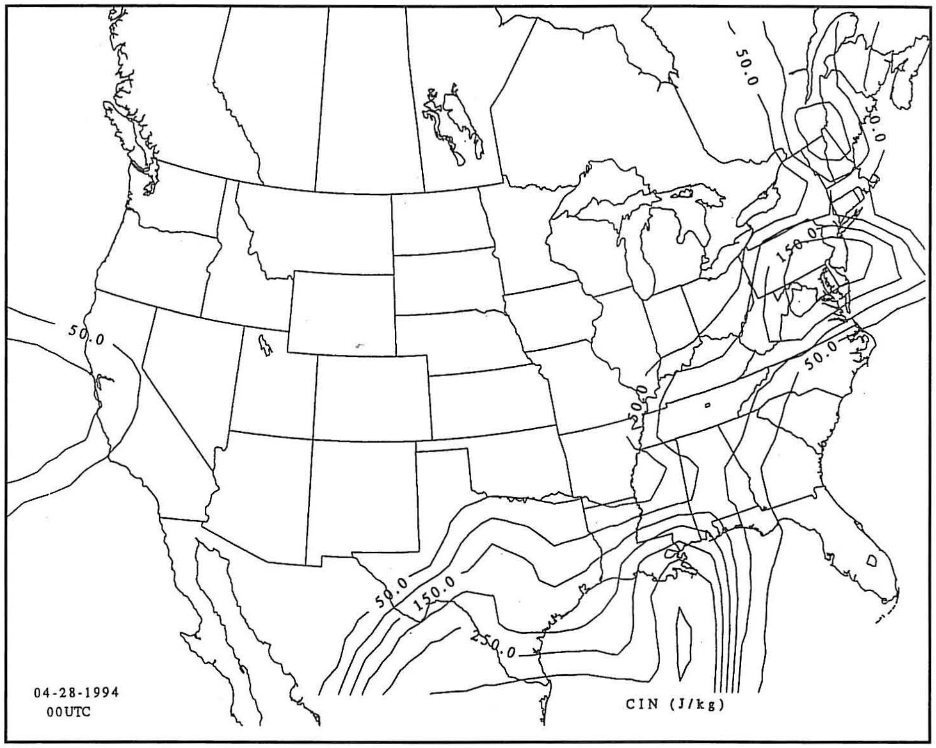

Fig. 19. 0000 UTC 28 April 1994 objective analysis of mean-parcel CIN (J kg^{-1}).

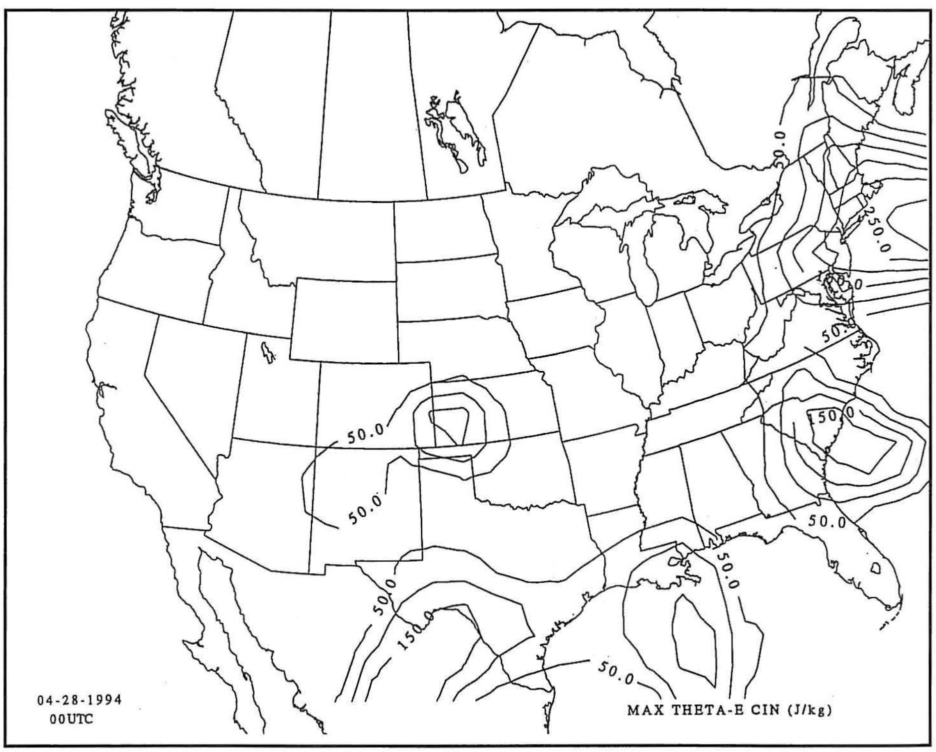

Fig. 20. As in Fig. 19, except for best CIN (J kg^{-1}).