THE FEBRUARY 1989 FLOOD IN KENTUCKY

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Abstract

Strong low-level warm advection and other forcing mechanisms led to four consecutive days of heavy rain over Kentucky in February 1989. Isentropic analysis as well as low-level equivalent potential temperature (Θ_e) analysis indicated strong lift and ample moisture content of air advected into the state. A steady feed of subtropical and Gulf of Mexico moisture into a strong baroclinic zone produced record floods in parts of central Kentucky.

1. Introduction

During the period 12–16 February 1989, 10 to 12 inches of rain fell over parts of west and central Kentucky (Fig. 1). Almost half that amount fell in a 12-h period from 0000 to 1200 UTC on the 14th. Deep standing water around the upper air station at the Paducah National Weather Service Office prevented the launch of the radiosonde balloon for the 0000 and 1200 UTC observations on 14 February.

Above normal precipitation in the state for the months of December 1988 and January 1989 caused minor flooding by the end of January and set a presage for the February flood. By the end of the four-day event, record flooding was occurring on some rivers in central Kentucky. Three people lost their lives and 2100 had to evacuate their homes. Forty-five counties in the state were declared disaster areas.

This paper will stress the importance of low-level features, along with isentropic and 850-mb equivalent potential temperature (Θ_e) analyses during the event. Emphasis is on the period of heaviest rain from the evening of 13 February to the morning of 14 February, while comparison is made with flash flood signatures documented in previous studies. Finally, although hydrological considerations are important, only the meteorological facet of the event is discussed.

2. Upper Level Features

On 12 February, prior to the period of heaviest rainfall, a zonal 100-kt jet was observed at 300 mb over Kentucky (not shown). By the 13th, the jet increased to 150 kt in speed and began to lift northward as the upper-level flow backed in response to a digging trough in the western United States. By the evening of 13 February, southwesterly flow at 300 mb began tapping subtropical middle and high-level moisture as the main trough amplified in the western states (Fig. 2). Ahead of the trough, a 150-kt jet streak extended from the Texas and Oklahoma panhandles northeastward into Illinois and northern Indiana with broad anticyclonic flow occurring south of the jet over Kentucky.

Convection, possibly aided by the right rear quadrant of the lifting jet streak, developed from northern Arkansas into central Illinois and moved southeastward into Kentucky by the early morning of 14 February (Fig. 3). Southwest flow at 300 mb continued on 15–16 February as the jet streak continued to lift northward (not shown). At 500 mb and 700 mb, broad southwest flow existed with an absence of significant short-waves during the four-day event (not shown).

3. Surface Analysis

High pressure held dominion over the lower Ohio Valley on 12 February, while a warm front extended from eastern Texas into southern Arkansas (not shown). By 1200 UTC 13 February (Fig. 4), the warm front moved northward and was located from Missouri to western Kentucky and Tennessee, while a cold front extended from Iowa into central Oklahoma. Rain overspread Kentucky in the frontal overrunning pattern during the night of the 12th, leaving one-half to one inch over most of the state.

During the next 24-h period, from 1200 UTC 13 February to 1200 UTC 14 February, four to six inches of rain fell over much of western and central Kentucky (Fig. 5). By 0000 UTC 14 February, the warm front had moved little, in part due to continued rain-cooled air which helped to enforce and maintain its position over extreme southern Kentucky (Fig. 6). Strong speed convergence existed across the front from Tennessee into Kentucky. On the other hand, the cold front continued to move eastward and approached western Kentucky. By 1200 UTC 14 February (Fig. 7), the cold front moved into eastern Kentucky, causing rain to diminish in intensity over most of the state.

During the next 48-h period, the cold front became stationary over eastern Tennessee then lifted northward into Kentucky as a warm front (not shown). An additional two to four inches of rain occurred over the state. By 1200 UTC 16 February, the meandering front dropped southward into the northern Gulf states as high pressure moved into Iowa and northern Illinois. Thus, the rain finally ended over most of Kentucky.

4. 850 MB And Θ_e Analysis

Examination at the 850-mb level shared some analysis procedures used by Maddox (1979) to locate important features such as low-level jet streams, fronts, and regions of high absolute low-level moisture content. These enhanced analyses helped to identify synoptic scale conditions preferred for both stratiform and convective type rainfall while equivalent potential temperature (Θ_e) analyses were beneficial in finding favored areas for convective development.

Equivalent potential temperature is a thermodynamic parameter dependent on temperature and moisture. Since Θe is conserved for adiabatic processes, it is a useful forecasting tool in the development, movement, and propagation of convective systems when used in combination with satellite, surface, and upper air data (Scofield and Robinson 1989). 850-mb Θe patterns are less chaotic than surface patterns, and may be better suited for forecasting convective development. Higher values of Θ_e denote a warmer and/or wetter air mass that can be conducive for convective development.

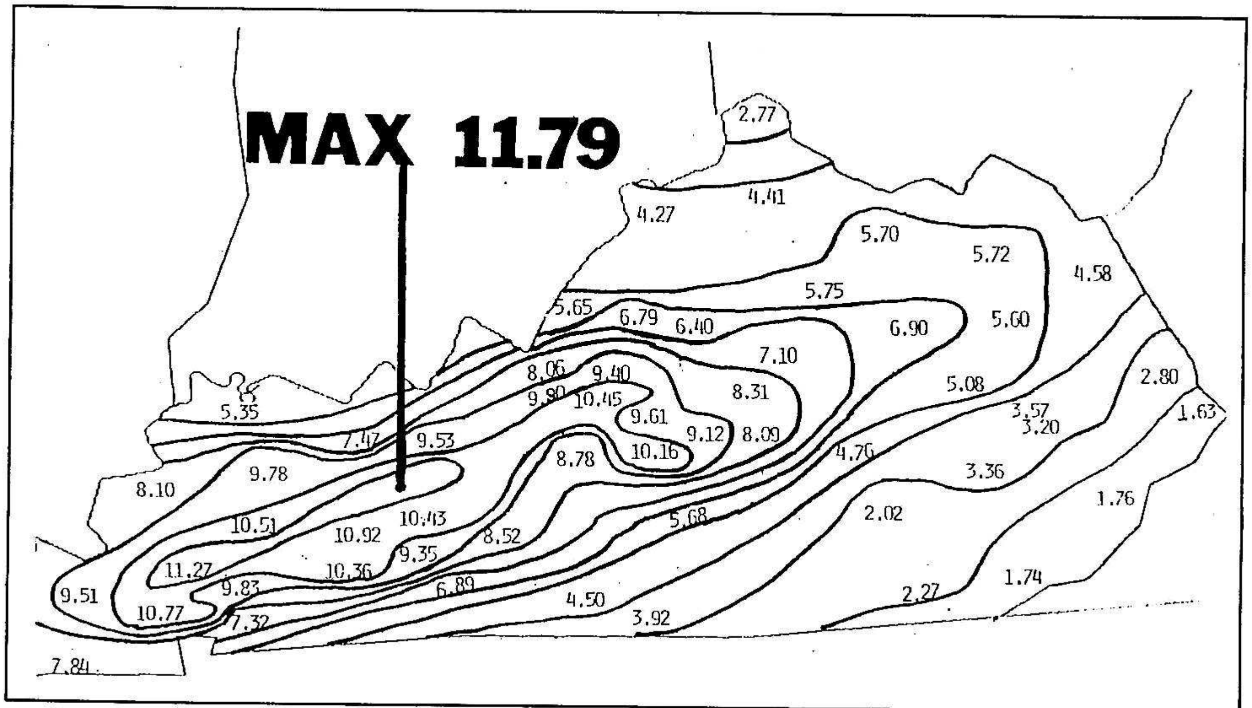

Fig. 1. Four-day rainfall totals (in inches) ending at 1200 UTC 16 February 1989.

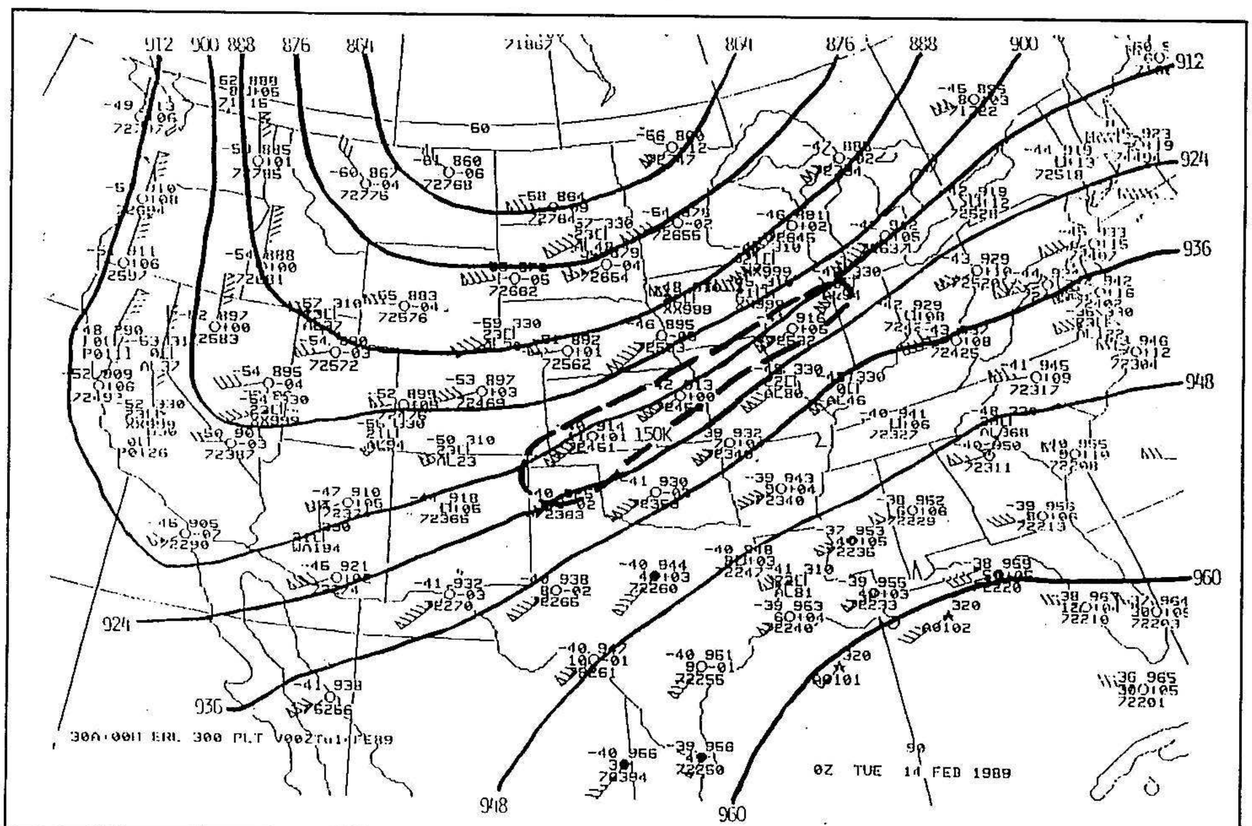

Fig. 2. 300 mb analysis for 0000 UTC 14 February 1989. Contours every 120 meters (solid). 150 kt isotach (dashed).

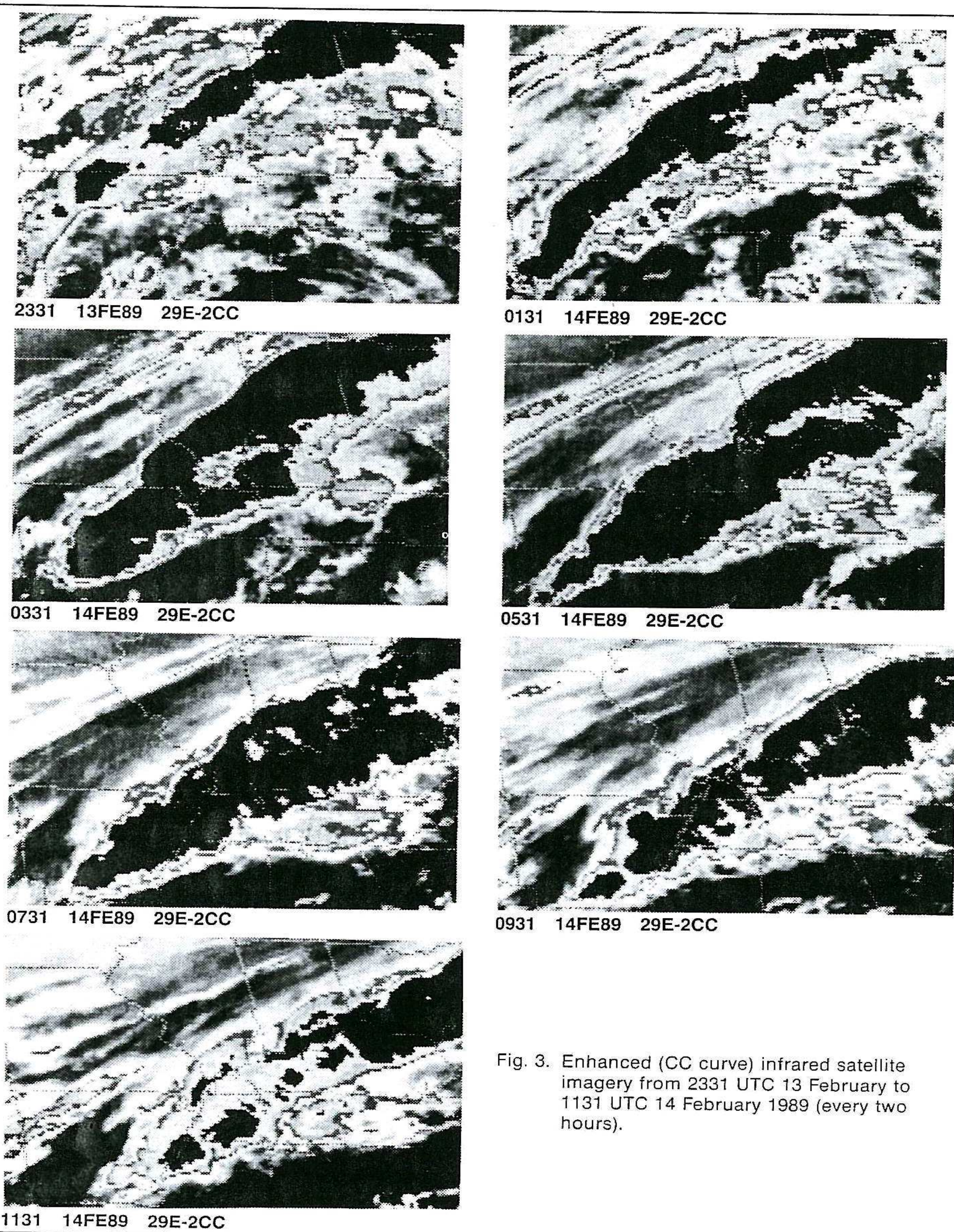

Fig. 3. Enhanced (CC curve) infrared satellite imagery from 2331 UTC 13 February to 1131 UTC 14 February 1989 (every two hours).

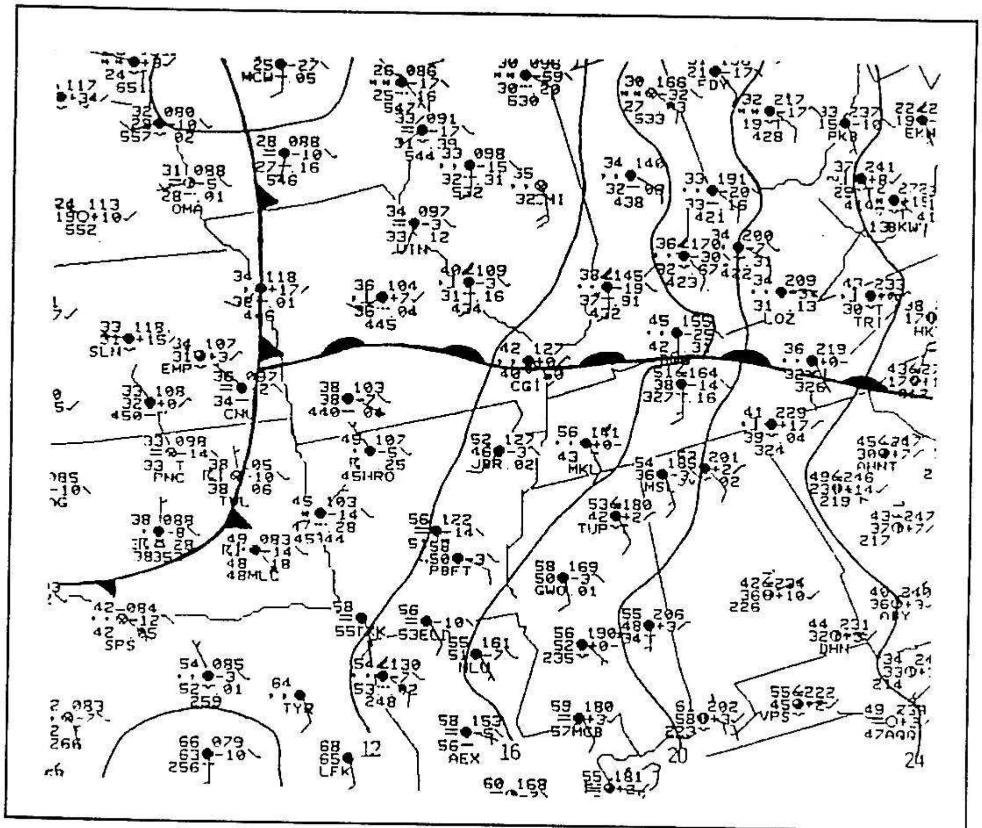

Fig. 4. Surface analysis for 1200 UTC 13 February 1989. Pressure increments every four mb.

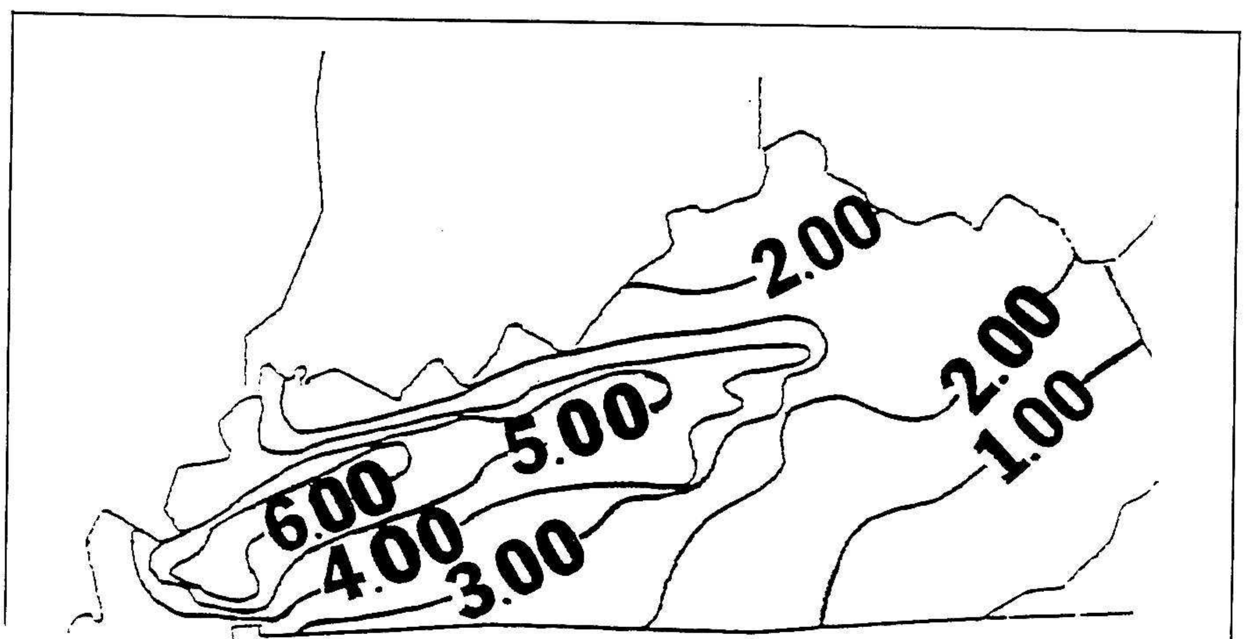

Fig. 5. Observed 24-h rainfall totals (in inches) ending at 1200 UTC 14 February 1989.

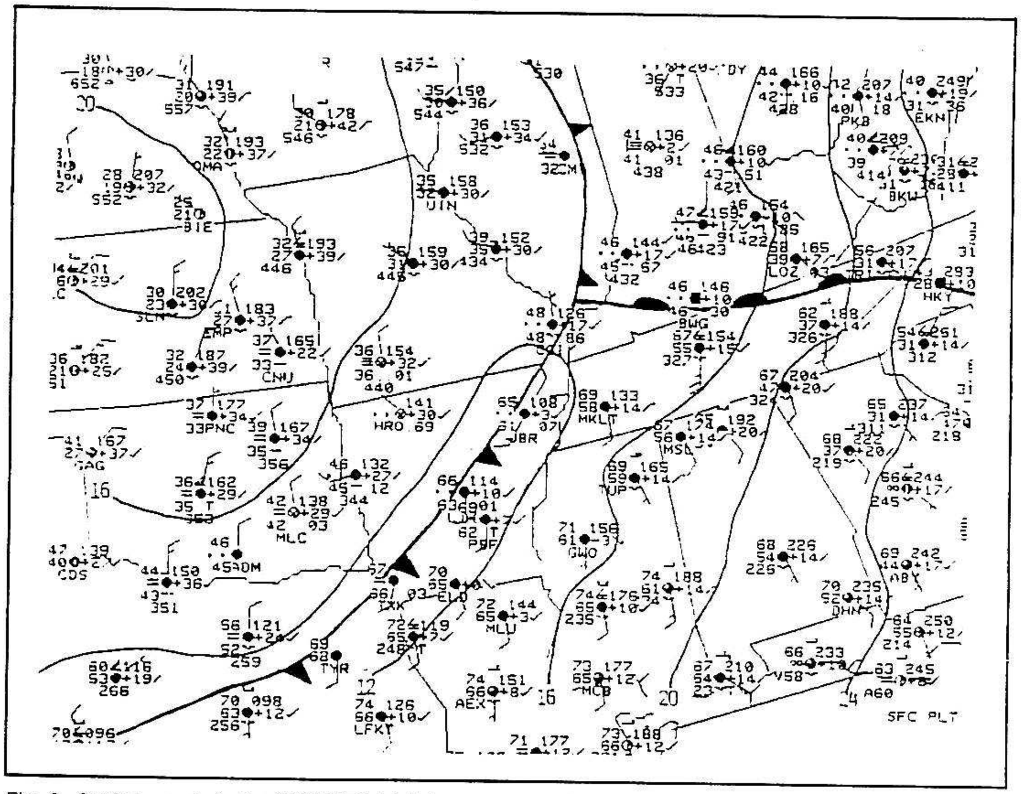

Fig. 6. Surface analysis for 0000 UTC 14 February 1989. Pressure increments every four mb.

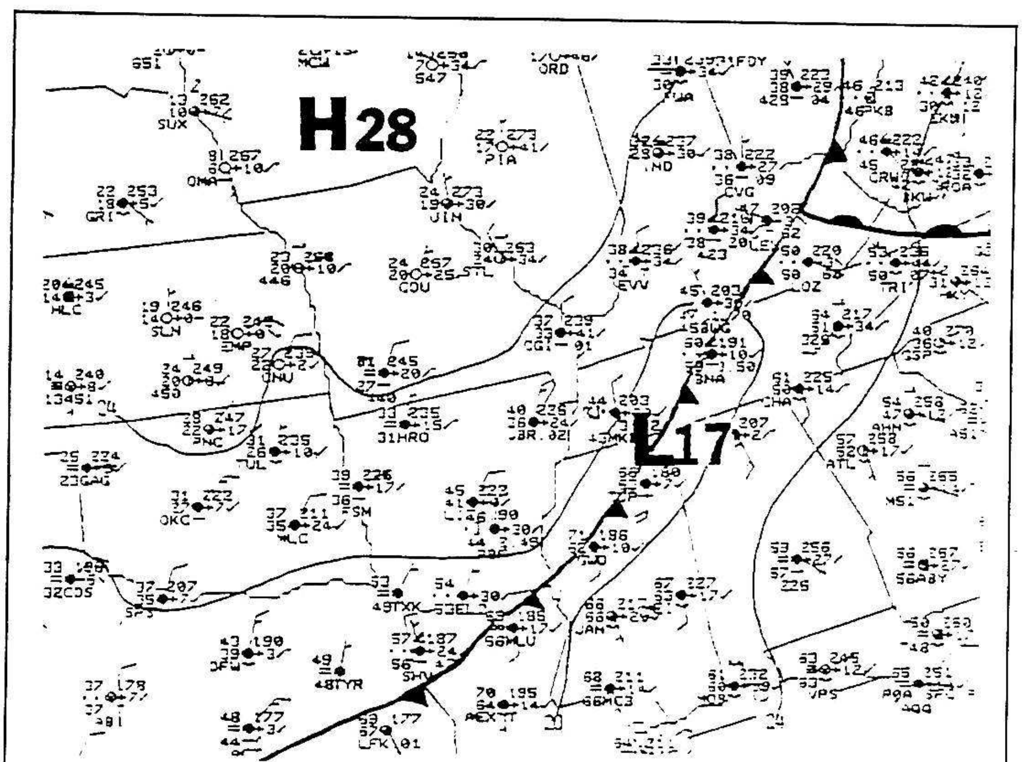

Fig. 7. Surface analysis for 1200 UTC 14 February 1989. Pressure increments every four mb.

In this event, convective rainfall in the 12-h period from 0000 to 1200 UTC 14 February accounted for almost half the total rainfall during the four-day period.

At 1200 UTC 12 February, warm air and moisture advection were occurring over northern Texas and Oklahoma at 850 mb (Fig. 8a). A Θ_e maximum at 850 mb was positioned over eastern Texas and Louisiana with a broad Θ_e ridge extending northward into Arkansas and Oklahoma (Fig. 8b).

At 0000 UTC 13 February (Fig. 9a), a 40-kt jet transported moisture from eastern Texas into Oklahoma and parts of Arkansas, Kansas, and Missouri. Maxima of Θe continued over eastern Texas with a ridge axis extending north across Oklahoma, northwestern Arkansas, and southwestern Missouri (Fig. 9b).

By 1200 UTC 13 February (Fig. 10a), the jet strengthened to 50–70 kt, and advected moisture-laden air into western and central Kentucky. The packing of the isotherms and the strength of the jet implied strong synoptic scale lift and destabilization due to warm air advection over Kentucky. Maximum Θ_e air was located over northeastern Texas while the Θ_e ridge axis moved northeastward into Kentucky and Tennessee (Fig. 10b).

A strong inflow of warm, moist air at 850 mb (dewpoints of 12°C) continued toward Kentucky at 0000 UTC 14 February (Fig. 11a). This moisture axis was coincident with a thermal ridge axis observed across Arkansas, western Kentucky, and into Indiana and Ohio ahead of an approaching 850-mb cold front. As a result, a broad Θ_e maxima area continued over the lower Mississippi Valley, with the primary ridge axis extending northeastward across Kentucky (Fig. 11b).

Juying and Scofield (1989) and Shi and Scofield (1987) showed that Θ_e ridge axes and embedded Θ_e maxima at 850 mb are favored areas for convective development if coincident with unstable air and sufficient upward vertical motion. Scofield and Robinson (1989) also revealed that in overrunning situations, Mesoscale Convective Systems (MCSs) often develop along or north of the Θ_e ridge axis and within areas of Θ_e gradients. Depending on the synoptic environment, convective systems will either 1) continuously propagate forward with the maximum 850 mb flow maintaining unstable air at the leading edge of the MCS, 2) propagate forward but with convective regeneration upstream within higher Θ_e values and more unstable air, or 3) propagate backward along the Θ_e ridge axis.

In this case, higher Θ_e values lay upstream from the initial convective development. On the evening of the 13th, an MCS developed ahead of the cold front in the Θ_e gradient from northern Arkansas and southeastern Missouri into southern Illinois and Indiana as shown by the 0131 UTC 14 February image (Fig. 3). By 0531 UTC, the line-shaped MCS propagated southeastward into the Θ_e maxima and ridge axis from central Arkansas to the western portions of Kentucky and Tennessee (Fig. 3). Rainfall rates of one-half to one inch per hour occurred over western and central Kentucky at this time.

The cold front pushed southeastward by 1200 UTC 14 February and extended from Ohio to central Tennessee (Fig. 12a). By 1131 UTC, the convection weakened across Kentucky (Fig. 3) as the strongest warm air advection shifted into New England. However, along the western portion of the front, overrunning rainfall developed over northern Texas and Oklahoma. The corresponding 850-mb Θ_e analysis (Fig. 12b) showed highest values from eastern Texas through

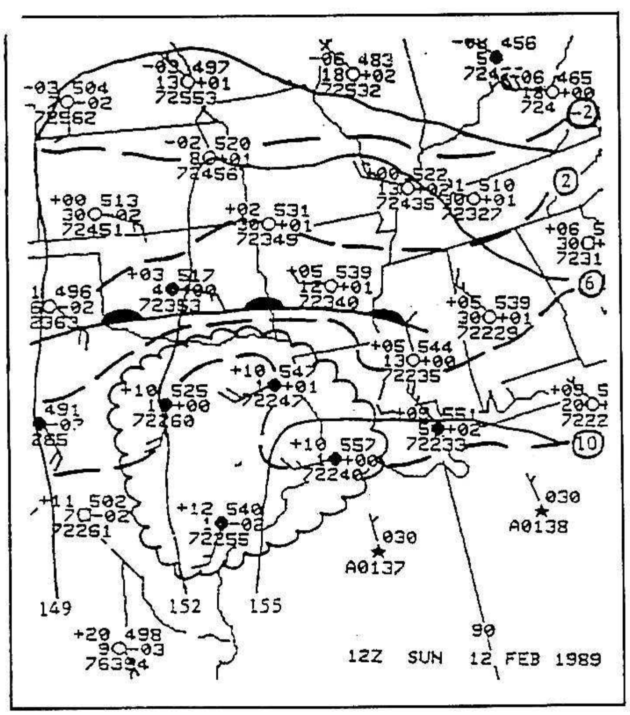

Fig. 8a. 850-mb analysis for 1200 UTC 12 February 1989. Contours every 30 meters (solid). Isotherms every 4°C (dashed). Regions with dewpoints 8°C or greater (scalloped).

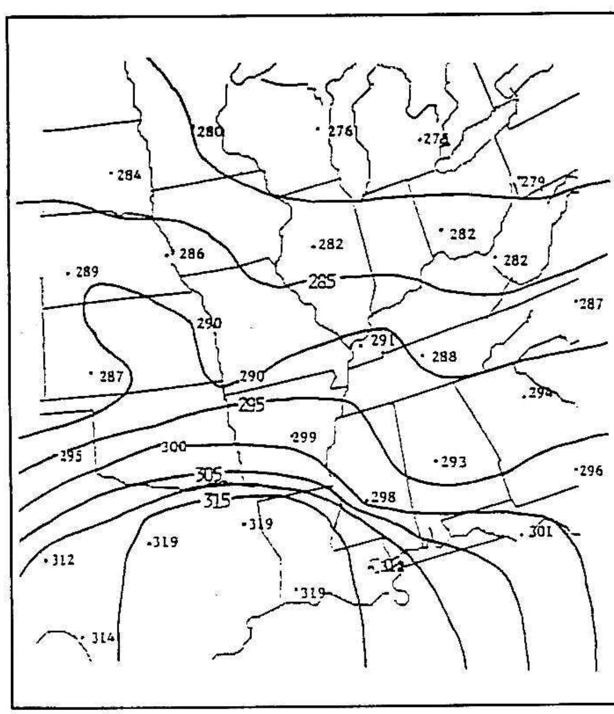

Fig. 8b. 850-mb Θ_e analysis for 1200 UTC 12 February 1989. Contours every 5K.

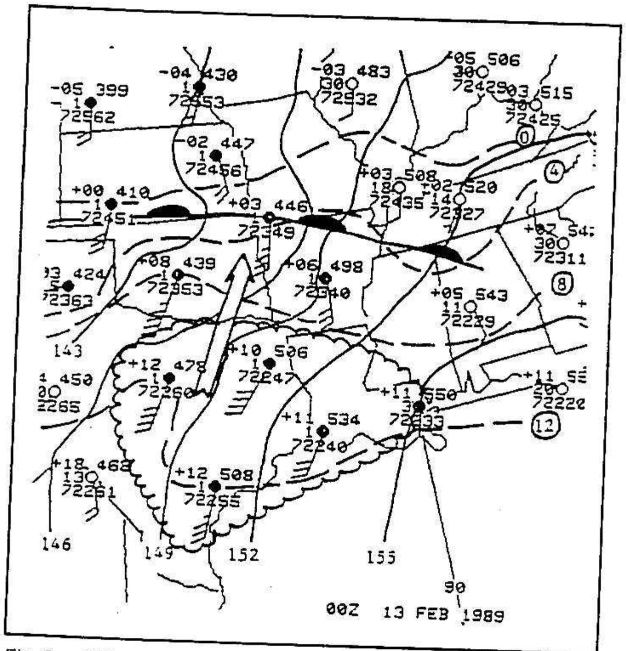

Fig. 9a. 850-mb analysis for 0000 UTC 13 February 1989. Units same as Fig. 8a. Arrow denotes jet axis.

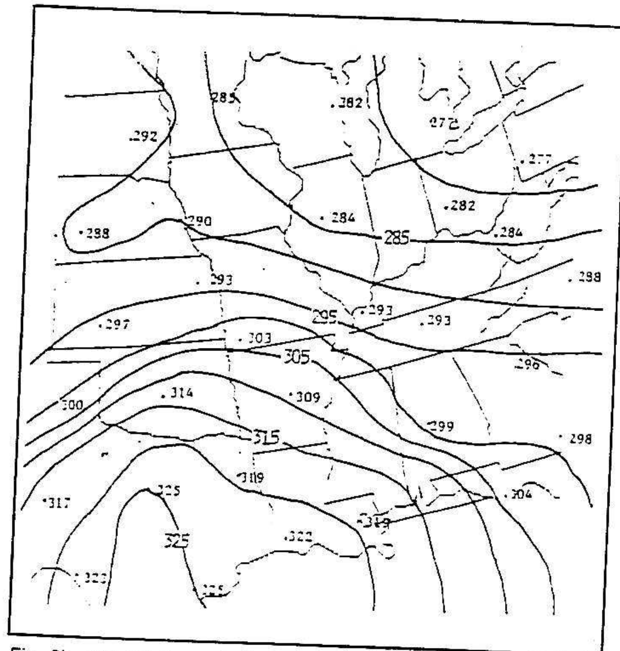

Fig. 9b. 850-mb Θ_e analysis for 0000 UTC 13 February 1989. Units same as Fig. 8b.

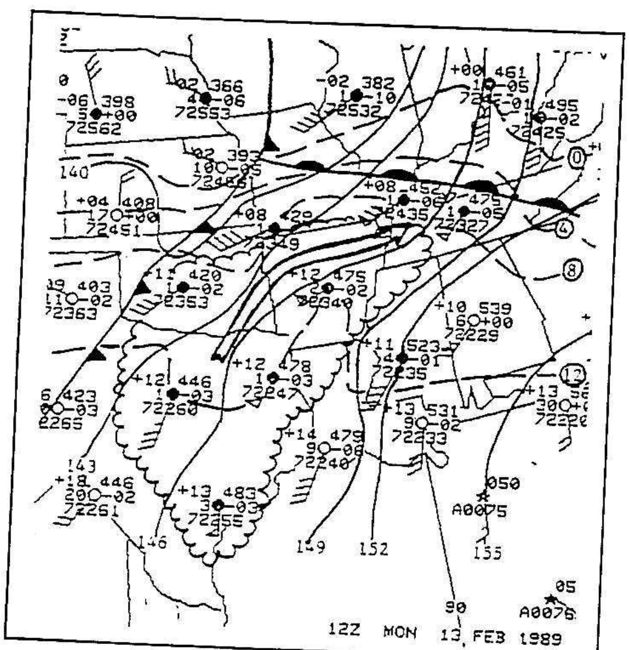

Fig. 10a. 850-mb analysis for 1200 UTC 13 February 1989. Units same as Fig. 8a. Arrow denotes jet axis.

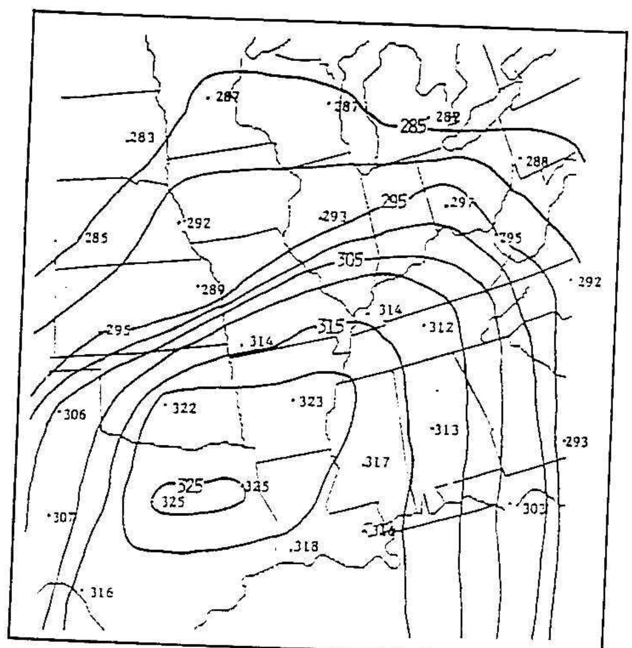

Fig. 10b. 850-mb Θ_e analysis for 1200 UTC 13 February 1989. Units same as Fig. 8b.

the Gulf coast states with a Θ_e gradient located just to the north.

By 0000 UTC 15 February (Fig. 13a), strong warm advection was again taking place over northern Arkansas, Tennessee, and the lower Ohio Valley. The exit region of a 40–50 kt 850-mb jet across eastern Texas and Arkansas resulted in speed convergence and implied upward vertical motion over the lower Ohio Valley. Maximum Θ_e values and the primary Θ_e ridge axis at this time (Fig. 13b) extended from eastern Texas to Alabama with the sharpest gradient located over Arkansas where a warm front at 850 mb now was positioned. Due to the strong low-level speed convergence and warm

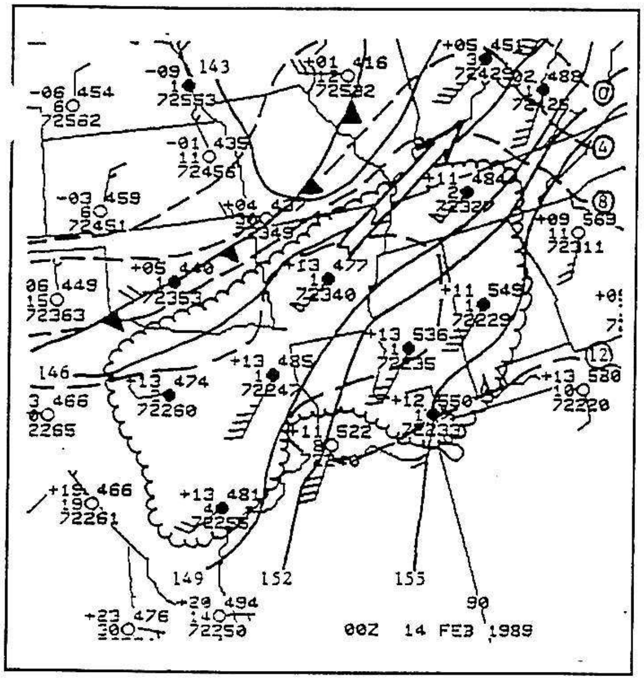

Fig. 11a. 850-mb analysis for 0000 UTC 14 February 1989. Units same as Fig. 8a. Arrow denotes jet axis.

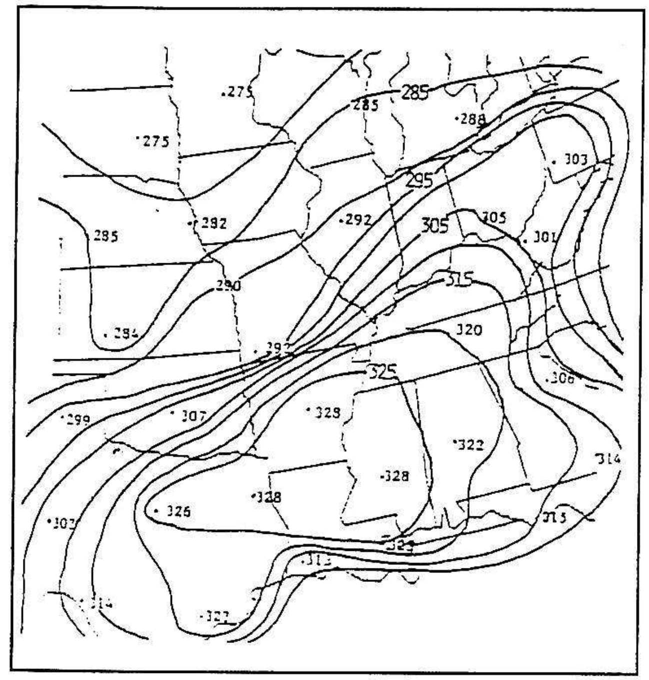

Fig. 11b. 850-mb Θ_e analysis for 0000 UTC 14 February 1989. Units same as Fig. 8b.

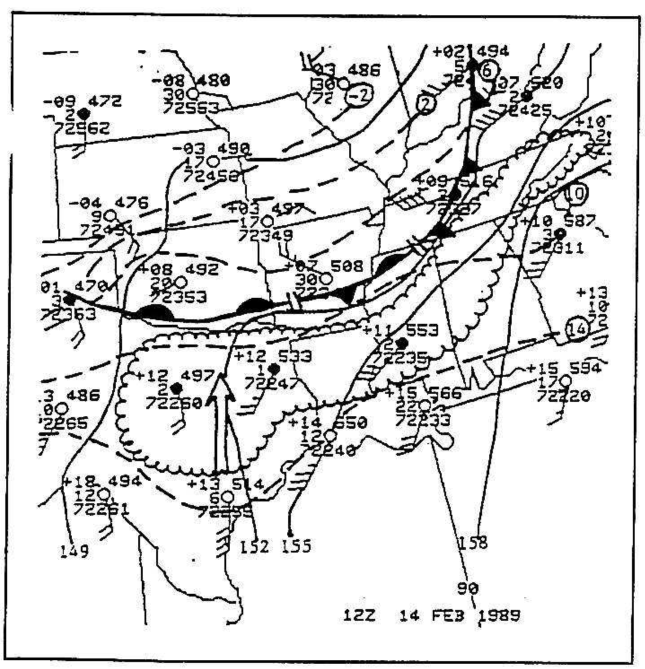

Fig. 12a. 850-mb analysis for 1200 UTC 14 February 1989. Units same as Fig. 8a. Arrow denotes jet axis.

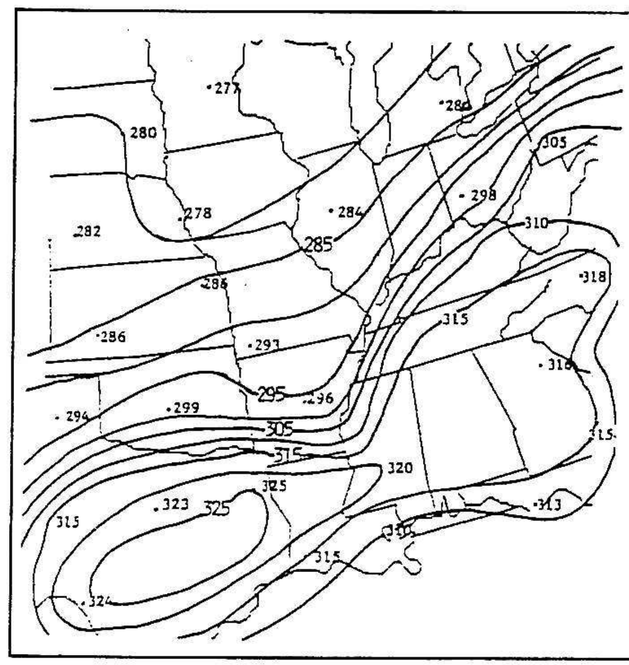

Fig. 12b. 850-mb Θ_e analysis for 1200 UTC 14 February 1989. Units same as Fig. 8b.

air advection, overrunning rainfall spread across most of Kentucky by 0000 UTC 15 February (not shown).

Light to occasionally moderate rainfall was prevalent over Kentucky through 1200 UTC 16 February as low-level moisture continued to be lifted over a thermal boundary in Tennessee.

5. Isentropic Analysis

Isentropic analysis has proven very beneficial during the cool season when strong thermal gradients exist with synoptic scale systems. In this case, strong baroclinicity was present from eastern Texas to Kentucky during 12–16 February.

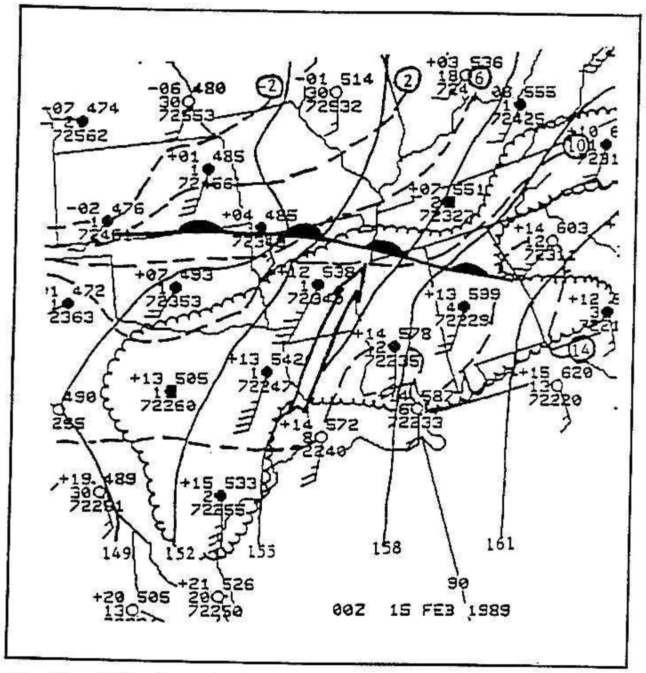

Fig. 13a. 850-mb analysis for 0000 UTC 15 February 1989. Units same as Fig. 8a. Arrow denotes jet axis.

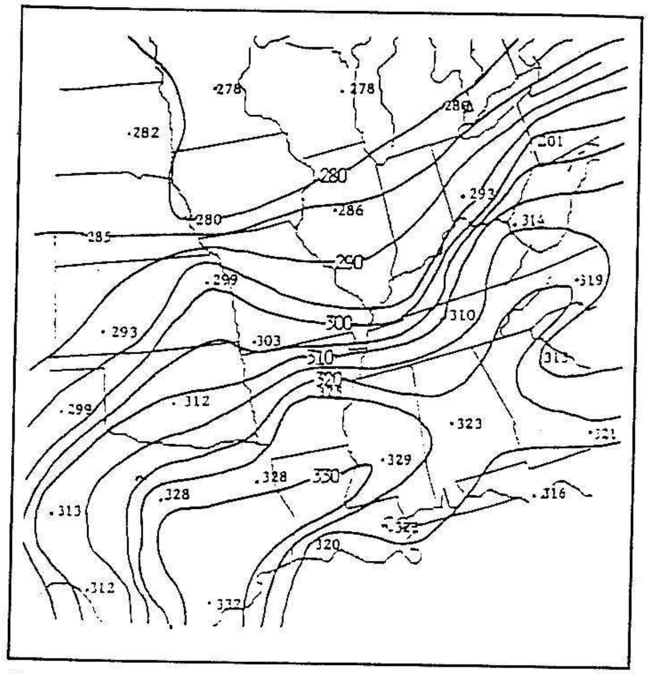

Fig. 13b. 850-mb Θ_e analysis for 0000 UTC 15 February 1989. Units same as Fig. 8b.

The three dimensional picture of moisture transport and synoptic scale lift via isentropic analysis was perhaps the best tool available for predicting the flood-producing rains. As is often true in many overrunning situations, isentropic analysis did an excellent job of delineating the location and intensity of the precipitation in this case.

Isentropic analysis has several advantages over standard constant pressure analysis in estimating vertical motion and moisture transport. A major advantage is that isentropic surfaces vary with respect to height or pressure. Moore (1988) noted that horizontal flow along isentropic surfaces contains the adiabatic component of vertical motion which would otherwise be computed as a separate component in either a Cartesian or isobaric coordinant system. Moore (1986) described this component of vertical motion with respect to pressure in isentropic coordinates in terms of 1) local pressure tendency, 2) advection of pressure on the isentropic surface, and 3) the diabatic heating/cooling contribution.

The local pressure tendency represents the effect of an isentropic surface moving up or down at a specific point while the advection of pressure on an isentropic surface can be evaluated by noting the cross-isobaric flow. Upward (downward) vertical motion can be derived from air flowing from high (low) to low (high) pressure along the isentropic surface. Wilson (1985) observed that the advection term and the local pressure tendency term are usually opposite in sign [i.e., (+) for advection and (−) for local pressure tendency] but that the advection term dominated in regions of strong advection as was the case in this event. The diabatic heating/cooling term measures primarily the effect of latent heating and evaporative cooling above the planetary boundary layer. The term is positive with heating and negative with cooling (i.e., diabatic heating will cause upward motion with respect to the isentropic surface while diabatic cooling will induce downward motion).

Another advantage of isentropic analysis over constant pressure charts is that moisture transport, including the vertical advection component, is more consistent in space and time. Movement of moisture can be forecast using the wind component in conjunction with the isohume (line of constant mixing ratio) pattern.

Isentropic data can now be plotted rapidly at National Weather Service Forecast offices via computer programs soon after the receipt of upper air soundings. Data in this case were analyzed using the isentropic plotter program developed for AFOS by Little (1985), called "ISENT." The plotting model station components are described in the appendix. With this type of plot, a qualitative estimate of adiabatic vertical motion, condensation pressure, and moisture advection/convergence can be derived.

Adiabatic vertical motion can be estimated from the advection pattern by observing the strength of the winds, the slope of the isobar gradient, and the wind component across the isobars. Winds blowing from higher to lower pressure indicate uplift, with greatest lift where strong winds blow perpendicular to a tight isobaric gradient. Conversely, winds blowing from lower to higher pressure indicate descent.

Condensation pressure on the plot is defined as the pressure to which unsaturated air must be raised dry-adiabatically to reach saturation. If a parcel is lifted beyond its saturation point it is assumed that the excess moisture either condenses out to form clouds or produce precipitation.

Moisture advection/convergence can be analyzed by superimposing the wind flow over the isohumes. The combined effect of moisture advection and convergence can lead to destabilization and subsequent convection.

The choice of isentropic surface was important to get the best picture of moisture transport. Since this case was dominated by low-level forcing, the surface selected was based on the upstream parameters of low-level temperature, moisture, and wind. As upstream temperatures warmed during this four-day occurrence, it was necessary to raise the selected isentropic surfaces utilized in sequential analyses to avoid grounding the surface. A step by step selection procedure for this event is found in the appendix.

At 1200 UTC 12 February (Fig. 14), a mixing ratio in excess of 8.0 g/kg was observed over eastern Texas and western Louisiana on the 293K isentropic surface. Upward vertical motion led to saturation of air parcels in Louisiana as winds were cross-isobaric from higher to lower pressure. The amount of lift needed to achieve parcel saturation was small (12 mb at Longview, Texas).

At 0000 UTC 13 February (Fig. 15), increasing moisture and lift were evident across eastern Texas, Louisiana, Arkansas and Missouri. The mixing ratio and pressure increased on the isentropic surface at Little Rock after warm-frontal passage at 850 mb (Fig. 9a).

Strong moisture advection and lift were apparent across Kentucky at 1200 UTC 13 February (Fig. 16). The moisture axis was aligned from Arkansas into Kentucky with winds blowing perpendicular to the isobars. As a result, an isentropic upslope pattern, as defined by Namias (1940), was developing as strong, moist southwesterly flow (up to 70 kt at Paducah) on the isentropic surface produced significant upslope motion (100 mb rise between southwestern and northeastern Kentucky). At this time, overrunning rain was increasing over Kentucky, enhanced by warm, moist air overriding a surface warm front (Fig. 4) extending from southeastern Tennessee to southwestern Kentucky. In the following 24-h period, four to six inches of rain fell over parts of western and central Kentucky (Fig. 5).

By 0000 14 February (Fig. 17), the moisture axis on the 297K isentropic surface shifted somewhat to the east, but 6.0 to 8.0 g/kg still covered most of Kentucky. In addition, a 50 kt cross-isobaric jet continued to support significant rising motion. A cold front approaching the state (Fig. 6), in conjunction with the moist, unstable air over the area, produced convective rainfall rates of one-half to one inch per hour over western and central Kentucky during the early morning of the 14th. Drier air behind the front is indicated by the isohume gradient from southeastern Missouri to northwestern Arkansas (Fig. 17).

The moisture feed from Arkansas into Kentucky shut off by 1200 UTC 14 February (Fig. 18). Winds nearly parallel to the isobaric gradient were providing negligible lift. The rain temporarily ended over western Kentucky and diminished to drizzle over northern portions of the state. However, moist southerly flow over Louisiana and eastern Texas was

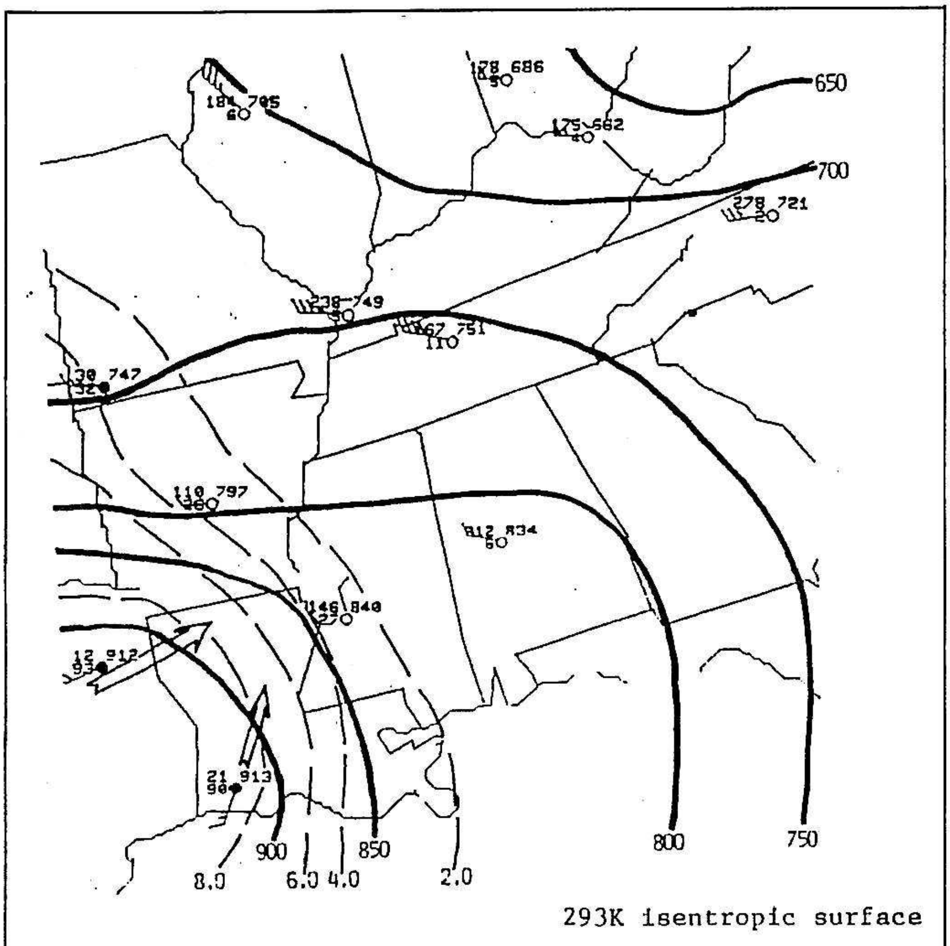

Fig. 14. Isentropic analysis for 1200 UTC 12 February 1989 on the 293K isentropic surface. Isobars every 50 mb (solid). Mixing ratios every two g/kg (dashed). Arrows denote apparent upward vertical motion.

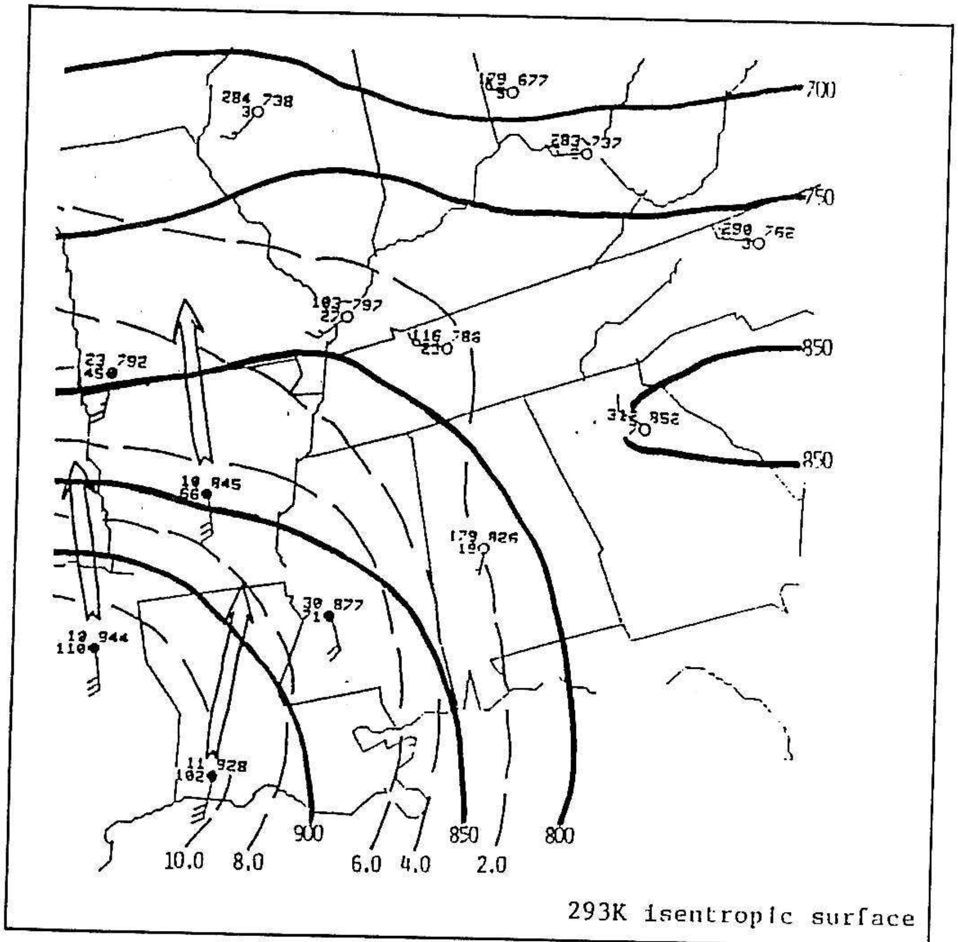

Fig. 15. Isentropic analysis for 0000 UTC 13 February 1989 on the 293K isentropic surface. Units same as Fig. 14.

providing renewed isentropic lift, and subsequent rain developed over southern Arkansas. The position of the 850-mb front corresponds with the isohume packing in southern Arkansas (Fig. 18).

By 0000 15 February (Fig. 19), the 298K analysis indicated strong lift and moisture advection returning across Arkansas, Tennessee, southern Missouri, and Kentucky. The packing of isohumes and isobars over northern Arkansas corresponded with the location of the northward moving warm front at 850 mb (Fig. 13a). Rain continued over southern and eastern Kentucky and would soon redevelop over the rest of the state.

Copious moisture again was evident over Kentucky at 1200 UTC 15 February (Fig. 20) as a 50-kt jet impinged on the state. The best lift, however, was occurring over the northern half of Mississippi, northeastern Arkansas, and western Tennessee where rain was heaviest. Despite little or no isentropic lift, lighter overrunning rainfall was prevalent over Kentucky due to southwesterly flow over a low-level thermal boundary in Tennessee.

At 0000 UTC 16 February (Fig. 21), ample moisture (mixing ratios at or above 6.0 g/kg) and weak lift combined to produce light rain over eastern and southern Kentucky, while somewhat drier air and weak subsidence ended the rain over northern portions of the state.

Finally, by 1200 UTC 16 February (Fig. 22), drier air overspread all of Kentucky. Winds on the 299K isentropic surface became westerly, resulting in downward motion as winds blew slightly across the isobars from lower to higher pressure. Thus, the rain ended over the entire state.

6. Comparison With Basic Heavy Rainfall Patterns

Three to five inches of rain fell over most of western and central Kentucky in the 12-h period from 0000 to 1200 UTC 14 February 1989, which represented the period of heaviest rain during the four-day event. Environmental conditions during this time period shared similar characteristics to both the "Synoptic" and "Frontal" type flash flood conceptual models developed by Maddox et al. (1979) (not shown).

Initially, heavy rain fell on the cool side of an east-west warm front near 0000 UTC 14 February (Fig. 6), which is most characteristic of the "Frontal" type model. Then, convective rainfall occurred in the warm sector between 0000 and 1200 UTC ahead of an eastward moving cold front (Figs. 6 and 7). This was similar to the "Synoptic" pattern in that heavy rain fell along and ahead of the cold front, however, in this case, the front was not quasi-stationary as normally characteristic of the "Synoptic" type model. Other features analogous to the "Synoptic" type included broad

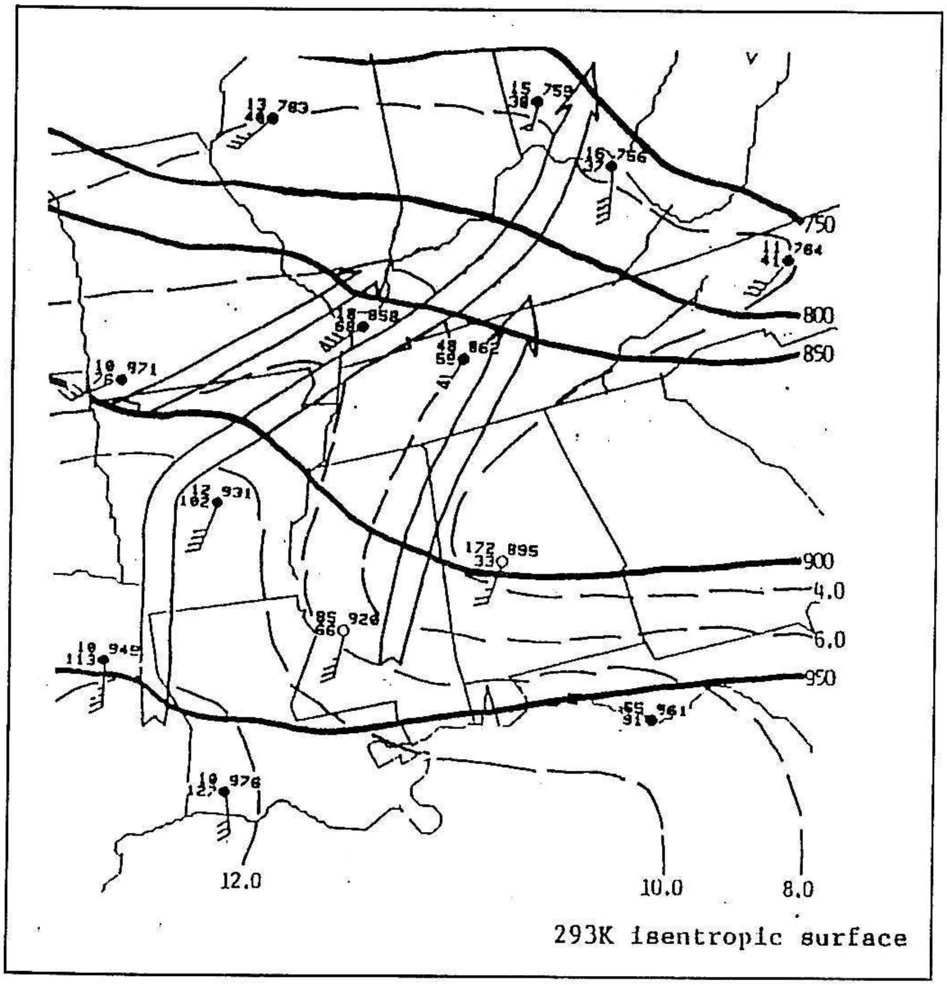

Fig. 16. Isentropic analysis for 1200 UTC 13 February 1989 on the 293 K isentropic surface. Units same as Fig. 14.

southwesterly flow at 500 mb and 700 mb over Kentucky which nearly paralleled the surface cold front. Similar qualities also were noted at 850 mb (Fig. 10a), as the exit region of a 50-kt jet provided strong moisture convergence and advection over the warm-frontal zone and ahead of the approaching cold front. In addition, tropospheric wind fields were quite strong, with about 30 degrees of veering observed between the 850-mb and 300-mb levels.

Maddox et al. (1979) also noted certain features to be common in many flash flood events over the central United States. These features were evident in this study, and included 1) the heaviest rain was produced by nocturnal convection (Fig. 3), 2) inflow surface dewpoints were very high (50s and 60s F) for the winter season (Fig. 6), 3) deep-layered moisture was present, and 4) vertical directional wind shear was weak to moderate through the cloud depth.

7. Summary

Low-level forcing mechanisms combined with a subtropical and Gulf of Mexico moisture supply led to the heavy rain and flood event of 12–16 February 1989 over Kentucky. Analyses of the low-level thermal advection fields were key in diagnosing vertical motion in the absence of significant positive differential vorticity advection.

Maddox and Doswell (1982) have noted that many flash flood situations can catch the operational forecaster by surprise, especially if the rainfall forecasts are built around analyses and model forecasts of 500-mb vorticity and vorticity advection. However, low-level forcing is often very important in the development of overrunning rainfall and convection. In this case, a combination of surface, 850 mb, θ_e, and isentropic analyses provided important diagnostic information needed to assess the magnitude and approximate location of the flood producing rains over Kentucky.

Isentropic analysis was of particular importance in the current case. Forecasters should become familiar with generating and interpreting isentropic data since valuable forecast information, especially in overrunning situations, is contained within the data. In other situations, however, operational meteorologists may need to examine additional forecast techniques as described by Funk (1991), including pat-

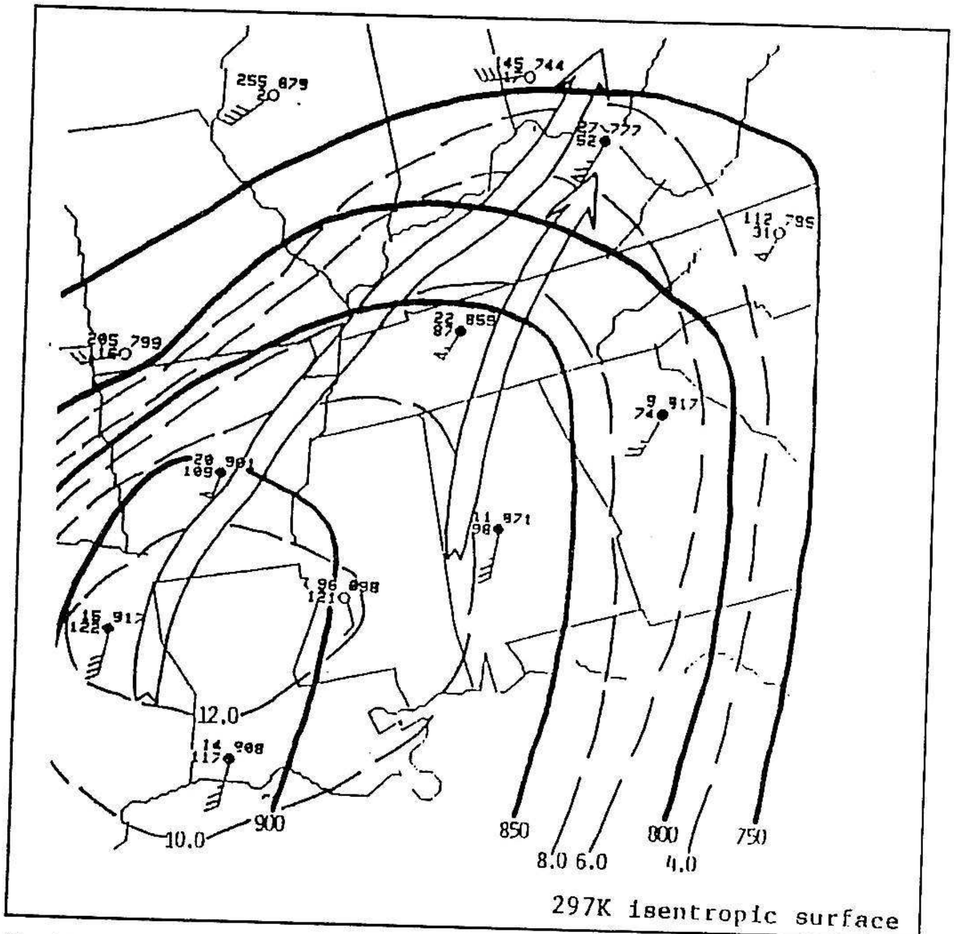

Fig. 17. Isentropic analysis for 0000 UTC 14 February 1989 on the 297K isentropic surface. Units same as Fig. 14.

tern recognition, moisture availability, low-level inflow and convergence, diffluent, saturation, and climatologically preferred thickness, and upper-level jet structure. In doing so, forecasters will be better equipped for predicting heavy rainfall accurately.

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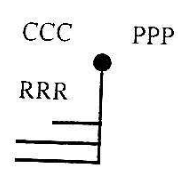
Appendix

Station plot resulting from the AFOS program "ISENT."



CCC = Pressure at condensation level if lifted from isentropic surface.
PPP = pressure on isentropic surface.
RRR = mixing ratio on isentropic surface (g/kg/10).

Wind barb = observed significant-level wind closest to isentropic surface.
Station circle shaded = temperature-dewpoint spread 5 degrees C or less.

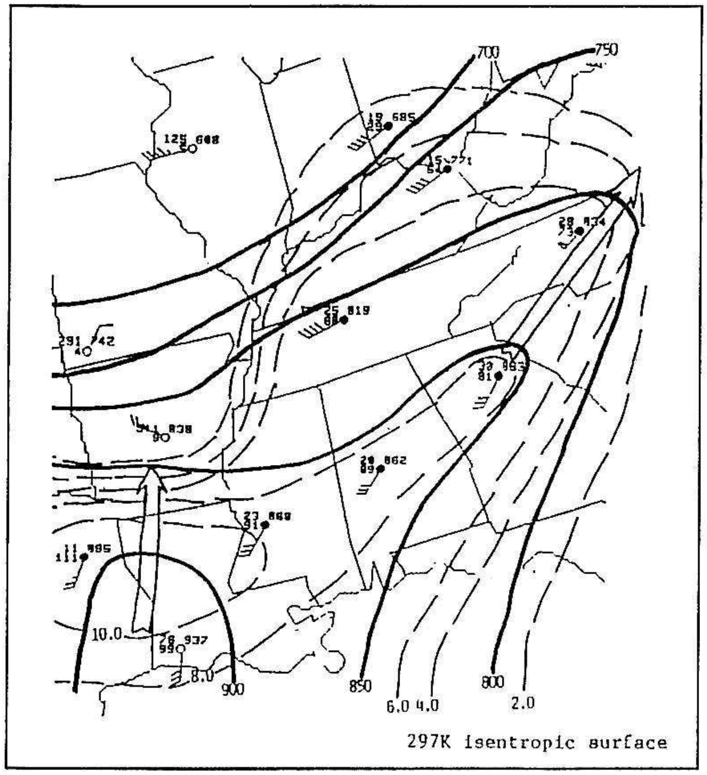


Fig. 18. Isentropic analysis for 1200 UTC 14 February 1989 on the 297K isentropic surface. Units same as Fig. 14.

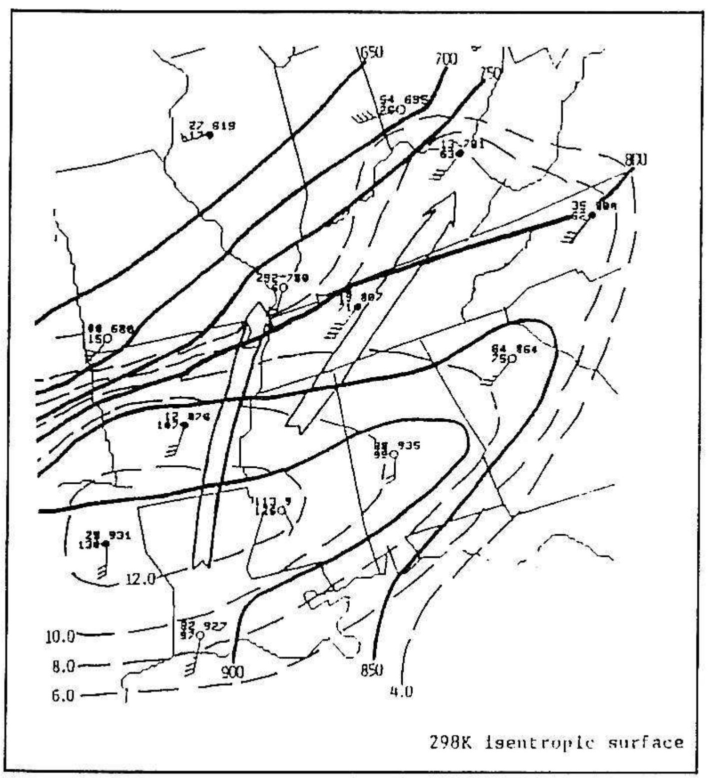


Fig. 19. Isentropic analysis for 0000 UTC 15 February 1989 on the 298K isentropic surface. Units same as Fig. 14.

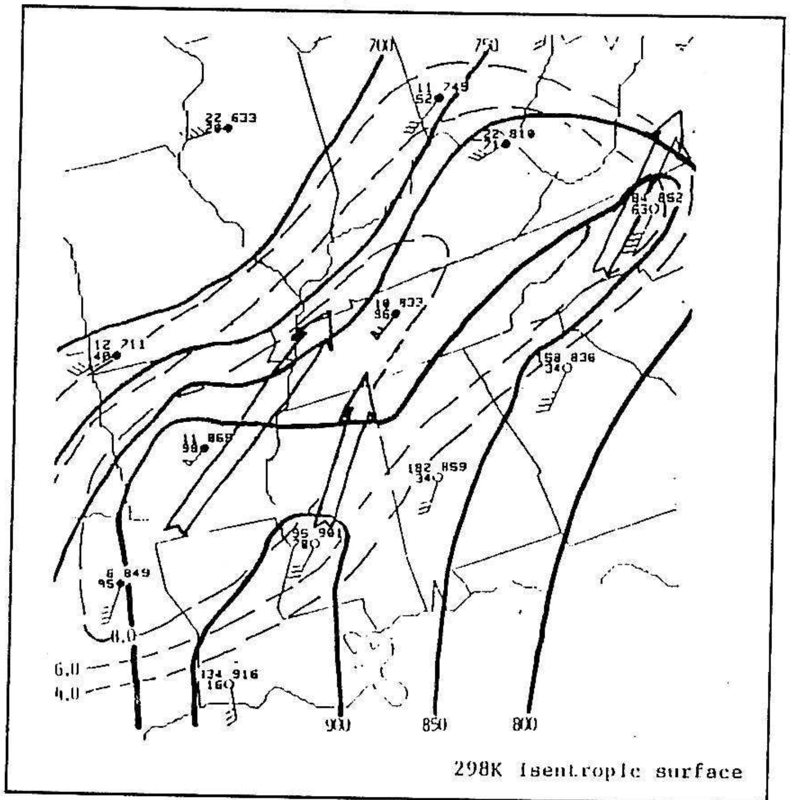


Fig. 20. Isentropic analysis for 1200 UTC 15 February 1989 on the 298K isentropic surface. Units same as Fig. 14.

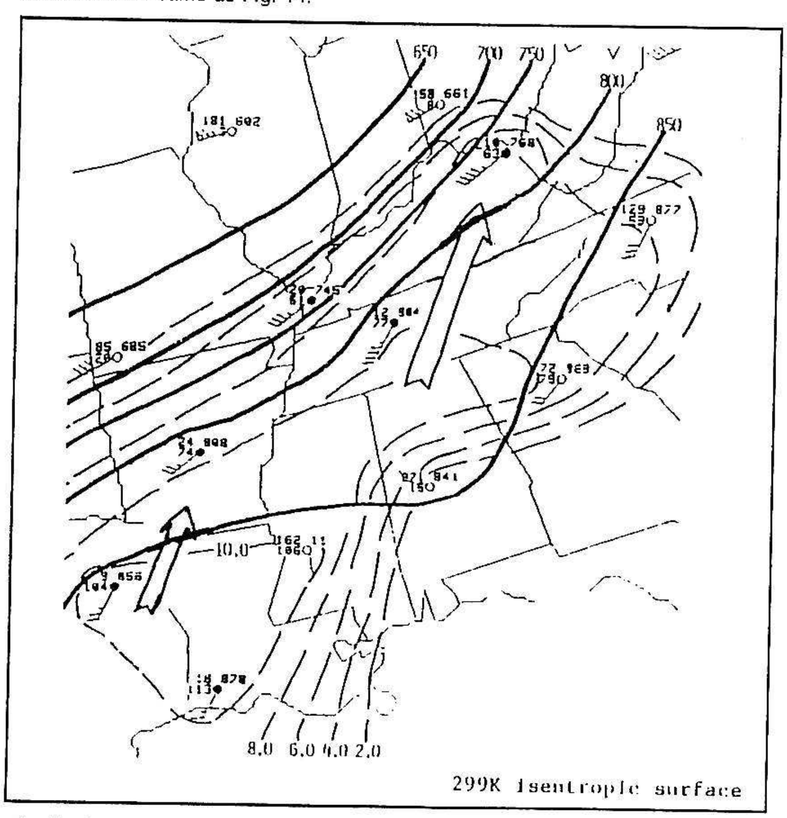


Fig. 21. Isentropic analysis for 0000 UTC 16 February 1989 on the 299K isentropic surface. Units same as Fig. 14.

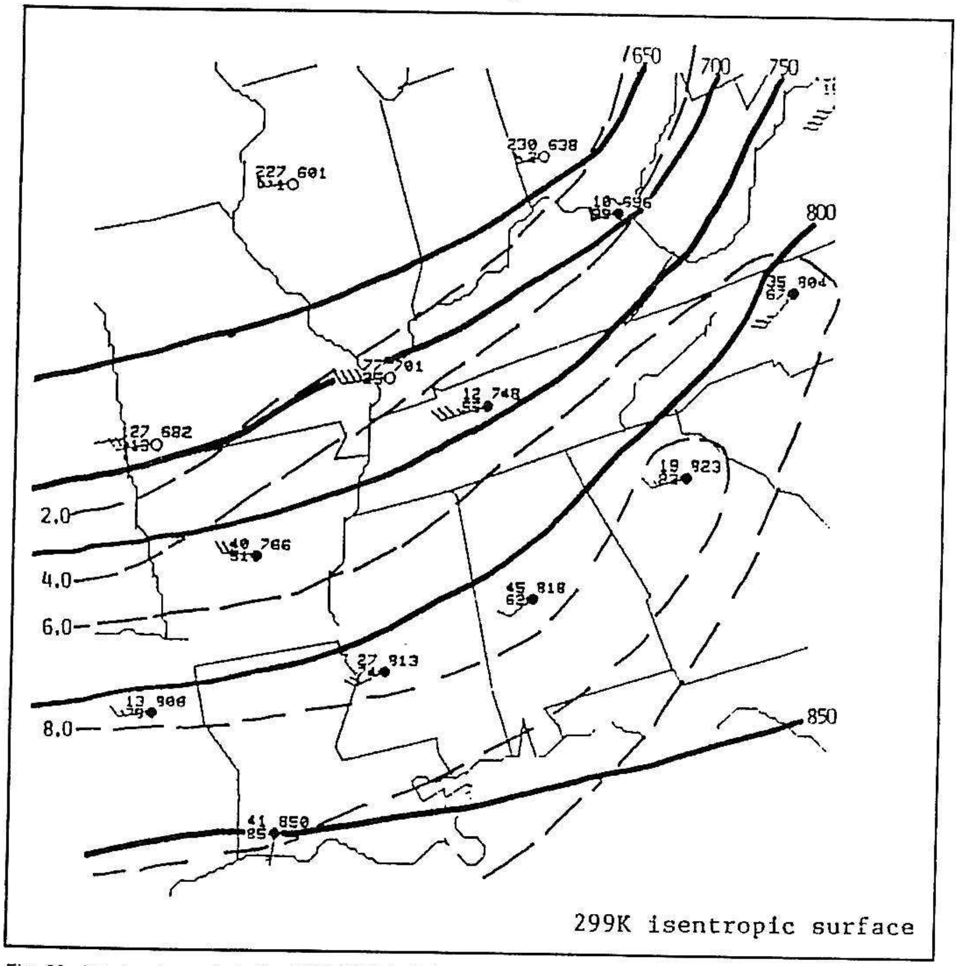


Fig. 22. Isentropic analysis for 1200 UTC 16 February 1989 on the 299K isentropic surface. Units same as Fig. 14.

Procedure for selecting an isentropic surface.

1. At 850 mb, find the co-existence of a jet and moist tongue. In this case, the lower Mississippi Valley was selected. Calculate the average 850-mb temperature in this area.
2. Determine the isentropic surface by matching the average 850 mb temperature to the corresponding value on a pseudo-adiabatic chart (i.e., 11C ≈ 298K).

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