

# USING THE MESOSCALE ANALYSIS AND PREDICTION SYSTEM TO PINPOINT HEAVY SNOWFALL OVER SOUTHEAST COLORADO

Ronald T. Holmes

National Weather Service Forecast Office  
Denver, Colorado

## Abstract

*During the night of 29–30 March 1991, an intense snow storm materialized over southern Colorado depositing up to 41 inches of snow at Cuchara in the Sangre De Cristo mountains and heavy snow throughout other portions of southern Colorado. This heavy snow was the result of a strong digging trough which developed into a cyclone. The Mesoscale Analysis and Prediction System (MAPS) available on the Advanced Weather Interactive Processing System (AWIPS) prototype workstation at the Denver National Weather Service Forecast Office was employed to provide better temporal and spatial resolution in depicting mesoscale features not handled well by the larger grid lengths displayed on the Automated Observing and Forecasting System (AFOS).*

*Specifically, MAPS analyses showed that a cyclonically curved upper level jet streak forced upward vertical motion through enhanced divergence in the left exit region. This upward forcing was pinpointed over southern Colorado by MAPS analyses of converging  $Q$ -vectors and isentropic lift. Strong upward forcing resulted in an intensification of the low level convergence field and further deepening of the cyclone. As a result, the low level northeasterly flow increased which produced additional orographic lift along the northwest-to-southeast elevated terrain of southern Colorado.*

## 1. Introduction

During the night of 29–30 March 1991, an intense snow storm moved across southern Colorado depositing 41 inches of new snow at Cuchara and heavy snowfall throughout southern Colorado. Other snowfall totals included a foot of snow at Wooten Ranch, 9 inches at Walsenburg, 8 inches at Beulah, 6 inches at Westcliffe, and 5 inches at both La Junta (LHX) and Eads. (Fig. 1)

Various diagnostic fields analyzed by the Mesoscale Analysis and Prediction System (MAPS), were employed to investigate this storm. Analyses revealed that several mesoscale features combined to produce upward motion over southern Colorado coincident with an area of heavy snow. This upward motion was a result of quasi-geostrophic upward forcing through a deep layer in which the atmosphere responded positively due to low static stability. Additional lift was provided orographically as northeasterly low level winds provided good upslope along the northwest to southeast oriented topography of southeast Colorado. The MAPS model not only provides analyses and forecasts on constant pressure charts but also provides a 3-dimensional structure of the atmosphere through the use of isentropic surfaces. This paper will focus on how the MAPS generated fields pinpointed where the best upward forcing coincided with the heavy snow.

## 2. Mesoscale Analysis and Prediction System

The National Weather Service Forecast Office in Denver (DEN) has had access to data from the Mesoscale Analysis and Prediction System (MAPS, Benjamin et al. 1991) for the last several years. Grid point data as well as a small set of graphical output from this model are available on the prototype Advanced Weather Interactive Processing System (AWIPS) workstation in use at Denver since 1989. The model, developed by the Forecast Systems Laboratory (FSL), one of NOAA's Environmental Research Laboratories in Boulder, Colorado, provides mesoscale analyses of surface and upper air parameters over the entire U.S. One big advantage of MAPS is that it produces analyses and forecasts with a finer temporal resolution than the operational models produced at the National Weather Service's National Meteorological Center (NMC).

Hourly mesoscale surface analyses of such parameters as mean sea level pressure, wind speed and direction, lifted indices, moisture convergence, relative vorticity, and divergence are available. Every three hours an upper air analysis and 3 and 6 h forecasts are produced. At 0000 UTC and 1200 UTC 3, 6, 9, and 12 h forecasts are also generated. These analyses and forecasts form a gridded database from which fields such as vorticity advection, divergence, moisture advection, condensation pressure deficit, and divergence of  $Q$ -vectors may be produced. These analyses and forecasts are available on both isobaric and isentropic surfaces.

The MAPS model incorporates hourly surface observations, wind profiler data, aircraft reports typically made every 7.5 minutes, and data from rawinsondes for its analyses and forecasts. The three-dimensional grid contains 18 levels in the vertical (5 terrain-following sigma layers and 13 isentropic layers) with a resolution of 80 km in the horizontal. A new 60 km, 25 level version of the MAPS model has recently been implemented.

## 3. Synoptic Overview of 29–30 March 1991

At 1200 UTC 29 March 1991, a surface low (1003 mb) was centered over northwest Nebraska with a cold front southwest from the low through southeast Wyoming to west central Colorado and across southern Utah (not shown). At 500 mb a strong short wave trough extended from southeast Montana through central Wyoming to southern Nevada (not shown). There was strong cold advection occurring in the base of the trough over western Wyoming and northern Utah indicating that the trough would continue to deepen. 500-mb height falls of 100 m in 12 h ahead of the trough indicated that it would continue to move south. At 300 mb, a 70 kt jet on the back side of the trough was digging southward across Idaho (not shown).

By 0000 UTC 30 March 1991, the cold front had indeed dropped southeast across Colorado and a strong inverted

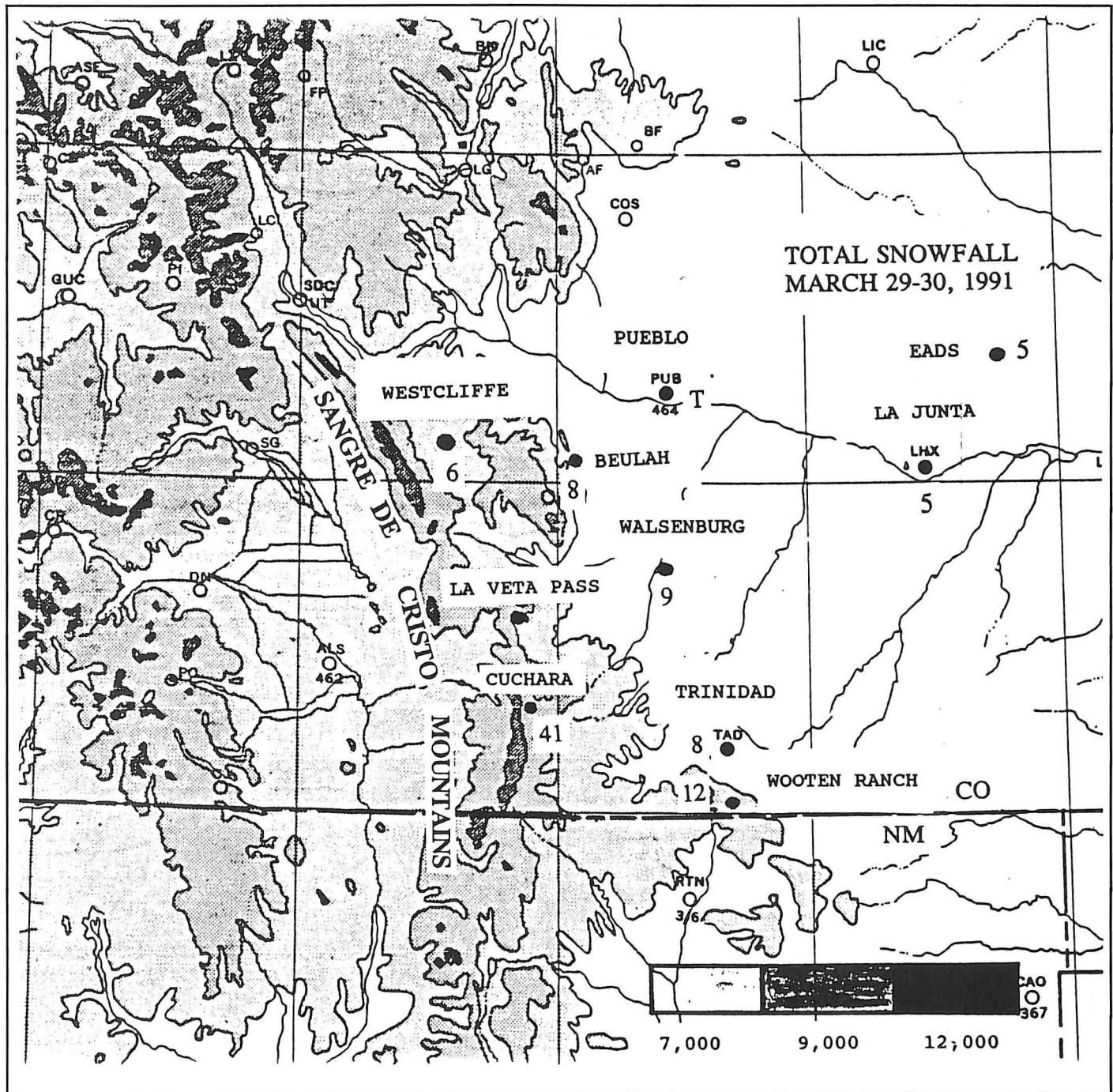


Fig. 1. Storm total snowfall (in.) for the night of 29–30 March 1991. Elevations (ft msl) are shaded.

surface trough developed over the eastern part of the state. At 500 mb the short wave trough moved south during the past 12 h and height falls over southern Colorado and northern New Mexico indicated that it would most likely continue to move south (Fig. 2). Cold advection aloft into the backside of the trough continued over Colorado deepening the trough and providing increasing instability as lapse rates steepened. At this time, the evening state forecast discussion mentioned the development of cold, convective looking tops on the color enhanced infrared satellite imagery over southern Colorado.

#### 4. Using MAPS to Pinpoint Heavy Snowfall Across Southern Colorado

MAPS analyses of surface and upper air data were used to pinpoint the heavy snow across southern Colorado because of its increased temporal resolution and variety of diagnostic fields over conventional data sets.

Figure 3 shows the MAPS winds and temperature at 700 mb for 0000 UTC 30 March 1991. Note the strong cold advection behind the trough indicating further deepening while slight

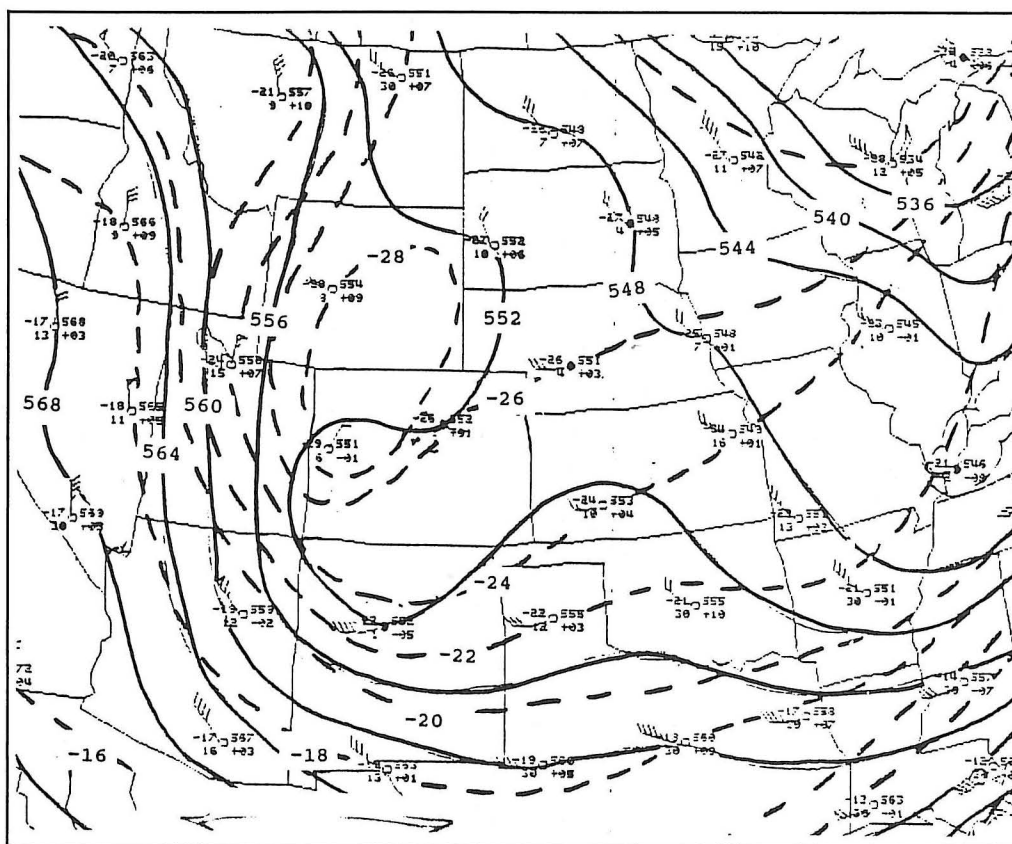


Fig. 2. 0000 UTC 30 March 1991 500-mb heights (10 gpm) and temperatures (°C).

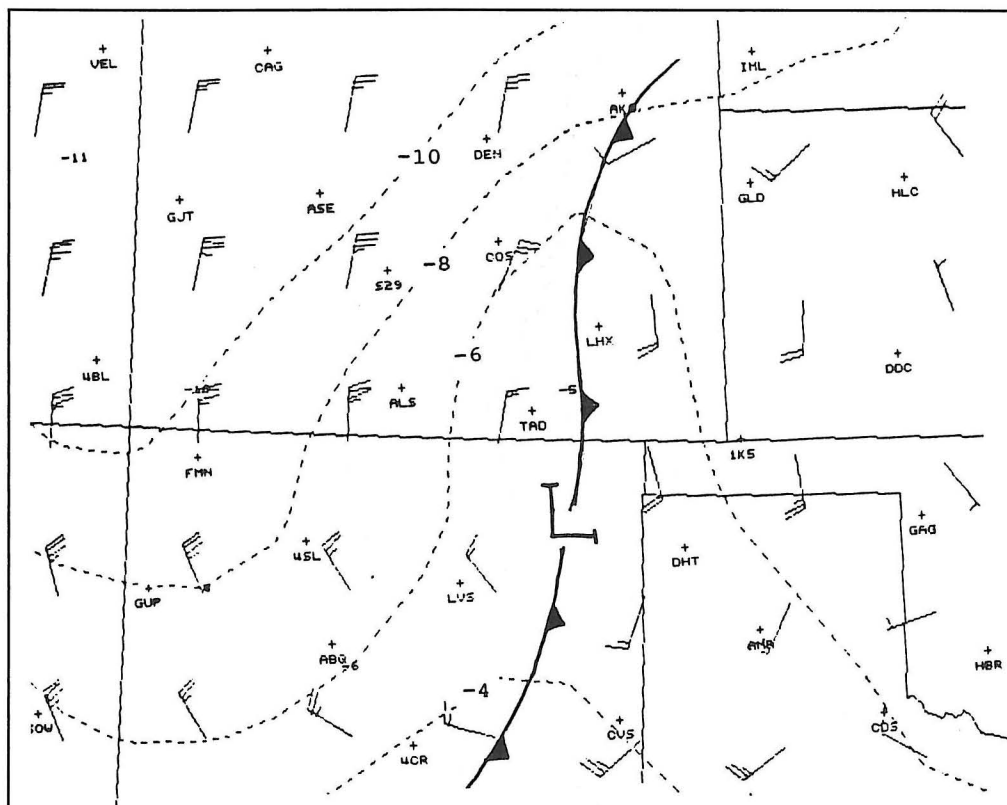


Fig. 3. 0000 UTC 30 March 1991 700-mb winds (kt) and temperatures (°C) showing position of cold front.

warm advection was occurring over southeast Colorado. Strong convergence in the cyclonic shear axis extended from Akron (AKO) south to just east of Trinidad (TAD).

By using conventional data, one can only guess the strength of the low level convergence by observing the wind field. However with MAPS one can actually see where convergence is occurring and compare the actual values to note any temporal changes. Figure 4 shows surface divergence for 0000 UTC. There was a minimum of divergence of  $-12 \times 10^{-5} \text{ sec}^{-1}$  (maximum convergence) over eastern Colorado, which was aligned along the inverted pressure trough from Amarillo, Texas (AMA) to Cheyenne, Wyoming (CYS). This convergence maxima was moving west toward the southern foothills.

Figure 5 shows the 500-mb winds and vorticity for 0000 UTC 30 March. Note the closed circulation just to the northeast of Alamosa (ALS). There was strong positive vorticity advection (PVA) across northern New Mexico into southeast Colorado. Recall from Fig. 3 there was also weak warm advection across southeast Colorado. Forecasters often use vorticity advection and temperature advection to approximate the magnitude and sign of the vertical motion. However, neither vorticity advection nor warm advection by

themselves "force" vertical motion. The Omega equation (Holton, 1972) links upward motion to the Laplacian of the temperature advection and increasing vorticity advection with height. Forecasters generally assume that low level warm advection and mid level positive vorticity advection both satisfy the two main terms of the Omega equation to yield upward motion. However, warm advection is not the same as the Laplacian of temperature advection and mid-level PVA does not necessarily mean that positive vorticity is increasing with height (Durrant and Snellman, 1987). Trenberth (1978) has also shown that the Omega equation can be rewritten to show how vertical motion is forced from positive vorticity advection by the thermal wind and deformation terms. So what tool can a forecaster use which accounts for the complete terms of the Omega equation and diagnoses the quasi-geostrophic forcing? The answer can be found in Q-vectors.

Q-vectors quantitatively account for how much temperature advection and vorticity advection together contribute to forcing for vertical motion. At the Denver NWSFO the AWIPS prototype workstation is able to display actual Q-vector fields or the more commonly used divergence of Q-vector fields for several pressure levels. As shown by Hos-

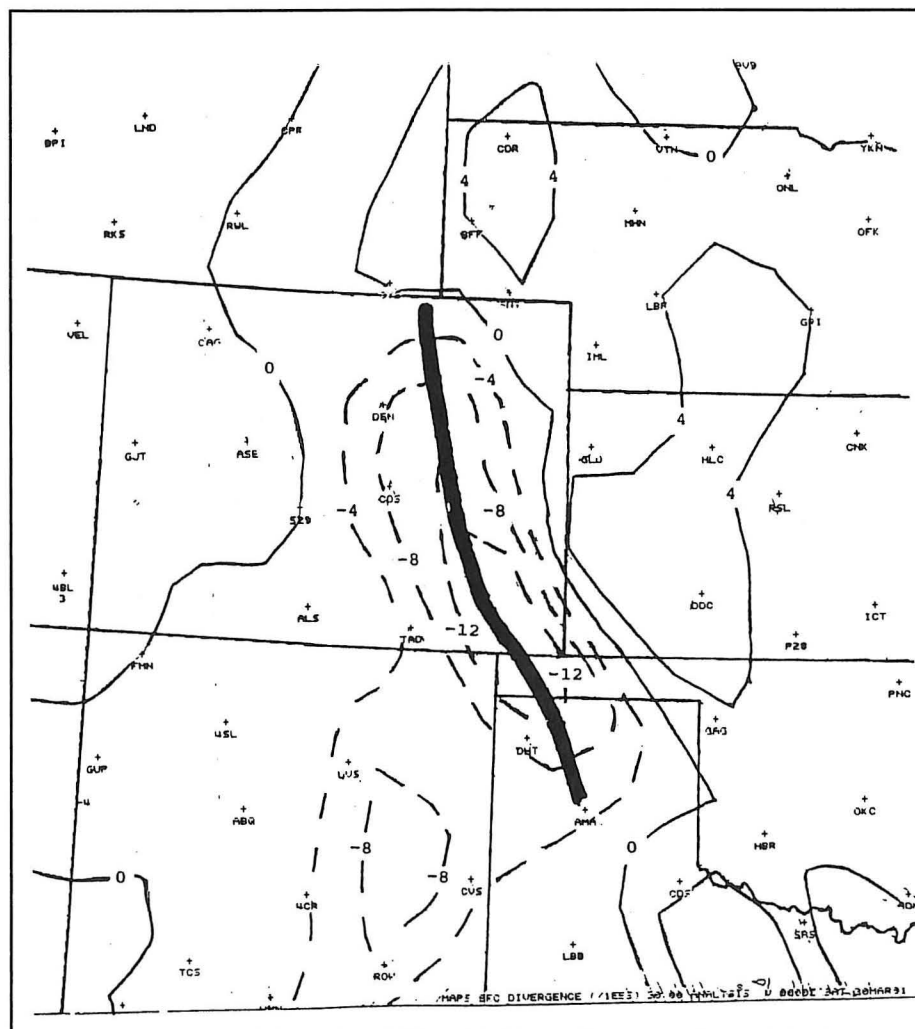


Fig. 4. 0000 UTC 30 March 1991 surface divergence ( $\times 10^{-5} \text{ sec}^{-1}$ ). Negative values indicate convergence and thick line depicts axis of maximum convergence.





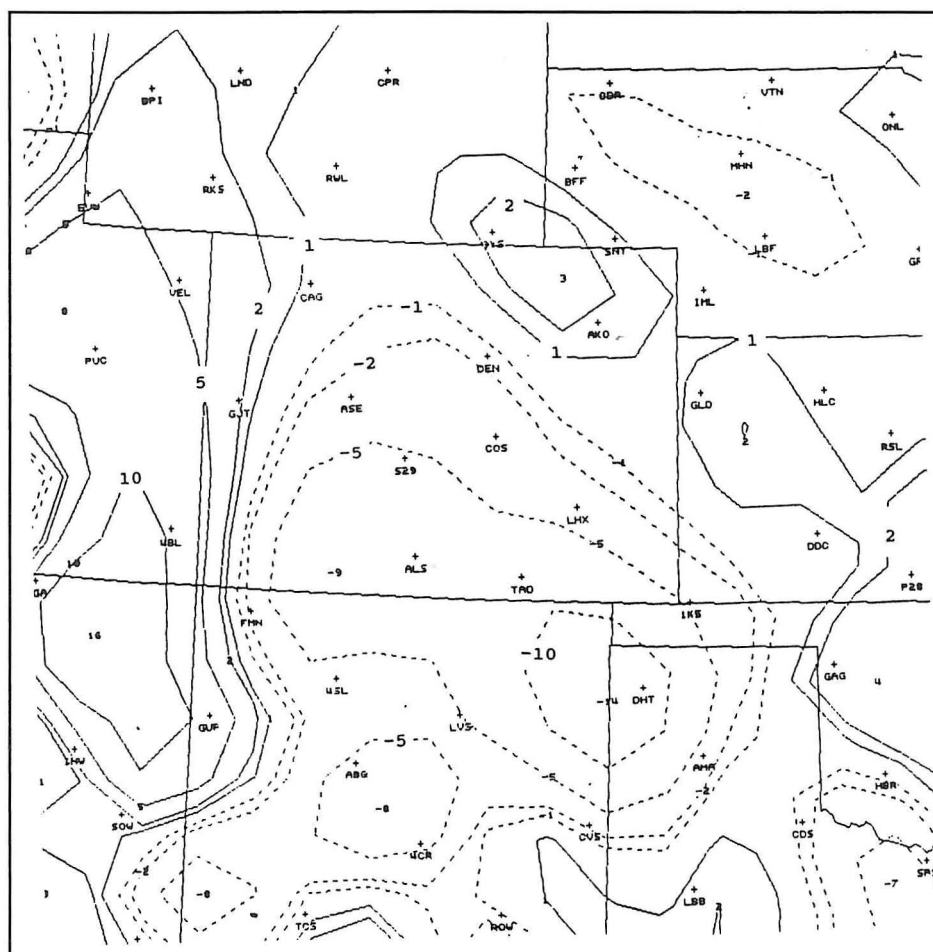


Fig. 6. 0000 UTC 30 March 1991 500-mb divergence of Q-vectors ( $\times 10^{-15} \text{ } ^\circ\text{K m}^{-2} \text{ sec}^{-1}$ ).

east of the trough while convergence is enhanced west of the trough due to along-contour ageostrophic circulations.

Moore and Molinaro (1989) have proposed and proven that superimposing the two patterns of divergence/convergence couplets associated with straight-line and cyclonically curved jet streaks resulted in regions of enhanced divergence in the left exit region and enhanced convergence in the left entrance region of the jet.

At 0000 UTC 30 March, a strong cyclonically curved jet at 300 mb was located over eastern Utah and the four corners region into southern New Mexico (Fig. 10). Note how extreme southern Colorado and northern New Mexico, in the lee of the Rockies, are under the left exit region of the jet streak.

Actor and Horn (1986) have shown that the left exit region of an upper-level jet streak is a favored location for lee cyclogenesis in Colorado. This suggests that the upper level divergence associated with the left exit region of the jet may have played a role in the development and strengthening of the cyclone over southeast Colorado and northeast New Mexico. The intensification of this low helped strengthen the low level east to northeasterly upslope flow into the Sangre De Cristo mountains.

Figure 11 shows the divergence field associated with this jet streak for 0000 UTC 30 March. The enhanced divergence aloft associated with the left exit region of the cyclonically curved jet is linked to low level convergence and upward motion through the continuity equation. Recall from Fig. 4 that low level convergence was located beneath this upper level divergent area. The location of the convergent Q-vectors at the mid-levels over southeast Colorado shown in Fig. 6 and 7 is consistent with the upward forcing one would expect in the left exit region of an upper level jet streak. Each of these diagnostic variables analyzed by MAPS all showed forcing for upward motion over southern Colorado.

By 0900 UTC, the surface low was located in southeast New Mexico (not shown) with an inverted surface pressure trough and surface convergence field extending northward across southern Colorado to Colorado Springs (COS). The minimum of surface divergence had moved south of Cuchara to just northeast of Las Vegas (LVS) (not shown).

By 1200 UTC 30 March, the 500-mb low was located over eastern New Mexico with the cold pool of air ( $-26^\circ\text{C}$ ) over southern Colorado (not shown). The upper level jet streak had also rounded the base of the trough and was rotating

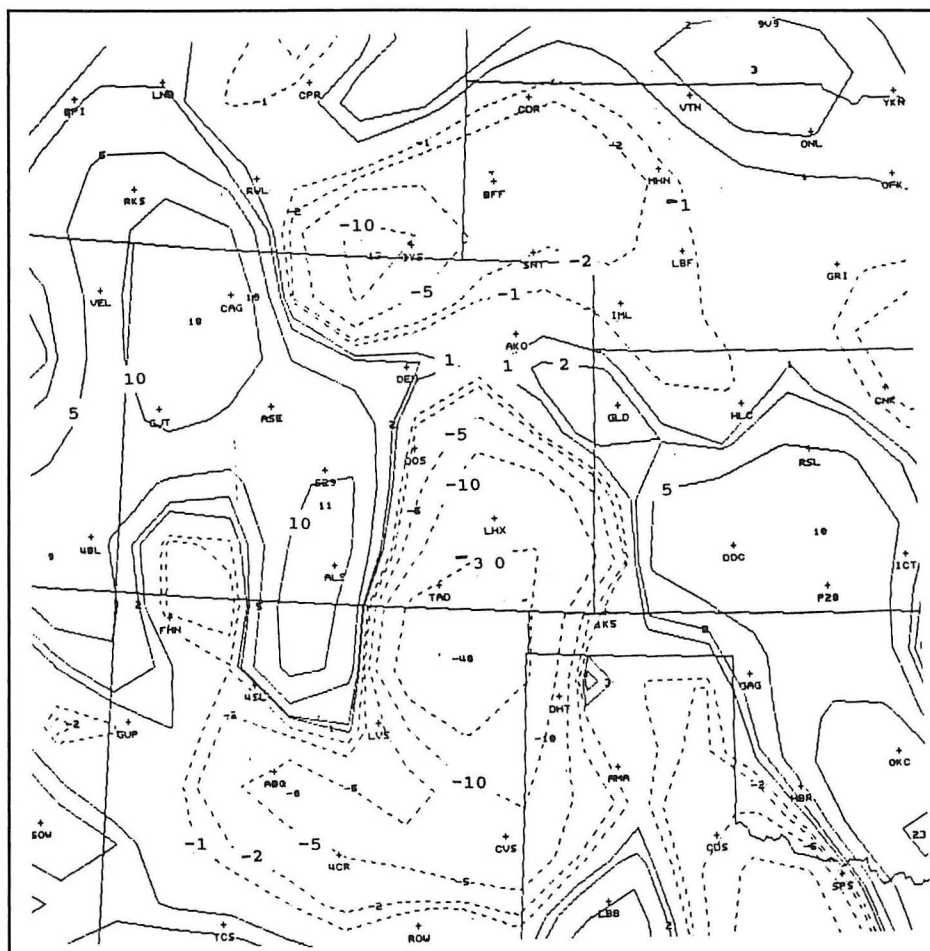


Fig. 7. 0000 UTC 30 March 1991 300-mb divergence of Q-vectors ( $\times 10^{-15} \text{ } ^\circ\text{K m}^{-2} \text{ sec}^{-1}$ ).

through the eastern side. It was clear the short wave was weakening and moving east.

## 6. MAPS Analysis of Isentropic Surfaces

Saucier (1955) shows that for stable conditions, the pressure gradient on an isentropic surface is in the same direction as the horizontal potential temperature and the gradients are directly proportional. Therefore, the lines of pressure on an isentropic surface can depict baroclinic zones. The closer the isobars are spaced, the stronger the temperature gradient and the steeper the slope of the surface. According to Moore (1988) isentropic surfaces slope up towards cold air (lower pressure). Therefore, winds blowing toward lower pressure can be an indication, as a first approximation, of the lifting across a baroclinic zone.

For example, Fig. 12 is the 294K isentropic surface showing winds and pressure for 0600 UTC 30 March. A cold trough of lower pressure was located across Colorado. Since

this air was colder the 294K isentropic surface in this region was higher (about 650 mb) in the atmosphere. A ridge of higher pressure was located across eastern New Mexico. This air was warmer so the 294K isentropic surface in this region was near the surface (about 800 mb). There was upglide motion across northeast New Mexico into southern Colorado (area within dashed line) where winds were blowing up the isentropic pressure gradient from higher pressure to lower pressure.

Figure 13 shows the winds and the condensation pressure deficit on the 294K surface for 0600 UTC 30 March. The condensation pressure deficit is the number of millibars of lift needed to saturate the air. This amount had decreased over southern Colorado from 50 mb at 0300 UTC (not shown) to less than 50 mb between ALS and TAD by 0600 UTC. Recall from the previous figure that about 50 mb of lift was occurring over southern Colorado to satisfy the condensation pressure deficits. Thus these two analyses also helped the forecaster pinpoint where the best upglide was producing enough lift to saturate the atmosphere.

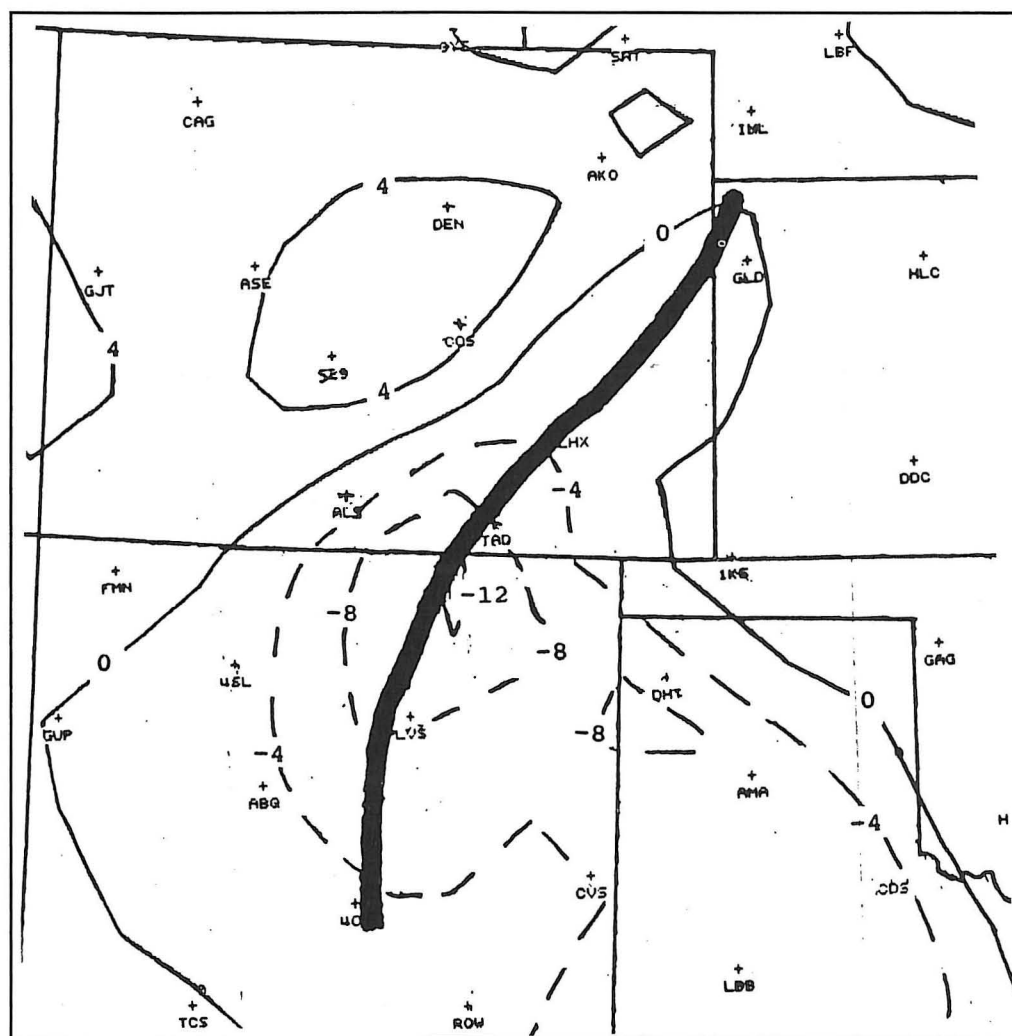


Fig. 8. 0600 UTC 30 March 1991 surface divergence ( $\times 10^{-5} \text{ sec}^{-1}$ ). Negative values indicate convergence and thick line depicts axis of maximum convergence.

## 7. Conclusion

The storm that dumped heavy snow over southern Colorado during the night of 29–30 March 1991 materialized over southern Colorado in response to a strong digging trough which developed into a cyclone. The MAPS analyses were employed to provide better temporal and spatial resolution in depicting mesoscale features not handled well by the larger grid length models displayed on AFOS.

Specifically, MAPS analyses showed that a cyclonically curved upper level jet streak forced upward vertical motion through enhanced divergence in the left exit region. This upward forcing was pinpointed over southern Colorado by MAPS analyses of converging Q-vectors and isentropic lift. Strong upward forcing resulted in an intensification of the low level convergence field and further deepening of the cyclone. As a result, the low level northeasterly flow increased which produced additional orographic lift along the northwest-to-southeast elevated terrain of southern Colorado.

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## Author

Ron Holmes is currently a journeyman forecaster at the National Weather Service Forecast Office in Denver, Colorado. His internship was completed at the National Weather Service Office in Columbus, Ohio. Previous work experience includes a forecaster position at The Weather Channel, meteorologist in charge at the Franklin Institute Science Museum in Philadelphia, and a meteorological technician at AccuWeather. He received the Bachelor of Science degree in meteorology from The Pennsylvania State University in May 1984.



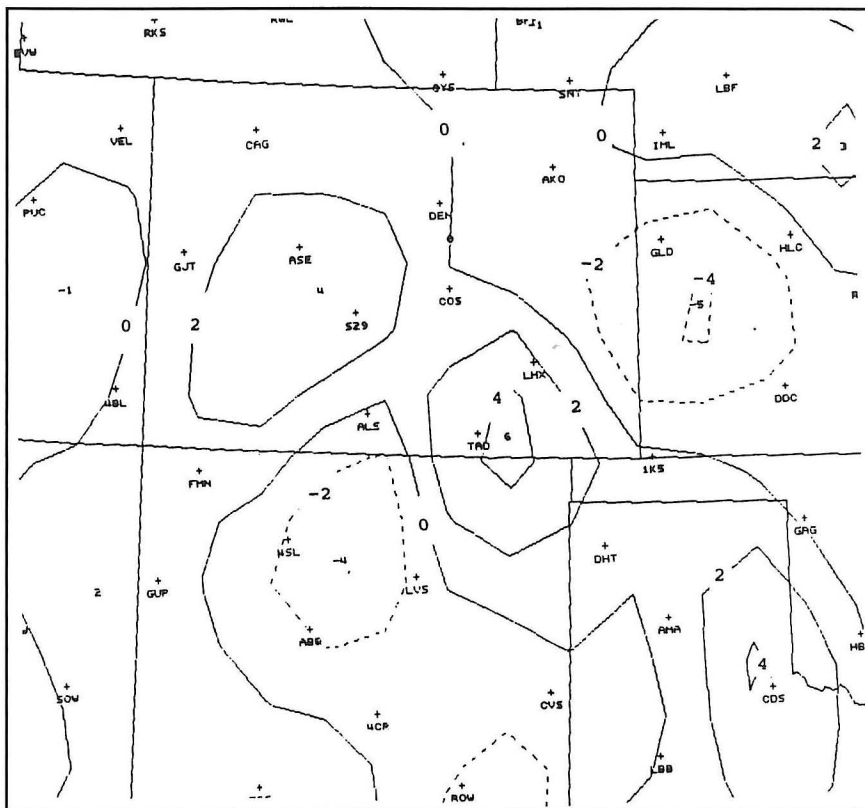


Fig. 9. 0600 UTC 30 March 1991 700-mb moisture convergence ( $\text{g kg}^{-1}(12 \text{ h})^{-1}$ ).

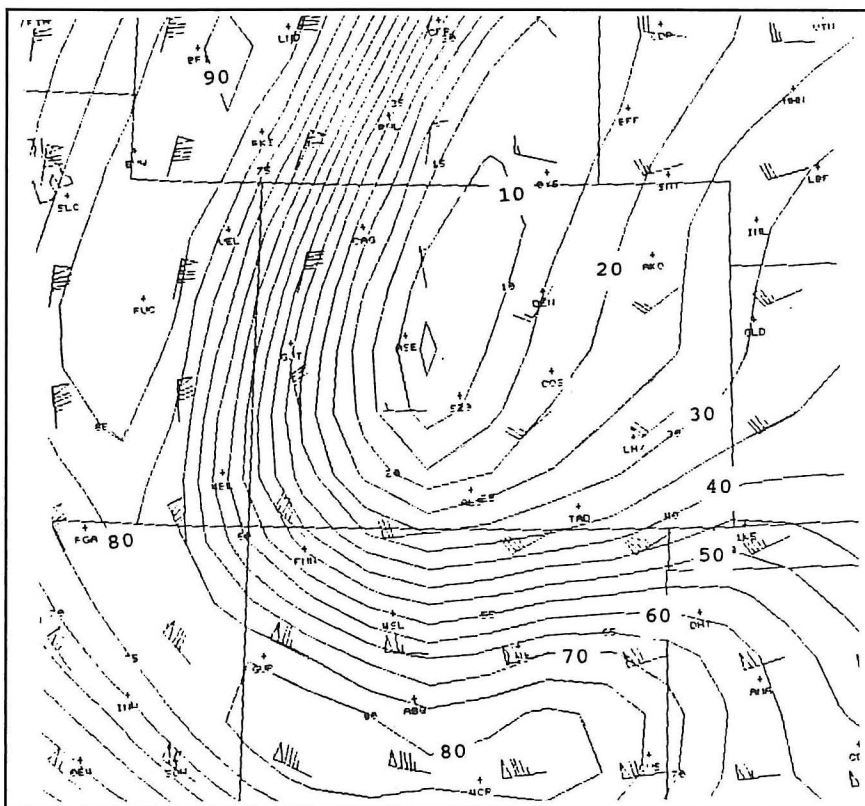


Fig. 10. 0000 UTC 30 March 1991 300-mb winds and isotachs (kt).

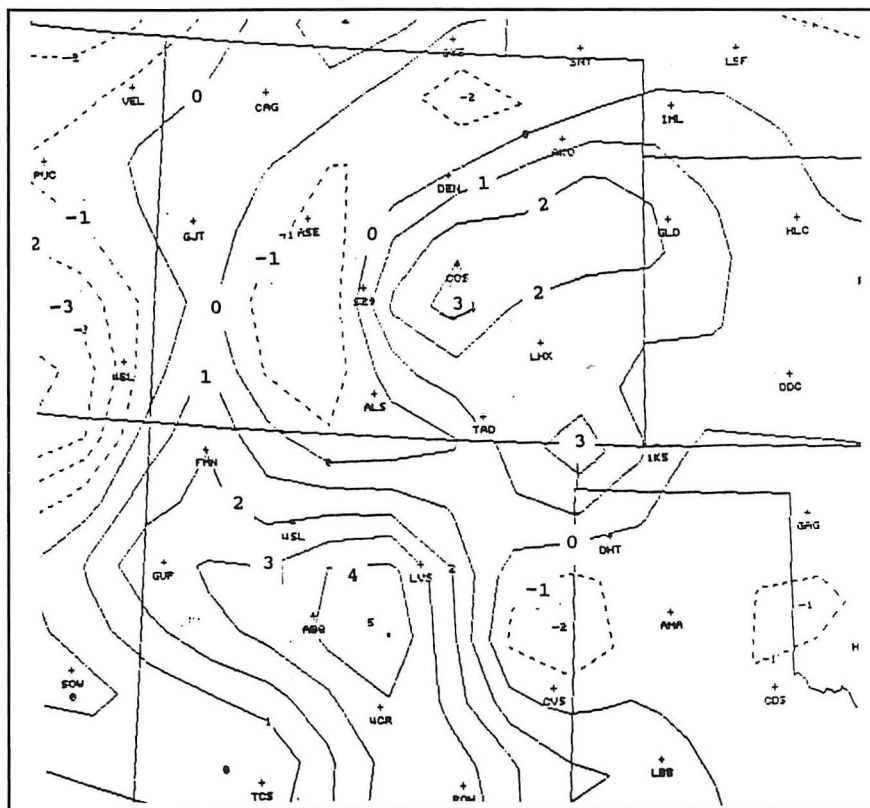


Fig. 11. 0000 UTC 30 March 1991 300-mb divergence ( $\times 10^{-5} \text{ sec}^{-1}$ ). Negative values indicate convergence.

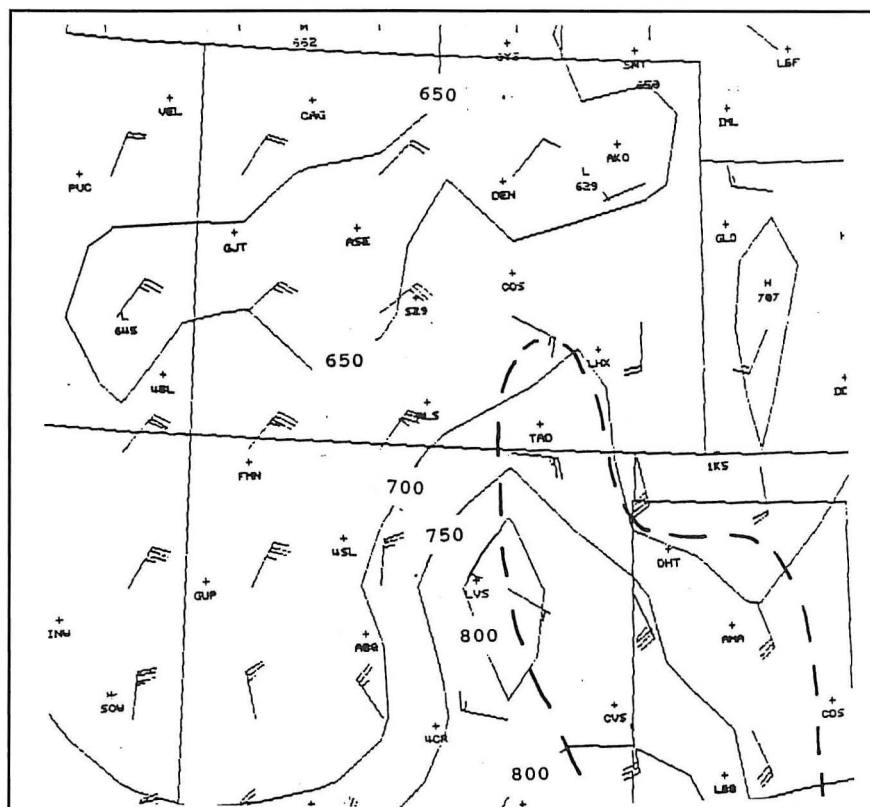


Fig. 12. 0600 UTC 30 March 1991 294°K isentropic surface showing isobars (mb) and winds (kt). Dashed line encloses area of upward motion along the isentropic surface.

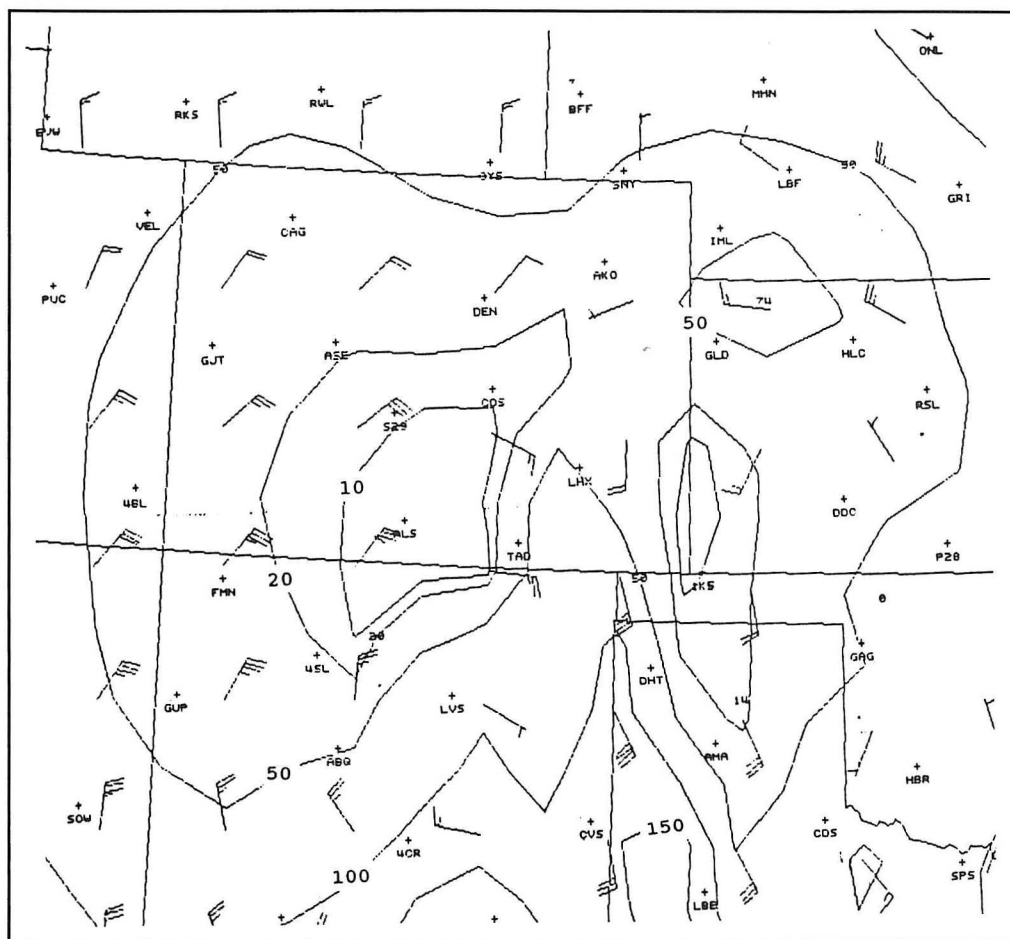


Fig. 13. 0600 UTC 30 March 1991 294°K isentropic surface showing winds (kt) and condensation pressure deficits (mb).

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