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USING NEW TECHNOLOGY TO OPERATIONALLY FORECAST SEVERE DOWNSLOPE WINDSTORMS ALONG THE FRONT RANGE

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1. Introduction

Severe downslope windstorms (Sustained winds >50 mph or gusts >70 mph; this is the agreed upon criteria that the Denver WSFO uses for high wind in favored chinook zones. This criteria is higher than what is commonly used by most other NWS offices.) plague the Front Range during the cool months, posing a hazard both to the aviation sector and the general public. In the past, most studies of downslope windstorms have focused on numerical simulations of various profiles of vertical tropospheric thermodynamic stability and mountain profiles conducive to strong winds (Klemp and Lilly 1975).

Operational forecasters have had difficulty incorporating the results of those studies in high wind prediction because they have mostly been written with the research community in mind. Forecasters also have had limited access, in real-time, to the advanced meteorological tools the research meteorologist employs. This will change as workstations capable of using gridded numerical models, such as the Advanced Weather and Interactive Processing System (AWIPS), become operational.

Advanced meteorological data sets available on the DAR^{3}E (Denver AWIPS Risk Reduction and Requirement Evaluation) workstation in Denver, Colorado, have been used to analyze the past three windstorm seasons. New ways of determining environmental conditions conducive to high winds, such as stability and wind shear structure, have been documented. Evidence suggests that vertical motion associated with upper tropospheric subsynoptic scale features plays an important role in generating strong winds. Various new methods of determining this vertical motion by using advanced data sets are presented.

2. Stability and Wind Shear

Various numerical simulations (Klemp and Lilly 1975) indicate strong mountain waves are favored when there is a shallow layer of statically stable air near mountain top level (650 mb) beneath a deep layer of near neutrally stratified air in the mid-troposphere (500 to 300 mb). This stability structure induces vertically propagating waves which amplify to produce severe downslope windstorms. These waves are efficient in transporting energy upward and momentum downward.

Wind shear is also another important factor in developing strong mountain waves. Weak vertical wind shear enables a phase shift to occur where troughs and ridges of the mountain wave in the lower troposphere are capped by ridges and troughs, respectively, in the upper troposphere. This phase shift provides a more efficient means for transporting energy upward and momentum downward (Durran 1986).

A. Case study: December 22, 1992

A moderately strong downslope windstorm developed during the morning of December 22, 1992. Winds reached greatest intensity between 1500 and 1800 UTC with peak gusts of 90 kts at Rollinsville, 76 kt at Idaho Springs, and 60 kts at Estes Park. The Denver 1200 UTC sounding did not show the classic stability structure for high winds discussed above. However, the Mesoscale Analysis and Prediction System (MAPS, Benjamin et al. 1991) cross sections later showed conditions were changing to become favorable for high winds.

Figure 1 shows the MAPS 6-hour forecast cross section of theta and potential vorticity valid 1500 UTC. This forecast suggests that conditions would become more favorable for strong winds. The isentropes indicate a vertically propagating structure where the wave crests and troughs tilt to the west (upstream) with height. Also, there was an indication of a shallow layer of high stability air near mountain top level with a deeper layer of less stable air above. There was a potential vorticity (PV) anomaly crossing the Front Range which was providing some downward forcing (to be discussed below).

Weak wind shear in the 700-500 mb layer plays an important role in producing high winds (Brown 1986). Figure 2 shows the Platteville wind profiler for December 22. Initially, 1200-1400 UTC, there was strong shear in the 700-500 mb layer and high winds were confined to higher elevations. By 1500 UTC, however, the shear weakened, enabling strong winds to reach the lower elevations and continue until 1900 UTC when the strong shear in this layer returned.

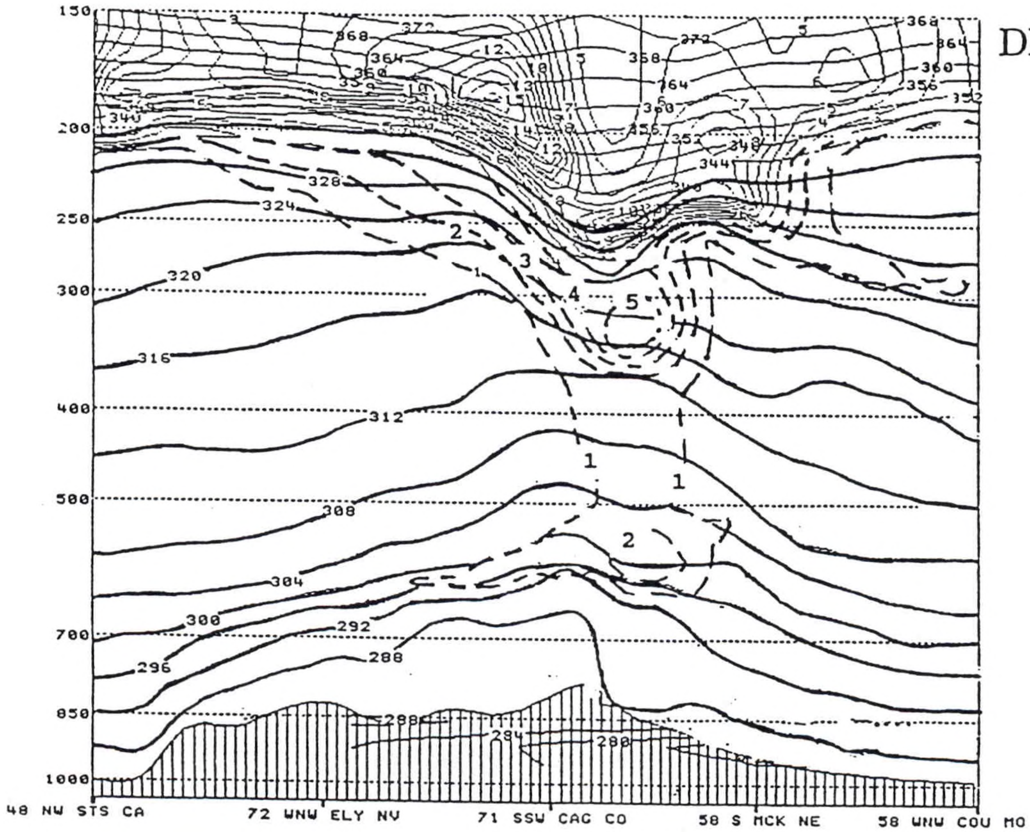

Figure 1. Maps 6-hour forecast cross section of theta (°K) and potential vorticity ($1*10^{-5}$ °K/mb/s) valid 1500 UTC, December 22, 1992.

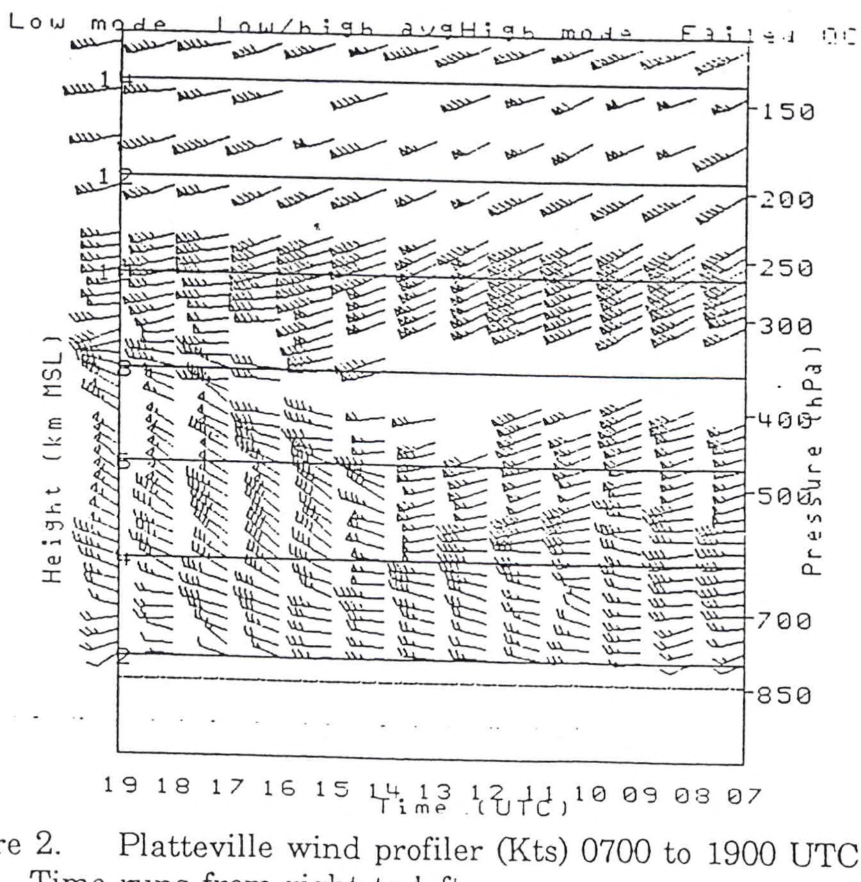

Figure 2. Platteville wind profiler (Kts) 0700 to 1900 UTC, December 22, 1992. Time runs from right to left.

3. Vertical Motion

Much has been written on the role of ageostrophic circulations associated with jet streaks. However, little has been written on how much downward motion in the left entrance or right exit region contributes to downslope windstorms. It is proposed that sub-synoptic scale downward motion associated with these jet streak quadrants may enhance the downward momentum transport of a vertically propagating mountain wave (the reader is asked not to get vertical momentum transport due to mixing confused with subsidence). Out of the 18 high wind events, during the past three seasons, there were 13 cases where a jet streak quadrant was identified. Of these, 85% had either a left entrance or right exit region (downward motion) moving over the Front Range during the event.

A. Q-vector divergence

With the advent of new data sets, forecasters can pinpoint areas of forcing for vertical motion through the use of Q-vectors (Hoskins and Pedder 1980). Forcing for downward motion can be maximized when there is cold advection and anticyclonic vorticity advection increasing with height occurring simultaneously. Thus, positive divergence of Q-vectors can be a useful tool to determine where downward motion may be enhancing downslope windstorms.

B. Case study: November 30 - December 1, 1992

At 0000 UTC, December 1, the MAPS analysis indicated a 140 kt jet streak at 250 mb over the Pacific Northwest (Figure 3). Ageostrophic winds at this level reveal the upper branch of the indirect thermal circulation in the exit region from western Montana to Utah. Here there is upward motion in the cold air over Montana and downward motion in the warm air over Utah. This circulation can also be implied through Q-vectors.

Q-vectors can be broken down into its components, Q_s and Q_n. Barnes and Colman (1993) explain that Q_s is the component of Q parallel to the isotherms while Q_n is the component of Q orthogonal to the isotherms. Q_s has a larger contribution when there is greater curvature in the wind field while Q_n has a larger contribution in straight flow. Figure 4 shows the divergence of Q_n (div-Q_n) field associated with this straightline jet streak. While the horizontal branch of the indirect circulation can be gleaned from Figure 3, the vertical branches can be implied from the div-Q_n couplet over Montana and Utah in Figure 4.

Converging Q_n vectors (negative div-Q_n) implies upward motion while diverging Q_n vectors (positive div-Q_n) implies downward motion. This circulation is frontogenetic, where cold air over Montana is forced to rise and warm air over northern Utah is forced to sink. It is proposed that the subsidence with right

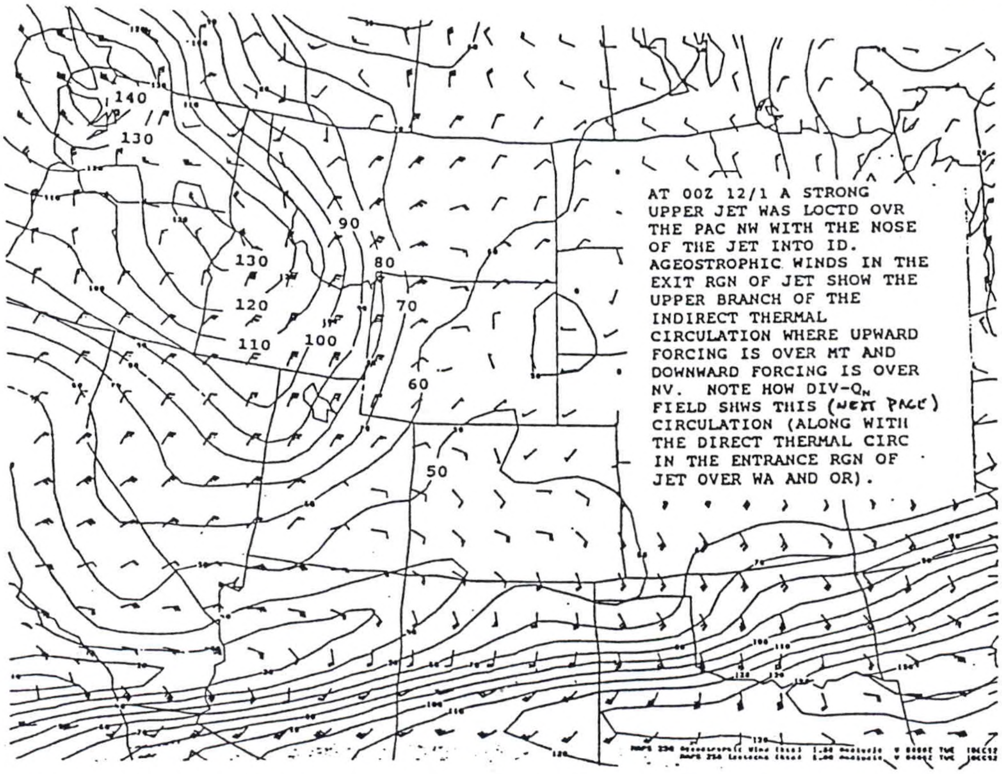

Figure 3. Maps analysis isotachs and ageostrophic winds (Kts) for 0000 UTC, December 1, 1992.

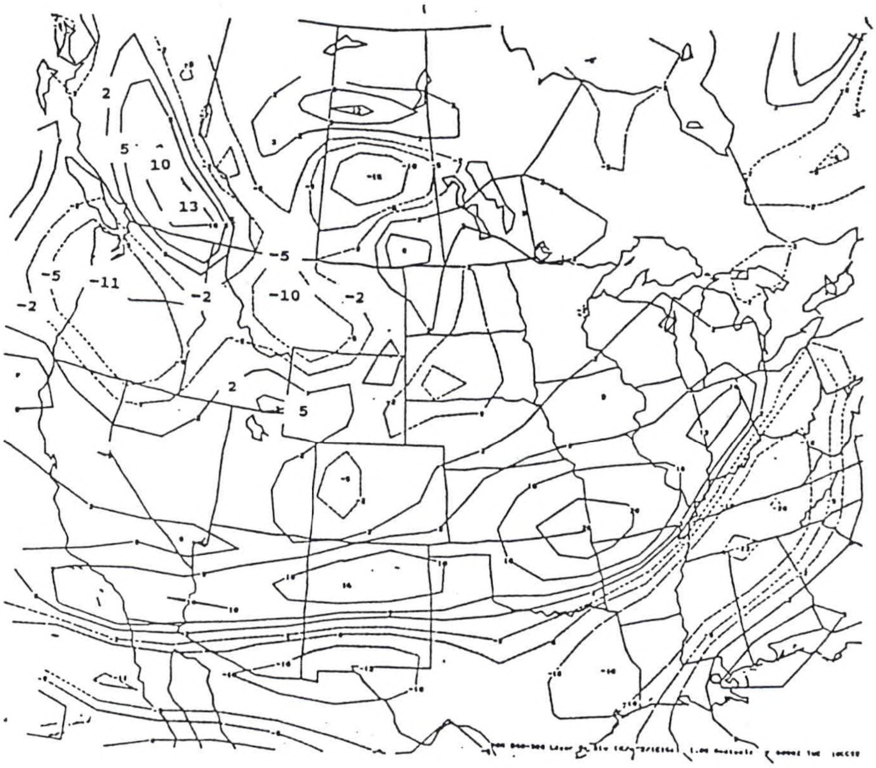

Figure 4. Ngm analysis of 500-300 mb layer Q_n-vector divergence ($1*10^{-16}\cdot K/m^2/s$) for 0000 UTC, December 1, 1992.

exit regions (and alternatively with left entrance regions) of jet streaks can enhance severe downslope windstorms. High winds began along the Front Range around 0600 UTC as the downward forcing with the right exit region approached. By 1200 UTC, the div-Q_n couplet strengthened, implying a stronger indirect thermal circulation (Figure 5). Subsequently, high winds reached peak intensity between 0600 and 1200 UTC as the strengthening forcing for downwared vertical motion moved over the Front Range.

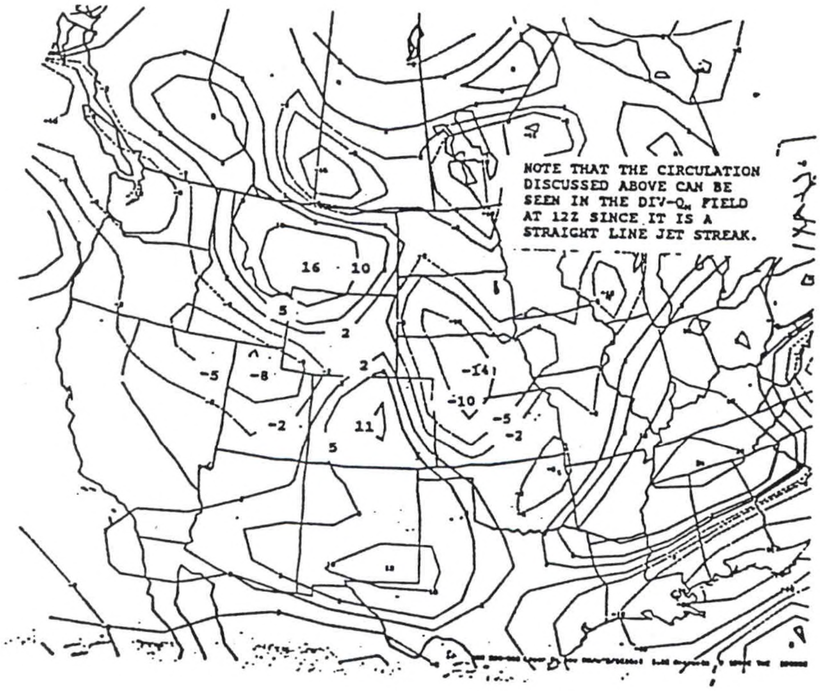

Figure 5. Same as Figure 4 Except for 1200 UTC December 1, 1992.

C. Potential vorticity and tropopause undulations

Circulations around jet streaks and the structure and maintenance of upper trospheric fronts have been well documented in the literature. Reed (1955) first described how these circulations generated tropopause folds where stratospheric air descended into the lower troposphere in the rear of a jet streak. Uccellini (1985) later documented the extrusion of high potential vorticity air within the tropopause fold to lower elevations, enhancing cyclogenesis. Hirschberg and Fritsch (1991) expanded on these ideas by looking at synoptic scale tropopause undulations where synoptic scale subsidence causes a lowering of the tropopause.

During the past three windstorm seasons there have been numerous examples of high wind events occurring as these phenomena approached and moved across the Front Range. The physical relationship may be that the downward transport of high momentum air by a vertically propagating wave from the mid and upper troposphere to lower levels may be enhanced by the downward vertical motion associated with these upper tropospheric phenomena.

D. Case study: June 16-17, 1992

This event began at 1900 UTC, June 16 as the left entrance region of a 110 kt jet streak moved from northeast Utah (not shown) toward the Front Range. During the day, a PV anomaly associated with the left entrance region moved east out of Utah and was located directly over the Front Range by 2100 UTC (Figure 6). A warm pool of air located in the upper troposphere (Figure 7) at 0000 UTC indicated this region was comprised of sinking stratospheric air. A region of lowered tropopause levels (Figure 8) suggested there was subsidence from the stratosphere into the mid troposphere.

Figure 6. Maps 316°K isentropic analysis of potential vorticity ($1*10^{-5}$°K/mb/s) for 2100 UTC, June 16, 1992.

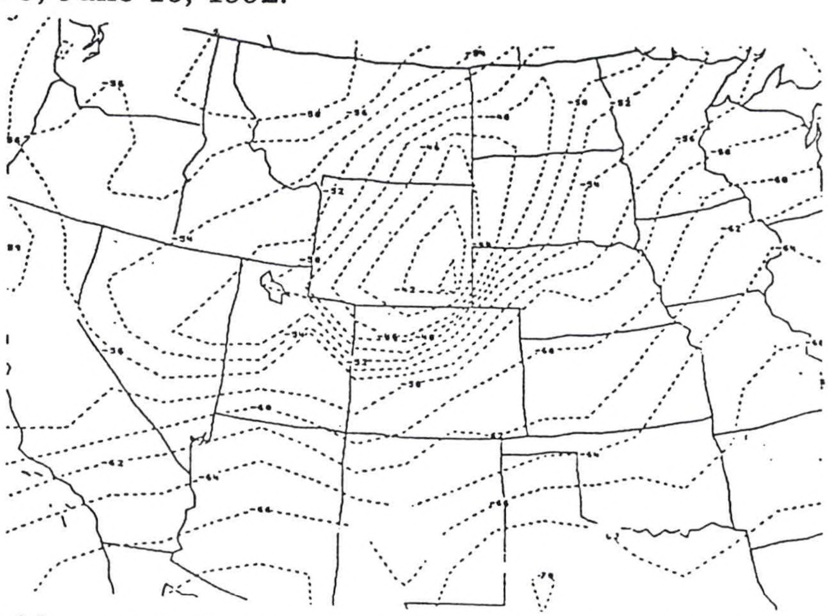

Figure 7. Ngm analysis of tropopause temperature (°C) for 0000 UTC, June 17, 1992.

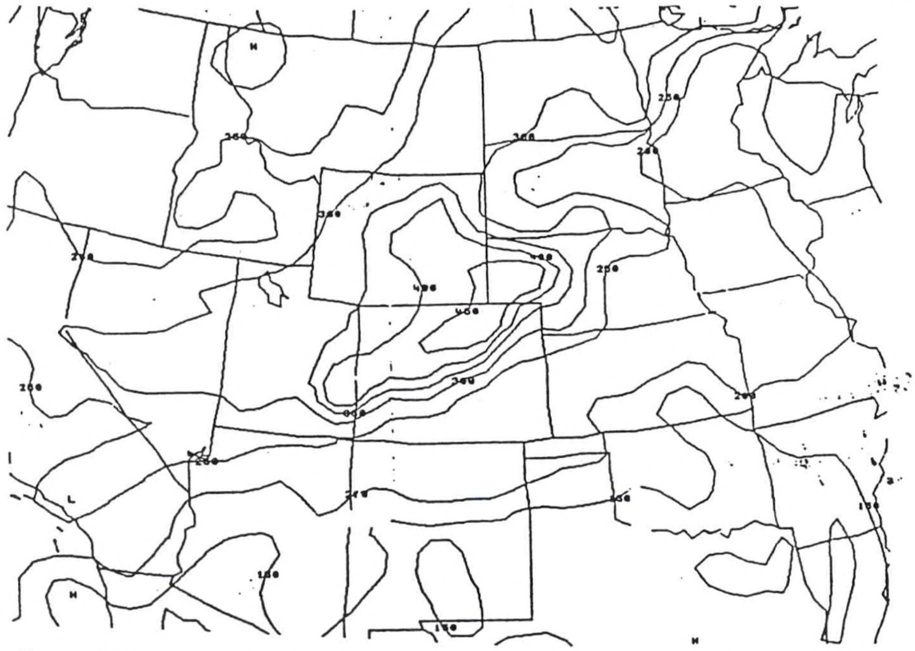

Figure 8. Maps analysis of tropopause pressure level (mb) for 0000 UTC, June 17, 1992.

MAPS vertical cross sections oriented west-to-east through the tropopause undulation show a different view (Figure 9). At 1800 UTC, just before the event began, the undulation was just reaching the Front Range. There is some evidence of a tropopause fold in advance of and to the rear of the undulation. As the subsidence associated with the rear of the undulation moved into the Front Range after 1800 UTC strong winds reached the lower plains. After 0300 UTC, the undulation moved east of the Front Range. At this time, high winds subsided at lower elevations along the Front Range since the downward motion weakened.

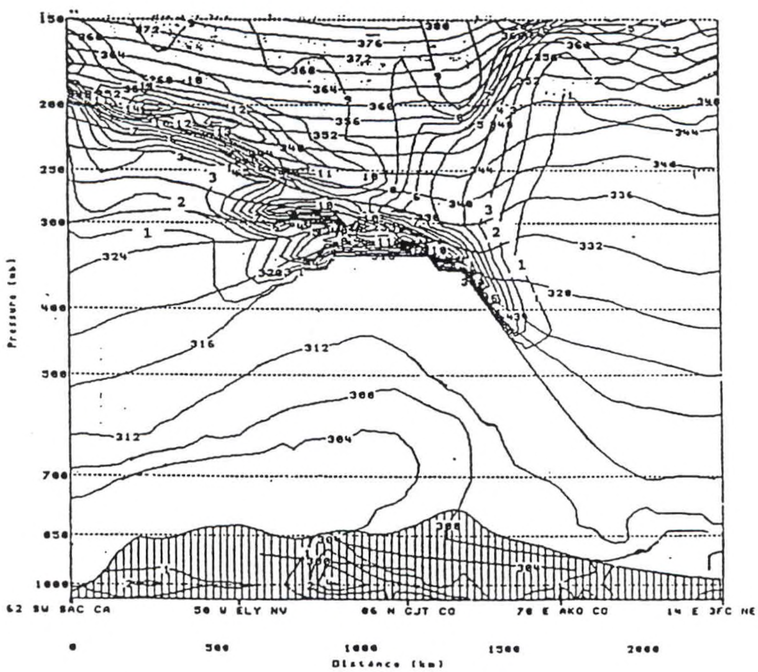

Figure 9. Maps cross section analysis of theta (°K) and potential vorticity ($1*10^{-5}$ °K/mb/s) valid 1800 UTC, June 16, 1992.

4. Conclusion

Severe downslope windstorms during the past three seasons have been analyzed using sets of advanced real-time gridded data and gridded model output available on the DAR^{3}E workstation. A few examples reveal how operational forecasters can use this new technology to analyze dynamical processes conducive to severe downslope winds.

Vertical stability can still be checked through conventional Skew-T analysis or through cross sections of potential temperature available with higher resolution mesoscale models. Wind shear can be analyzed using wind profiler data or, more frequently, from winds aloft measured by the WSR-88D Doppler radar.

Upper tropospheric dynamical forcing appears to play a very important role in generating windstorms. Evidence has shown that high winds are more likely to develop when there is some kind of forcing for downward motion crossing the Front Range. It is proposed that synoptic scale downward motion enhances the mesoscale downward transport of momentum produced by a vertically propagating mountain wave.

Synoptic scale downward motion can be achieved through ageostrophic vertical circulations associated with upper tropospheric jet streaks. In particular, forecasters can look for the right exit or left entrance region near the Front Range to produce downslope windstorms. One can more quantitatively assess vertical motion by observing Q-vector fields and noting dynamical forcing for downward motion where there is positive Q-vector divergence.

Lastly, there has been recent evidence linking fields of vertical motion with tropopause undulations. Downward motion occurs to the rear of an undulation where there is subsiding stratospheric air. Forecasters can locate this synoptic scale subsidence by noting warm pools of air at high isobaric levels (300-200 mb), low tropopause levels into the mid troposphere (600-400 mb) and/or isentropic potential vorticity maxima. Subsidence with these undulations can also be observed on moisture channel satellite pictures by noting areas of drying.

5. References

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