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A LOCALIZED DOWNSLOPE WINDSTORM IN NORTHERN ARIZONA

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Introduction

Strong winds are a common occurrence across northern Arizona, especially during the cool season when the jet stream and associated baroclinic zone frequents the lower latitudes of the Southwest. High winds create a significant hazard for the general public, particularly for the many motorists along Interstate 40, which runs east to west through Flagstaff and Winslow, as well as the many tourists who visit this Region. Due to the varied and unique terrain across the Region, many of the strong wind events are localized, making them quite difficult to forecast. One of the primary challenges facing forecasters at the National Weather Service Office in Flagstaff, Arizona, is to accurately assess the potential and specific location for high winds.

On 2 January 1996, strong and damaging winds developed overnight in the Flagstaff vicinity, peaking in a localized area on the east side of town. This area is only a mile or so directly downstream from a small, relatively isolated mountain (Mt. Elden), which rises about 2500 feet above the elevation of Flagstaff (Fig. 1). Wind speeds were estimated near 80 mph, mainly from damage to pine trees and power lines. However, less than 10 miles downstream, the Pulliam Airport ASOS reported winds under 30 mph. Figure 2 shows a wider view of the terrain over much of northern Arizona. The location of Mt. Elden, as well as the higher San Francisco Peaks (Humphrey's Peak being the highest peak in Arizona) and their elevations, are shown in relation to Flagstaff. Also shown in Fig. 2 are the locations of the NWS upper-air site and Pulliam Airport (ASOS) in relation to Flagstaff and the above-mentioned terrain features.

This Technical Attachment will examine this windstorm event and the utility of model gridded data in predicting it. Theoretical concepts generated from studies of downslope windstorms in other parts of the country (and the world) are first reviewed. The authors then examine how these theories might be applied to this particular case given the observations and gridded model forecasts, and how this case may differ somewhat from the more classic cases most prevalent in the literature.

Basic Theory And Forecast Methods

Previous studies of localized wind events in other mountainous regions have led to a number of theories concerning the mechanisms responsible. The main objective of this study was to determine if the windstorm on 2 January 1996 in Flagstaff could be explained by any of these mechanisms, or if several might have contributed. One complication is that the somewhat isolated character of the mountain peaks in this particular case is a potentially significant difference from the more two-dimensional mountain ridges that the common theories are based on. However, to our knowledge, very little work has been done to determine how the mechanisms for generating windstorms in the vicinity of isolated peaks may differ compared to mountain ridges, although some studies have simulated the general airflow patterns influenced by isolated mountains (see Durran 1990 for a summary of a few of these). Therefore, we had to begin with the assumption that current theories applied to two-dimensional ridges would have at least some application to the isolated peak. [In reality, the mountain in question near Flagstaff is not completely isolated, but neither are the mountains studied in other regions perfect two-dimensional ridges.]

Many studies and discussions on downslope windstorms and mountain waves often begin with the "hydraulic jump" concept. However, a simple hydraulic model by itself is often not considered a viable solution due to its limited view of the atmosphere where energy cannot be transported vertically through the upper boundary. In the real world, waves can indeed propagate energy in the vertical (Durran 1986).

One of the earliest and often-referred to studies on low-level amplification of vertically propagating mountain waves is that of Klemp and Lilly (1975). In this study, the authors focused on the importance of the stability structure of the troposphere in the low-level amplification of vertically propagating gravity waves. The structure favorable for this low-level amplification consists of a shallow layer of stable air near mountaintop level followed by a relatively deep layer of unstable air through the mid-troposphere (see Fig. 3a).

Clark and Peltier (1977) and Durran (1986) were among the first to discuss the role of a "critical level" in contributing to low-level mountain wave amplification (and ultimately the generation of a downslope windstorm). The critical level, defined as the level at which the wind component perpendicular to the ridge goes to zero, reflects energy back down toward the wave perturbation, which leads to an increase in the low-level winds. While mean state critical levels are not always observed upstream from the ridge during wave-induced windstorms, studies of Boulder windstorms have shown that a critical level can be induced by the mountain wave itself. Colman and Dierking (1992) suggested that an upstream critical level may be more important for shallower ridges compared to taller mountain ranges.

In the absence of a mean-state critical level, the vertical wind shear may also be important in determining the potential for strong downslope winds. The existence of weak vertical shear, or ideally reverse shear, is more favorable for low-level amplification compared to forward shear (Brown 1986). Strong forward shear may tend to prevent a wave-induced critical level from developing, and is thought to trap vertically-propagating waves, thus preventing amplification and wave breaking.

Work by Holmes (1994) focuses on the importance of synoptic scale forcing when determining the likelihood of strong downslope winds. The most significant contribution from synoptic scale downward forcing is believed to be its effect on the generation of the vertical stability structure in the lower troposphere, thought necessary for amplified mountain waves. Gridded output of NCEP numerical model data allows for three-dimensional diagnosis of this structure as well as the synoptic forcing mechanisms responsible for it.

Summarizing the above-mentioned studies and theories, a basic set of conditions thought to favor the onset of strong downslope winds can be considered to help forecast these events:

1. The wind flow is across a terrain barrier (generally within 30 degrees of perpendicular).

2. The atmospheric layer immediately above mountaintop level usually exhibits strong stability with a layer of weaker stability above.

3. A level may be observed that exhibits a wind direction reversal or where the cross-barrier flow simply goes to zero (the mean state critical level).

4. The existence of weak, vertical wind shear or reverse shear is more favorable than forward shear.

5. Synoptic scale downward forcing helps to generate and reinforce the vertical static stability structure conducive to strong mountain waves.

In addition, strong surface pressure gradients (that are not a direct reflection of the wave) may enhance downslope windstorms, but in many cases are thought to be incidental to the overall synoptic pattern generating the event. While surface pressure gradients play a primary role in gap flow windstorms, some studies in other regions suggested in can be difficult to separate gap flow and mountain wave effects in generating lee slope windstorms (Mass and Albright, 1985; Colman and Dierking, 1992).

With these basic principles in mind, the authors set out to examine the Flagstaff windstorm of 2 January 1996, and the performance of gridded data sets in forecasting this event over the variable and unique terrain of northern Arizona.

Case Study - 2 January 1996

The prelude to this event began on the previous morning (1 January 1996), when a wind advisory was issued for much of northern Arizona. Winds of 30 to 40 kts were noted just above the surface on the VAD wind profile from the KFSX WSR-88D (not shown). However, the advisory was canceled at midafternoon as strong winds failed to develop at the surface. Early the next morning (January 2) damaging winds raked through northeastern portions of Flagstaff, downing trees and power lines with estimated wind gusts of 80 mph around 0900 UTC. Fifty mph gusts continued until around 1400 UTC. Strong winds (25 mph with gusts to 40 mph) continued through the day in most areas, but never again reached the level of the localized winds in the early morning hours.

Numerical models were forecasting strong synoptic scale downward motion in association with a jet streak over northeastern Arizona during the early morning hours of January 2. This strong subsidence likely contributed to the development of a stable layer near mountain top level (shown later in Fig. 7). As noted earlier, favorable conditions for the low-level amplification of mountain waves include a stable layer just above the mountain top level.

[Note: The mountain in question in this case is Mt. Elden (about 9,300 feet above sea level), which is the relatively isolated mountain shown just upstream from the wind-damaged area of Flagstaff in Figs. 1 and 2. The taller San Francisco Peaks (the highest of which is 12,633 foot Humphrey's Peak) are a few miles to the northwest of Mt. Elden, and also relatively isolated. It is unknown whether any damaging winds occurred downstream or in the immediate vicinity of these peaks since this area is sparsely populated.]

Figure 4 shows the 29 km Meso Eta model 9-hour forecast of 250 mb winds valid at 1200 UTC. A 155 knot jet streak is entering the northeast quarter of Arizona placing the right exit region over northern Arizona. Further evidence of downward motion associated with this feature can be ascertained from Fig. 5, which shows the Meso Eta model 9-hour forecast of 700-500mb layer Qn vectors (the component parallel to the temperature gradient vector, and dominant for straight jets) and thicknesses valid at 1200 UTC. This shows a large area of strong Qn vector divergence (in association with the jet streak) at the mid levels, indicating strong ageostrophic flow and significant downward motion over northern Arizona. [Note: while gravity waves can often dominate QG diagnostics of vertical motion fields in high resolution numerical models, in this case there is a pronounced larger scale signature in association with the jet streak circulation in the 29km Eta model.]

The Meso Eta model time-height section forecast of equivalent potential temperature from the 0300 UTC run (Fig. 6) clearly depicts the changing vertical structure of the lower troposphere as isentropes begin to pack together. This developing stable layer lowers to around mountaintop level (roughly 700 mb) by 0900 UTC. Notice also the higher wind speeds gradually dropping to lower levels throughout the early morning hours. The observed FGZ sounding (see Fig. 2 for upper-air location at NWS Office) at 1200 UTC 2 January did indeed indicate a stable layer near mountaintop level (Fig. 7).

In Fig. 6, the forecast winds near mountaintop level can also be seen veering somewhat, beginning around 1200 UTC, which would clearly mean a change to the cross-ridge component of the wind speed (a decrease if you consider the orientation of the very short ridge line shown in Fig. 1). Since the damaging surface winds also began to diminish at this time, it does not seem unreasonable to conclude that this particular ridge orientation may have influenced the low-level amplification of a mountain wave. If the area affected by the damaging winds shifted westward as the winds aloft veered, that might suggest the ridge line was less important compared to the isolated nature of the mountain. On the other hand, without conducting a very high resolution numerical simulation (one that captures all the details of the terrain), we cannot be sure exactly how the shape of this mountain influenced the observed windstorm.

Both the observed sounding and model forecast wind profiles show no wind reversal or enough change in direction with height to suggest a cross-barrier component going to zero (in fact, all wind directions are cross-barrier if the mountain is assumed to be truly isolated), thus, there is no evidence for a mean-state critical level in this case. In addition, the forecast and observed wind profiles indicate especially strong forward shear through a deep layer. While the absence of a mean-state critical level is not necessarily a detriment to the production of a downslope windstorm (as mentioned earlier), the character of the vertical shear observed in this case would generally be considered a negative influence, since strong forward shear may act to prevent a wave-induced critical level. Perhaps the forward shear between 0900 and 1200 UTC in the layer where the mountain wave formed was not quite strong enough to prevent a wave-induced critical level from developing.

By 0000 UTC 3 January (late afternoon), the stable layer was forecast to drop below mountaintop level (Fig. 6), while wind speeds near mountaintop level were also forecast to decrease throughout the day on 2 January. During the afternoon and evening, a significant decrease in surface winds was observed across the forecast area.

Conclusion

The windstorm of 2 January 1996 in northeast Flagstaff appears to have been primarily the result of two factors. First, the exceptionally strong jet streak diving from the north across the area resulted in significant cross-barrier flow from north to south over Mt. Elden and the San Francisco Peaks. Secondly, the strong synoptic scale subsidence forecast to occur with this jet streak helped create a stability profile favorable for the low-level amplification of mountain waves. On the other hand, the absence of a mean-state critical level coupled with apparently strong forward vertical wind shear suggests conditions a little less favorable for an amplified mountain wave.

There could have been a few other factors which influenced the development of the damaging lee-side winds. A moderate northeast-southwest pressure gradient existed over the Region (not shown), but with sparse surface observations it is very difficult to determine the local strength of the gradient. Since some of the damage occurred more on the edge of Mt. Elden instead of strictly downstream, it is possible that surface winds accelerated around the side of the isolated mountain in a manner similar to gap flow accelerations.

The shape of the slope and the time of occurrence may have also played roles by reducing the frictional drag. A steep downwind slope (which exists in this case) may limit the length where surface friction can occur, and may also help amplify the effects of the wave (Lilly and Klemp, 1979). Since the event occurred primarily at night, a decoupled boundary layer may have allowed winds near mountaintop to increase with the reduced frictional drag, resulting in stronger surface winds when the vertically propagating mountain wave reached the surface. Other similar downslope windstorm events have been known to occur more frequently at night, such as the "Sundowner" winds in southern California (Ryan, 1996).

Gridded model data did well in recognizing the downward motion and strong flow with this case as well as the existence of a stable layer. However, the resolution of the operational models would not normally allow a forecaster to pinpoint the location of high winds during an event like this. It is hoped that simulations of this event using the MM5 model with an inner grid resolution of 3 km will reveal further evidence of the mechanisms behind this event.

The problem we will have with future events is related to the somewhat isolated nature of the mountains. A variety of wind directions could result in topography-related windstorms, but each at different locations relative to the mountain. Furthermore, most of the research efforts on mountain waves so far have dealt with elongated ridges or a range of mountains rather than isolated peaks typical of northern Arizona; much is still unknown about the flow characteristics around and over this type of isolated terrain. For example, how can gap flow arguments be applied around the edges of a relatively isolated peak?

Unfortunately, the relatively sparse observation and spotter networks across northern Arizona make it difficult to verify many of these localized wind events. Yet with more experience, higher resolution models, and further investigation, forecasters at NWSO Flagstaff will attempt to link certain synoptic patterns and atmospheric structures to local terrain-induced events and provide accurate forecasts of these windstorms to the public.

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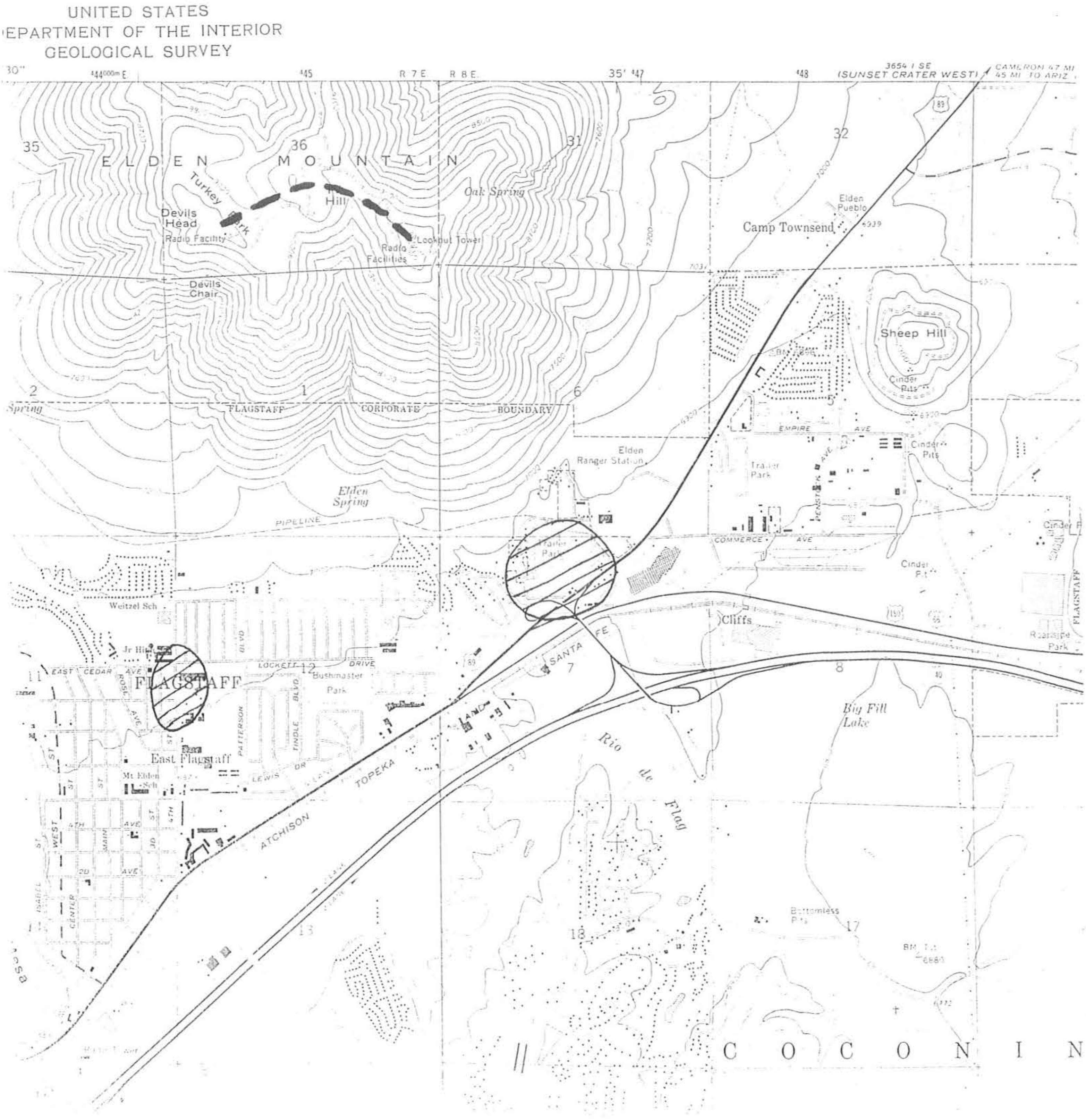

Fig. 1. East Flagstaff and Mt Elden. Dashed line shows ridge line of Mt Elden (over 2,000 feet higher than the elevation of Flagstaff). Known areas of wind damage are circled and hatched.

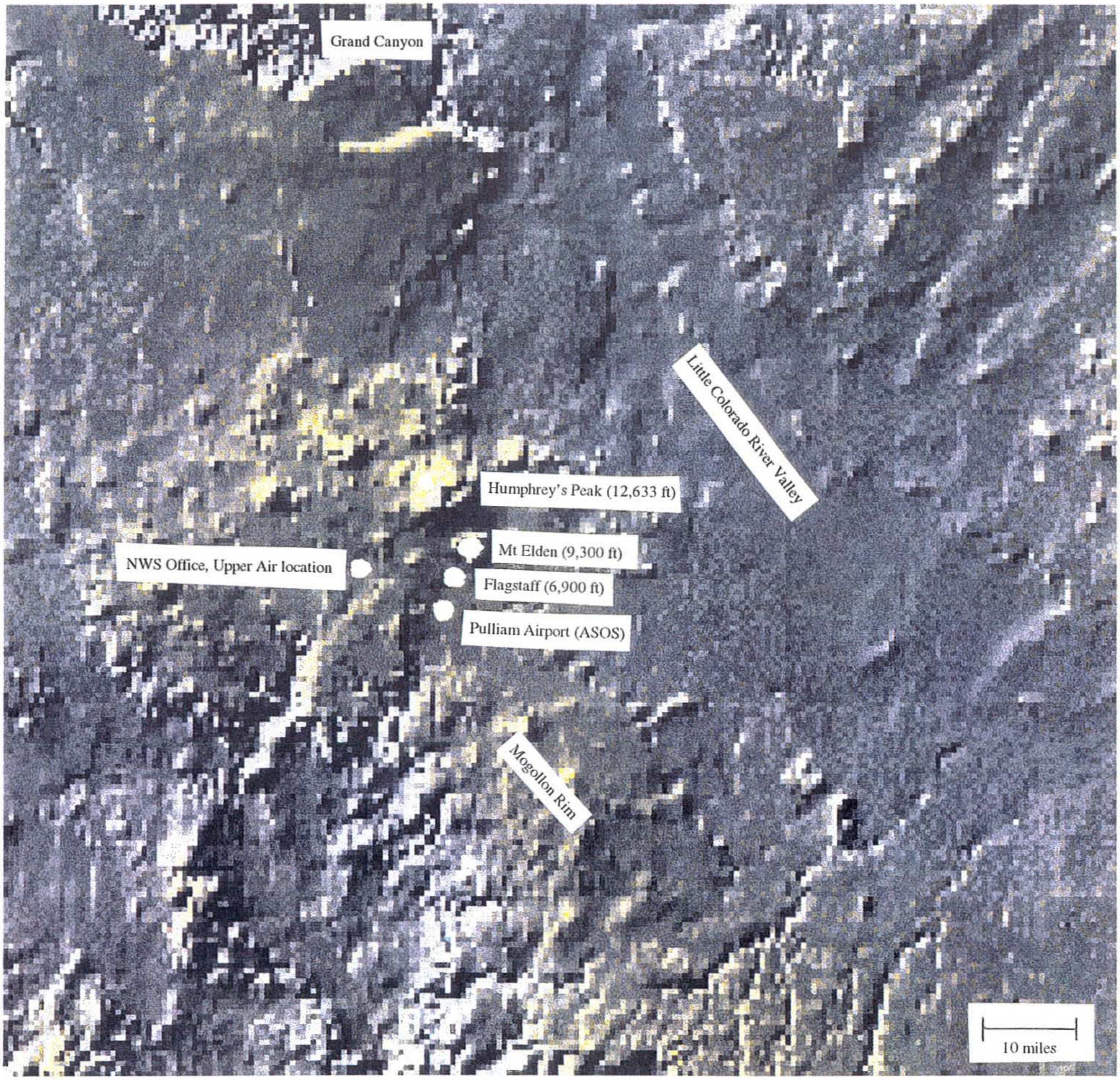

Fig. 2. Topography of northern Arizona

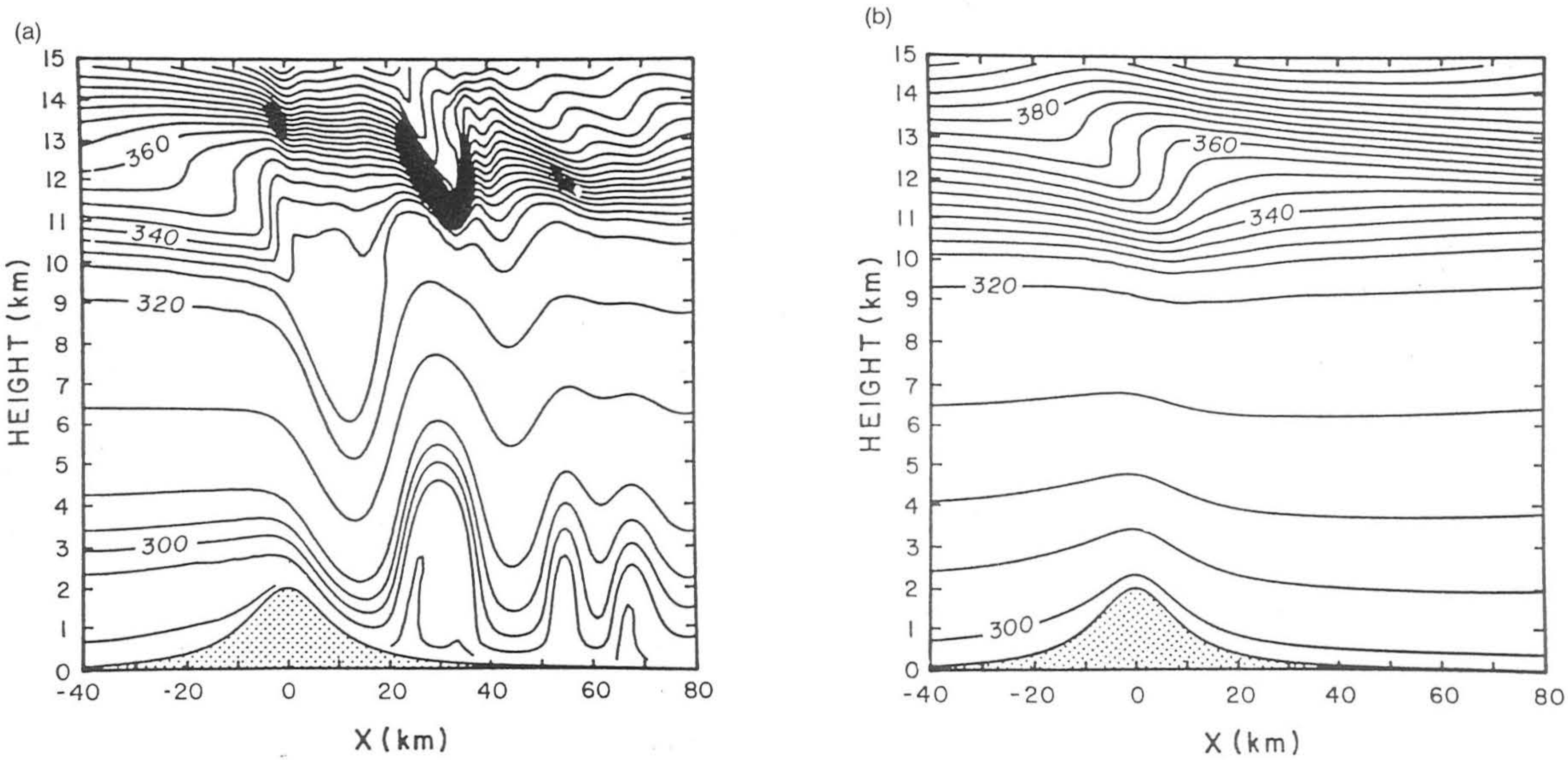

Fig. 3. (a) Isentropes from a simulation of the 11 January 1972 Boulder windstorm. (b) Same as in (a) except upstream sounding has been modified to remove the elevated inversion. (From Durran 1986).

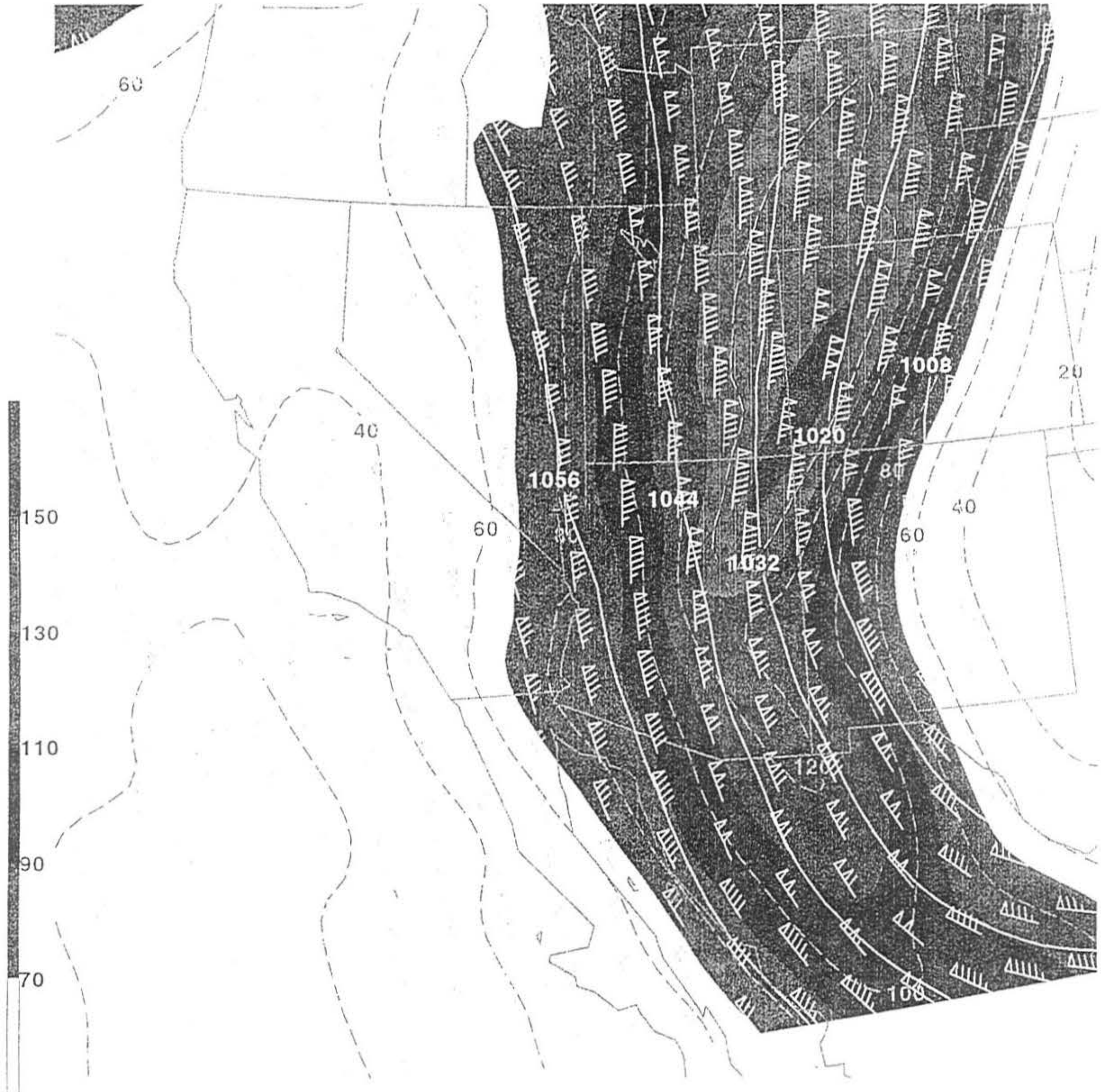

Fig. 4. Meso Eta 250mb winds and isotachs. 9 hr forecast, valid 1200 UTC 1/2/96

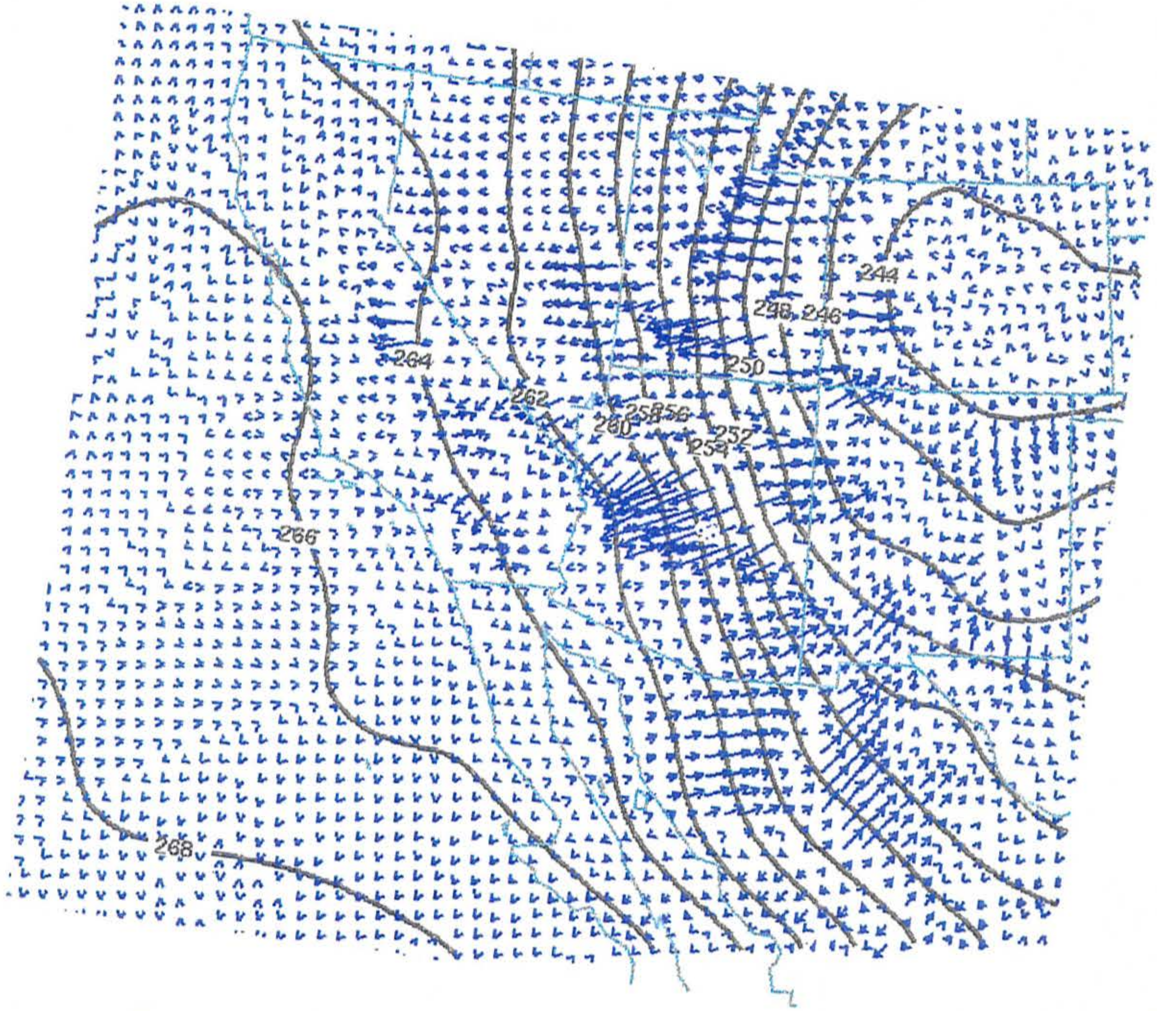

Fig. 5. Meso Eta 700-500mb layer Qn vectors and thickness. 9 hr forecast, valid 1200 UTC 1/2/96.

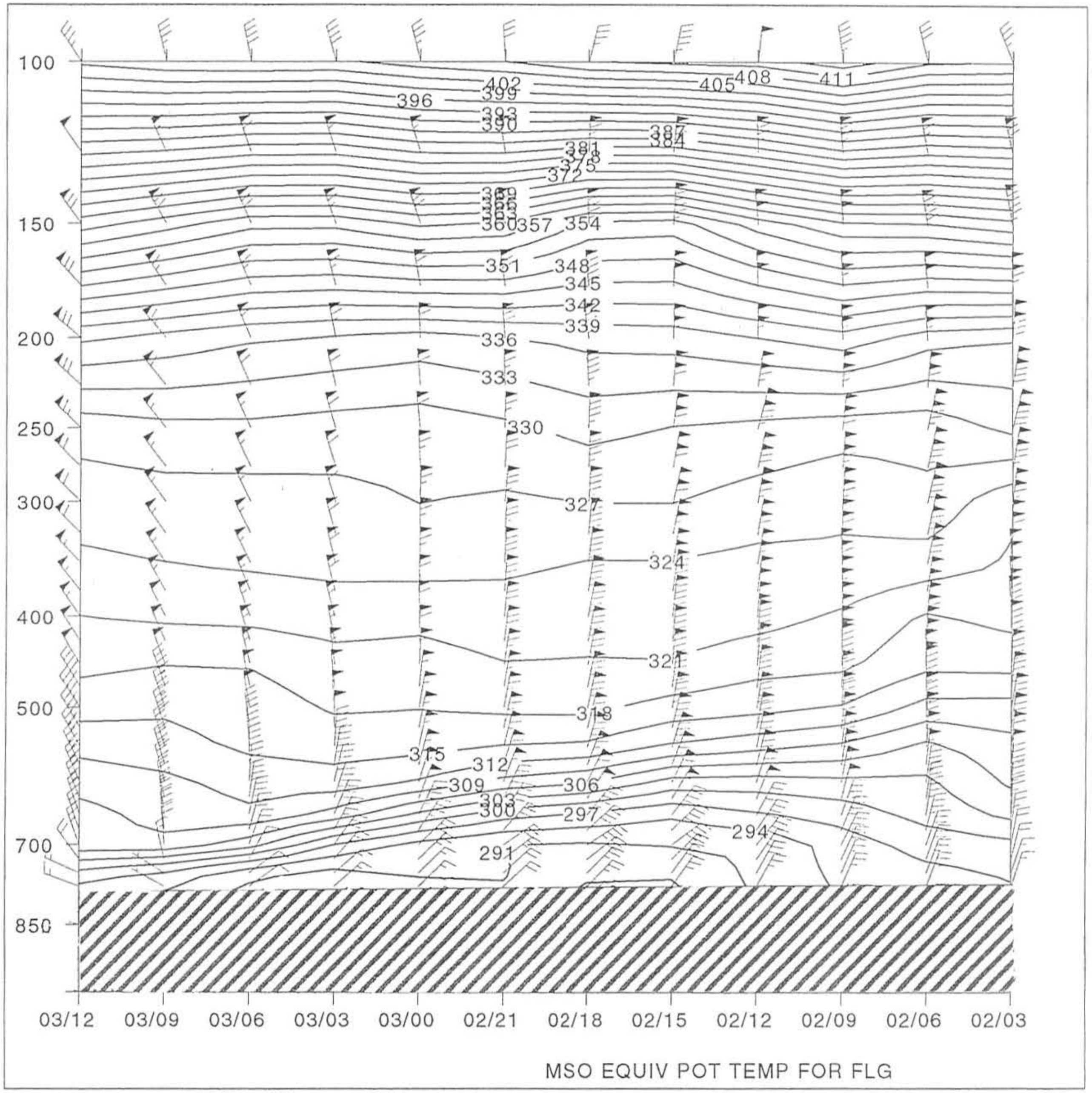

Fig. 6. Meso Eta forecast (from 0300 UTC 1/2/96 run) time-section of equivalent potential temperature (theta-e) and winds. Valid times increase from right to left. Area below ground level (approx. 780mb) is hatched. Height of the mountain in question is near 700mb.

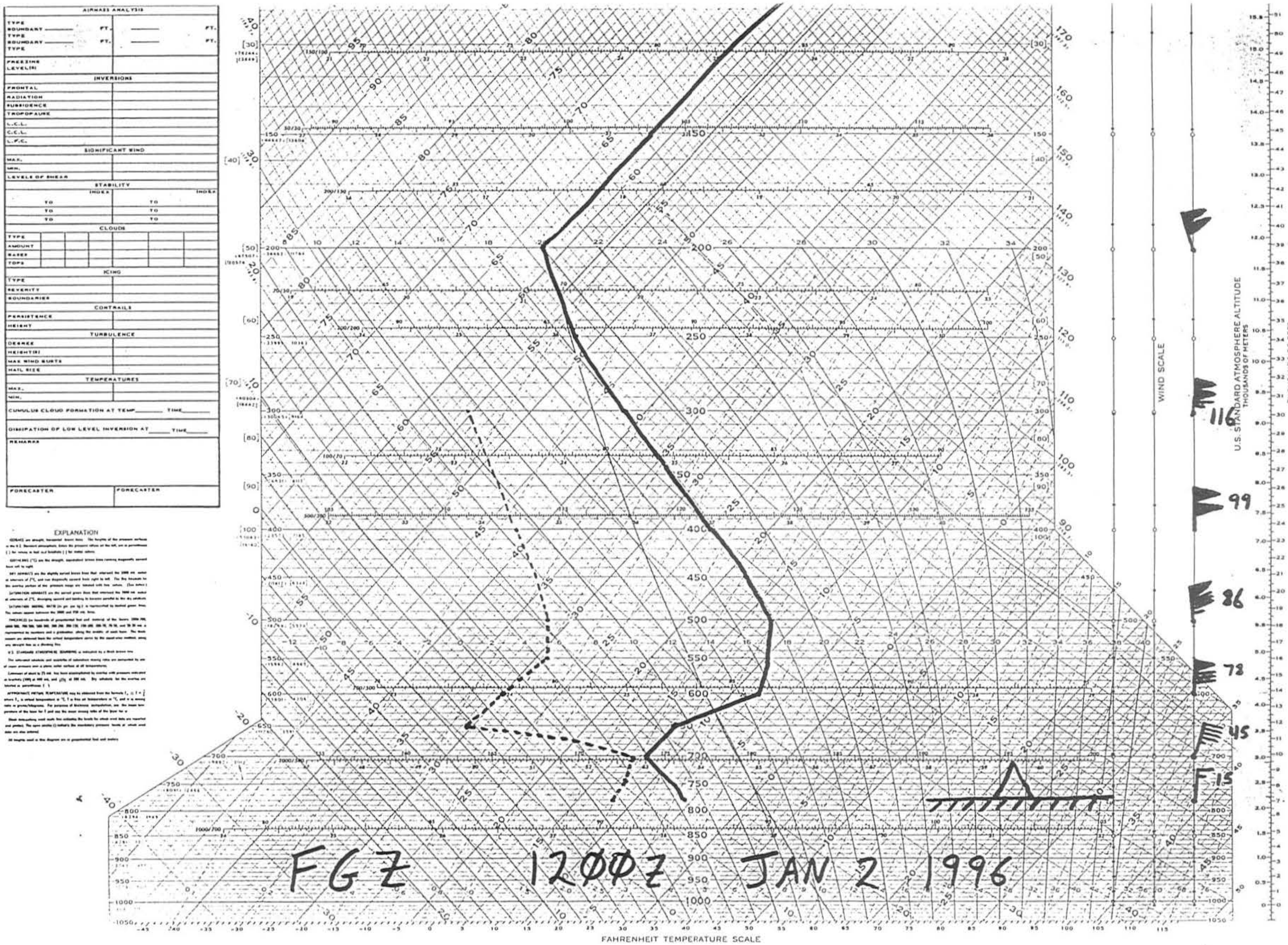

Fig. 7. Skew T - Log P diagram for Flagstaff sounding (see Fig 2 for upper air site at NWS Office) taken at 1200 UTC 1/2/96. Elevation of Flagstaff and height of Mt. Elden are depicted at lower right.