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AN ANALYSIS OF A HIGH WIND EVENT USING ISENTROPIC SURFACES

Scott F. Hickman - NWSFO Reno

Introduction

The most common approach to analyzing the atmosphere has been by constant pressure surfaces. However, faster and more powerful computers have made it possible to analyze the atmosphere in a three dimensional perspective using isentropic surfaces. This paper presents an analysis of a high wind event that took place in eastern Nevada and northwest Utah on June 5, 1995 from an isentropic perspective. On that day, high winds persisted through the evening hours, causing damage to vehicles and other property. In addition to isentropic analysis, the isallobaric wind theory and several equations will be discussed for purposes of background information and interpretation. The program PC-GRIDDS was utilized for the isentropic analyses, demonstrating its potential usefulness for forecasting wind events.

Background Information

In this particular case study, the Eta model was preferred due to its continuity from each model run. Before the analyses are presented, some background information is required to assist the reader in understanding the graphics presented.

A) Potential Temperature

Potential temperature will be discussed since its understanding is essential in studying adiabatic processes. Every meteorologist should be familiar with the following equation:

$$\theta = T \left(\frac{P_s}{P} \right) \kappa \qquad (1)$$

where κ = constant = R/c_p (gas constant for dry air divided by specific heat at constant pressure) , θ = potential temperature measured in units of Kelvin (K). This equation describes what temperature a parcel of air would obtain by moving it dry adiabatically from an initial pressure level p (measured in millibars or mb) to a final pressure level p_s which usually is 1000 mb. θ is a conservative property for dry adiabatic motion. Thus, "fractional potential temperature changes are indeed proportional to entropy changes. A parcel that conserves entropy following the motion must move along an isentropic surface (Holton 1993)." Hence, for adiabatic motion, parcels follow isentropic surfaces. This is useful because air flow can be traced three dimensionally using isentropic surfaces.

B) Fronts

For a particular isentropic surface θ, fronts can be located where isobars defining the surface are compacted. Referring to the potential temperature equation, if θ is constant and p is constant then T must be constant (Moore 1993). This means that for a given isentropic surface and an isobar defined on the surface, the isobar represents an isotherm. Thus, where isobars are compacted for a given isentropic surface, this depicts a frontal or baroclinic zone. Also, lower values of pressure (in mb) on an isentropic surface represent colder air while higher values of pressure represent warmer air. If one visualizes this in three dimensions, the colder air is like a "hill" and the warmer air is like a "valley." It is important to note that "isentropic surfaces are sloped down towards warm air and are compacted in the vertical within the frontal zone. The slope of the isentropic surface is a function of the thermal gradient (Moore 1993)." A vertically sloping isentropic surface shows a strong temperature contrast. The three dimensional visualization of the surface will become clear with the discussion of the wind event.

C) Montgomery Streamfunction and Isallobaric Wind on Isentropic Surfaces

The Montgomery Streamfunction, M, is comparable to heights used on a constant pressure surface. This is used to define geostrophic flow on an isentropic surface (Moore 1993). It is defined as

$$M = c_p T_\theta + g z_\theta \qquad (2)$$

where g = gravitational acceleration, c_p = specific heat at constant pressure, and T_θ and z_θ will be discussed below. From Bluestein (1992), the isallobaric wind component (which is a component of the ageostrophic wind) on an isentropic surface is defined as

$$\mathbf{v_a} = \frac{-1}{f^2} \nabla_\theta \left(\frac{\partial M}{\partial t}\right) \qquad (3)$$

where t = time, and f = Coriolis parameter dependent on latitude. M is proportional to the temperature and height of an isentropic surface (T_θ and z_θ) which can be calculated from a given point on a surface. It is the time tendency of the Montgomery Streamfunction ($\partial M/\partial t$) on an isentropic surface that determines the speed and direction of the isallobaric wind (Kapela and Van Ess 1990). It must be emphasized that the isallobaric wind is only one component of the total ageostrophic wind and is assumed to be the dominant factor in this particular case . The isallobaric wind component in this study is likely to enhance air parcel acceleration down an isentropic surface.

D) Vertical Motion Expressed in Terms of Isentropic Coordinates

As Moore states, vertical motion with respect to pressure in isentropic coordinates is defined as

$$\omega = \left(\frac{\partial p}{\partial t}\right)_\theta + \mathbf{V} \cdot \nabla_\theta p + \frac{\partial p}{\partial \theta}\frac{d\theta}{dt} \qquad (4)$$

A **B** **C**

where **V** is the velocity vector for the wind and the other symbols have been previously defined. The terms **A**, **B**, and **C** will be described below.

Local Pressure Tendency **A**: This term represents the effect of an isentropic surface moving up or down at specific point. A rising surface generates $\omega < 0$ and a sinking surface gives $\omega > 0$. (Note that $\omega < 0$ is upward vertical motion and $\omega > 0$ is downward vertical motion.)

Advection of Pressure on an Isentropic Surface **B**: This term can be understood by analyzing the cross isobar flow on a isentropic surface. Thus, air flowing from high to low pressure results in upward vertical motion or $\omega < 0$, and air flow from low to high pressure represents downward vertical motion or $\omega > 0$. Remember, isobars are like isotherms on an isentropic surface, and the previous description is essentially warm air and cold air advection respectively.

Diabatic Heating and Cooling Term **C**: Diabatic heating and diabatic radiative cooling contribute to ω. This plays a more minor role when dealing with synoptic scale systems and outside of convection.

The dominant term above tends to be **B**, especially if wind speeds are large and streamlines defining the flow are at an appreciable angle (more perpendicular) to the isobars on an isentropic surface. Thus, this term provides for a good approximation of ω (Kapela and Van Ess 1990). With an approaching cold air dome and appreciable wind, one would expect substantial downward vertical motion.

As a cold air dome begins to build and move toward a particular point, pressure rises at the surface correlate to strong upstream cold air advection. This cold air dome building signifies that both the slope and the height of isentropic surfaces are increasing with time. Isentropic surfaces rise to higher levels and create a **steep** slope. Recall that changes in M with time are related to changes in temperature and height of an isentropic surface with time. These changes in the relative position of isentropic surfaces produce an isallobaric wind which would accelerate air parcels down the surface in this situation. With this transport of air from a high level to a low level, it is apparent that a transfer of higher momentum air would occur and be brought down toward the surface.

E) Words of Caution

It is important that forecasters use caution when applying isentropic analyses in regions where: 1) the air is saturated; 2) where convection may occur; 3) near the ground where strong radiational heating and cooling may occur; and 4) when a synoptic system is moving rapidly. The first three points of caution are diabatic factors which violate the isentropic assumptions. This result is that an air parcel will move from one isentropic surface to another. These factors, however, are mitigated when analyzing a system on a synoptic spatial and temporal scale (Moore 1993). In this case study, pre-frontal and post-frontal precipitation were not widespread in the area of concern, a θ surface was chosen away from the ground as much as possible, and convection was isolated. Point four refers to the speed of the synoptic system. In certain cases, it is possible that (equation 4) term **A** could dominate term **B** for a fast moving system, resulting in upward vertical motion. However, in this case study, term **B** is substantially large due to the tight isobaric gradient and cross isobar flow.

The Event

The event that occurred in early June in eastern Nevada and northwest Utah was associated with a late spring weather system with winter-like characteristics. A cold air mass was moving in from the Pacific Northwest into the Great Basin. Sustained winds in the 40 to 50 kt range lasted for several hours in the area of concern after frontal passage. Of course, one could examine this synoptic system by means of pressure surfaces, surface analyses, etc. However, as will be shown, one can study this weather system by isentropic surfaces and have a three dimensional depiction of the atmosphere. As was stated earlier, the Eta model proved to be the model of choice because of its consistency. The following graphics were taken from PC-GRIDDS. Model runs from 0000 UTC 4 June, 1200 UTC 5 June , and 0000 UTC 6 June have been used. The event occurred Monday afternoon around 0000 UTC 6 June . Thus, for each model run above, the forecast time was selected (except 0000 UTC 6 June which is the initialization) to correspond on Monday afternoon. This will show how consistent the model was at providing an indication of a wind event. Moreover, other graphics will be displayed to add support for isentropic analysis usefulness.

48 hr forecast from 0000 UTC 4 June: Figure 1a

The 305 K surface was chosen in order to approach the earth's surface (but not intersecting it) at a particular observing location that experienced gusty winds with frontal passage Monday afternoon. This location was Wendover, Utah which is near the Nevada border (near 41° N, 114° W). The isobars defining the surface are contoured every 30 mb and winds are placed at their respective pressure levels. One can roughly envision streamlines with the wind flow (assuming geostrophic). Remember, lower values of pressure are like "hills" and higher values are like "valleys." This will help with visualizing in 3-D.

Note the compacted isobars in eastern Nevada/northwest Utah area. This is indicative of a baroclinic zone. Also, observe that the flow is downslope, i.e., from low to high values of pressure. Recalling the equation for vertical motion in isentropic coordinates, it is apparent that the **B** term or pressure advection is significant with the cross isobar flow. Hence, one would be inclined to predict some windy conditions behind the front, especially with 25 to 30 kt winds advected down the isentropic surface. In addition, observe that as the cold air dome moves southeastward, the local temperature and height of the isentropic surface would decrease and increase, respectively, due to cold air doming (Kapela and Van Ess 1990). The local air temperature decreases (with time) because the surface is located higher in the atmosphere. Thus, according to the definition of an isallobaric wind, this component would be generated due to the cold air dome moving towards a particular location with time (Kapela and Van Ess 1990). One can see the cold air dome clearly from the 420 mb pressure contour over Oregon/Washington, then rapidly increasing to 750 mb contour over Nevada/Utah. In this figure, it is also important to see that there is a weaker gradient in the isobars over Montana and Idaho with lighter downslope winds. This will be compared to the actual surface plot later to show that winds were not strong in Montana and Idaho with frontal passage as they were in eastern Nevada/northwest Utah.

12 hr Forecast from 1200 UTC 5 June: Figure 1b

This run clearly depicts the front and cross isobar flow over the area in discussion. Strongest winds are advected downslope in eastern Nevada/northwest Utah where there is a strong thermal gradient. Again, winds are much weaker in Montana and Idaho and parallel to the less steep slope there.

Initialization from 0000 UTC 6 June: Figure 1c

The initialization of the wind event is not as impressive as the previous forecast runs. However, it continues to show the tightest gradient and 25 to 35 kt winds advected downslope in the area of discussion. Notice still that the gradient is not as pronounced in Montana and Idaho as well as the wind flow.

6 hr Forecast from 0000 UTC 6 June: Figure 1d

In this final forecast, observe that the frontal boundary shifts eastward and 25 to 45 kt winds are advected into Utah where the wind event lasted into the late evening. Again, wind flow and gradient remain not as pronounced in Montana and Idaho, while cross isobar flow remains substantial over northwest Utah.

A few more graphics from PC-GRIDDS will be examined to supplement the discussion on isentropic analysis.

Figure 2a:

This cross section of isentropic surfaces (from 0000 UTC 6 June) shows the cold air dome to the west of the wind event area. The cross section is roughly along 41° N and between 120° W and 110° W. A line has been drawn on the 0000 UTC 6 June initialization to show approximately the location of the cross section (Fig. 1c). Notice the slope of the surfaces towards (in particular) Wendover, Utah (41° N, 114° W). Clearly, one can see that transferring higher momentum air from upper levels is likely with this slope.

Figure 2b:

Figure 2b shows pressure advection by the total wind on the 305 K surface from the 12 hr forecast 1200 UTC 5 June. This graphic represents term **B** in equation (4), and it clearly displays a quantitative value of **B**. Downward vertical motion is depicted by positive values with dashed lines, while upward vertical motion is depicted by negative values with solid lines. Maximum downward vertical motion for Monday afternoon due to the advection of pressure by the total wind is forecast for eastern Nevada. This is indicated by the + 9 maximum. Hence, this supports quantitatively that the advection of pressure by the total wind is indeed the greatest in the area of discussion.

Figure 2c and 2d:

In **Figure 2c**, the 48 hr 850 mb temperature and winds are shown (from 0000 UTC 4 June). This is a conventional method for analyzing fronts. It is apparent that the 850 mb winds and thermal gradient portray a cold front in the area of discussion, but the winds behind the cold front are only forecast to be in the 20 to 25 kt range. Also, compare this to the 305 K surface for the same forecast time period. The 305 K surface depicts a more detailed picture of the atmosphere because of its 3-D appeal. One can see the transfer of air parcels down the isentropic surface. In **Figure 2d**, the 850 mb temperature and winds from the initialization are shown. This also shows a cold front in the area of discussion, and the temperature gradient and winds are similar to the 48 hr forecast. Compare this to the initialization of the 305 K surface. Clearly, the 305 K surface has a better depiction of the cold front and a more logical explanation for the high winds generated behind the cold front.

Actual surface analyses of the wind event will now be presented in order to show what actually transpired at the surface. Surface plot charts (AFOS graphic P0A) are used, and a cold front has been drawn to show frontal position.

In **Figure 3**, at 1800 UTC 5 June or early Monday afternoon, wind speeds had increased (increase not shown from previous plot chart) behind the cold front at Winnemucca (WMC) and Ely (ELY), Nevada, and ahead of the cold front at Salt Lake City (SLC), Utah. Note the -2.9 mb pressure fall at SLC and the +1.7 mb rise at WMC over the last three hours. Compare this to similar pressure rises and falls over Montana and Idaho, but the winds were not as strong over this region. Also, Wendover (ENV) was reporting wind speeds less than 10 kts.

In **Figure 4**, at 0000 UTC 6 June or Monday afternoon, notice the significant change in the wind speed. The front has progressed into northwest Utah, and its passage is apparent at Wendover. In fact, Wendover was experiencing strong wind speeds around 55 kts **sustained**. The pressure fall of -4.4 mb at SLC and pressure rises of +4.6 mb and +7.6 mb in southern Idaho are quite interesting, leading one to conclude strong vertical motion ahead (rising air) and behind (sinking air) the cold front. Observe the strong contrast in temperature from Nevada and Utah and also from Idaho to eastern Montana. One usually concludes that where strong temperature gradients exist, there will be a strong pressure gradient, hence strong winds. However, in this case, we see a strong temperature gradient over the region, but the strongest winds are found in eastern Nevada and northwest Utah (corresponding to the significant pressure falls and rises). Recall that the isentropic surface forecast for this time was not as steep over Idaho and Montana and quite steep over eastern Nevada and northwest Utah. This seems to support a momentum transfer of air along an isentropic surface as well as the generation of an isallobaric wind with the approach of the cold air dome in the wind event region.

In addition to the surface plots, observations reported from Wendover are included as **Table 1.** The observations show that strong sustained winds lasted three to four hours after frontal passage. A maximum wind gust of 69 kts (79 mph) was reported. Also, the local storm report from SLC is displayed in **Table 2** to show how severe the wind event was across northwest Utah. Several high wind advisories and warnings were issued by the SLC forecast office in response to the strong winds that occurred behind the cold front.

At this point, it is important to mention that terrain may have had an added effect to the wind event. The winds generated from an isallobaric wind and the transfer of higher momentum air could have been supplemented by the high terrain of eastern Nevada to the salt flats of northwest Utah. In this case, air could have had an added acceleration from this abrupt change in elevation. In addition, some channeling of air could have taken place. All in all, the downward movement of air parcels on an isentropic surface along with terrain effects seem to be a logical explanation of the wind event studied here.

Conclusion

The use of isentropic analysis to study and forecast weather has gained more popularity over the last few years with the advent of a computer's ability to generate the data. Through this case study, one can see that isentropic analysis is a three dimensional approach of analyzing the atmosphere compared to the "old fashioned" two dimensional pressure surfaces. Isentropic analysis allows the forecaster to view the atmosphere like it should be, and it can be a useful tool not only for wind but for an array of parameters. Granted, more case studies need to be documented to show isentropic analysis usefulness. Hopefully, the reader has been intrigued to pursue isentropic analysis as a forecasting tool for synoptic scale events.

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References

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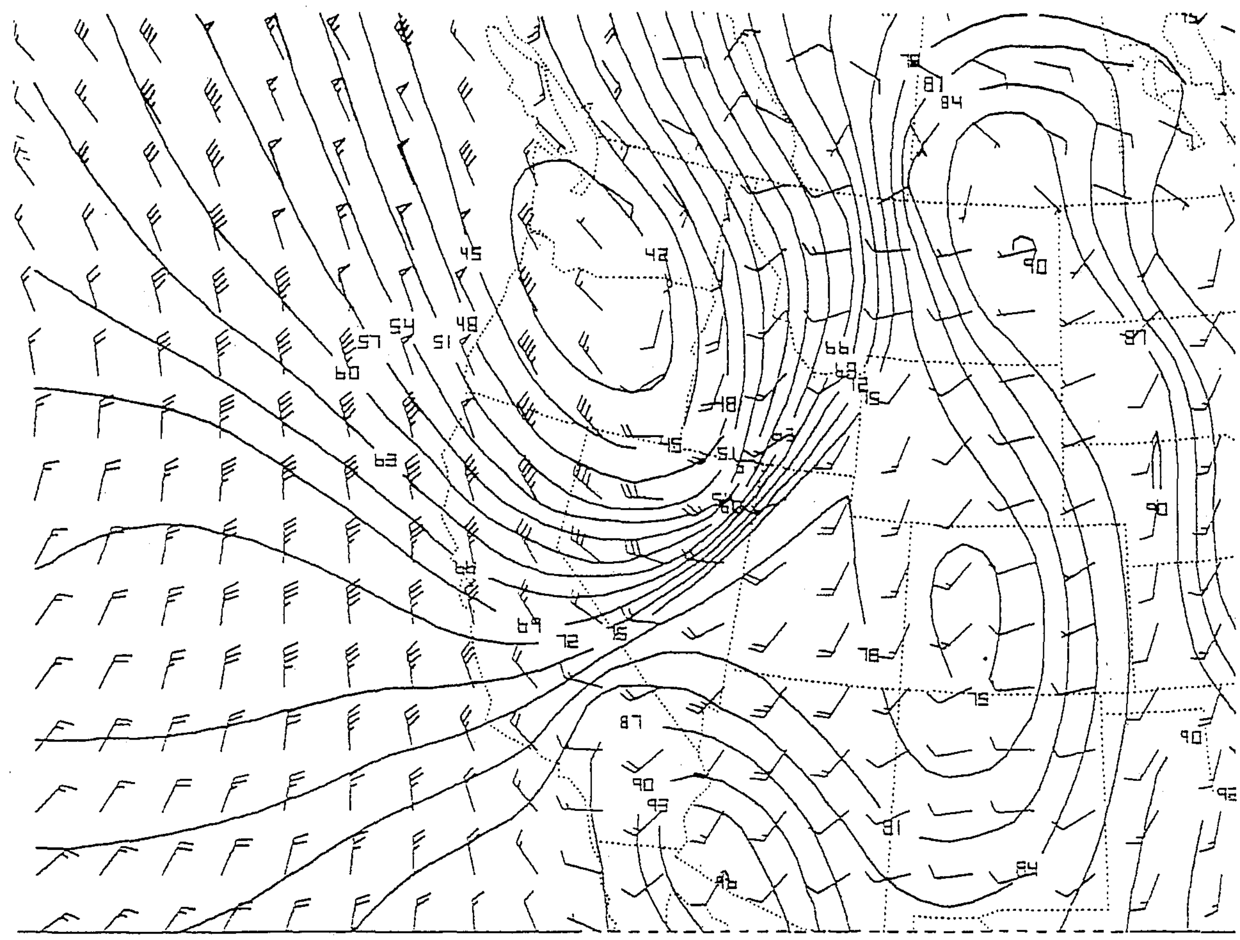
Holton, J.R., 1993: *An Introduction to Dynamic Meteorology*, 3rd ed., Academic Press, Inc., San Diego, 52.

Kapela, A. F. and R. L. Van Ess, 1990: A 3-D Isentropic Interpretation of the Isallobaric Wind Behind Cold Fronts. Unpublished, 17 pp.

Moore, J. T., 1993: Isentropic Analysis and Interpretation: Operational Applications to Synoptic and Mesoscale Forecast Problems, Saint Louis University, Dept. of Earth and Atmospheric Sciences, St. Louis, MO, 98 pp.



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95/ 6/ 4/ 0--PRES CI30&BKNT

Fig. 1a. Eta 48 hour forecast for the 305 K surface, isobars (solid lines; contour interval 30 mb) and winds (knots) valid 0000 UTC June 6, 1995.

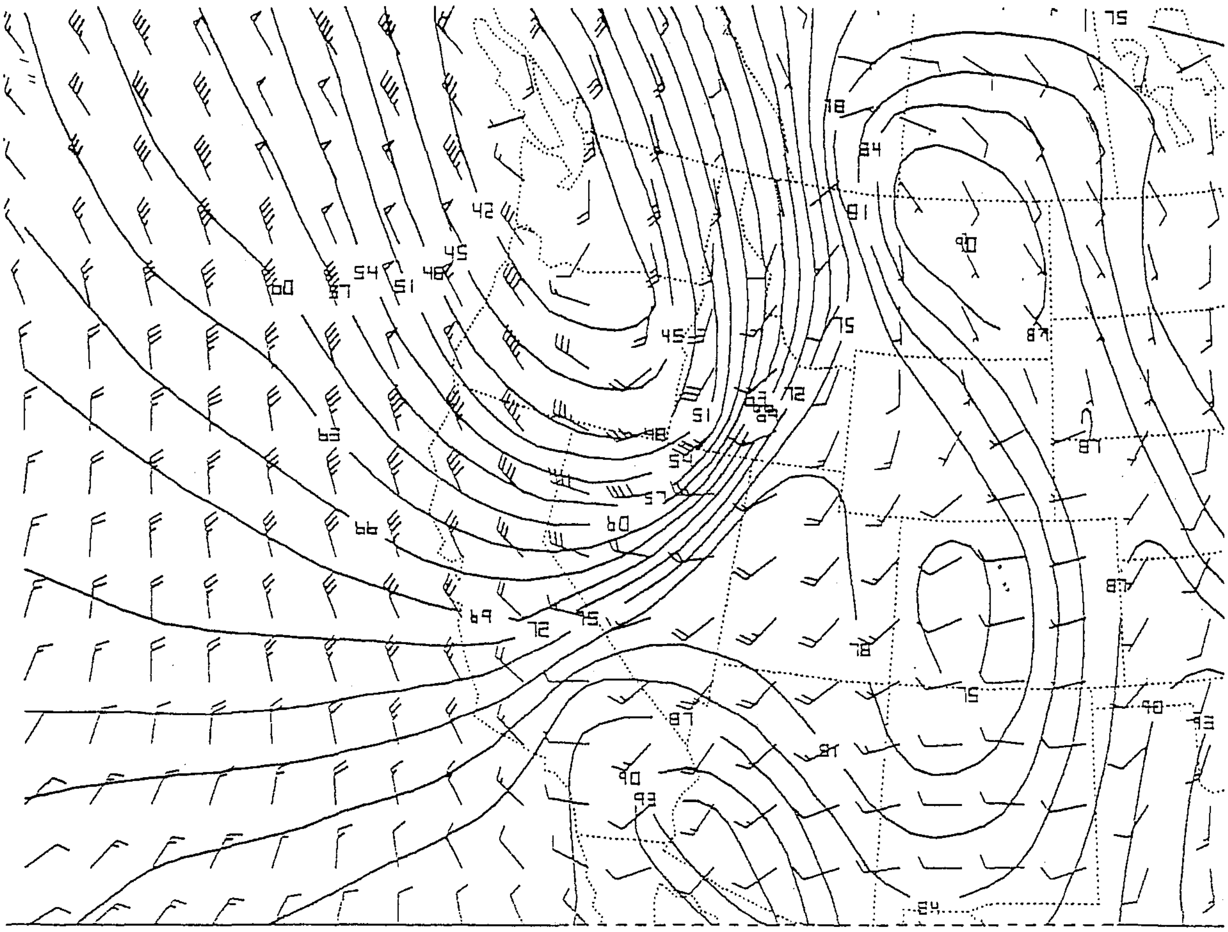

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Fig. 1b. Eta 12 hour forecast for the 305 K surface, isobars (solid lines; contour interval 30 mb) and winds (knots) valid 0000 UTC June 6, 1995.

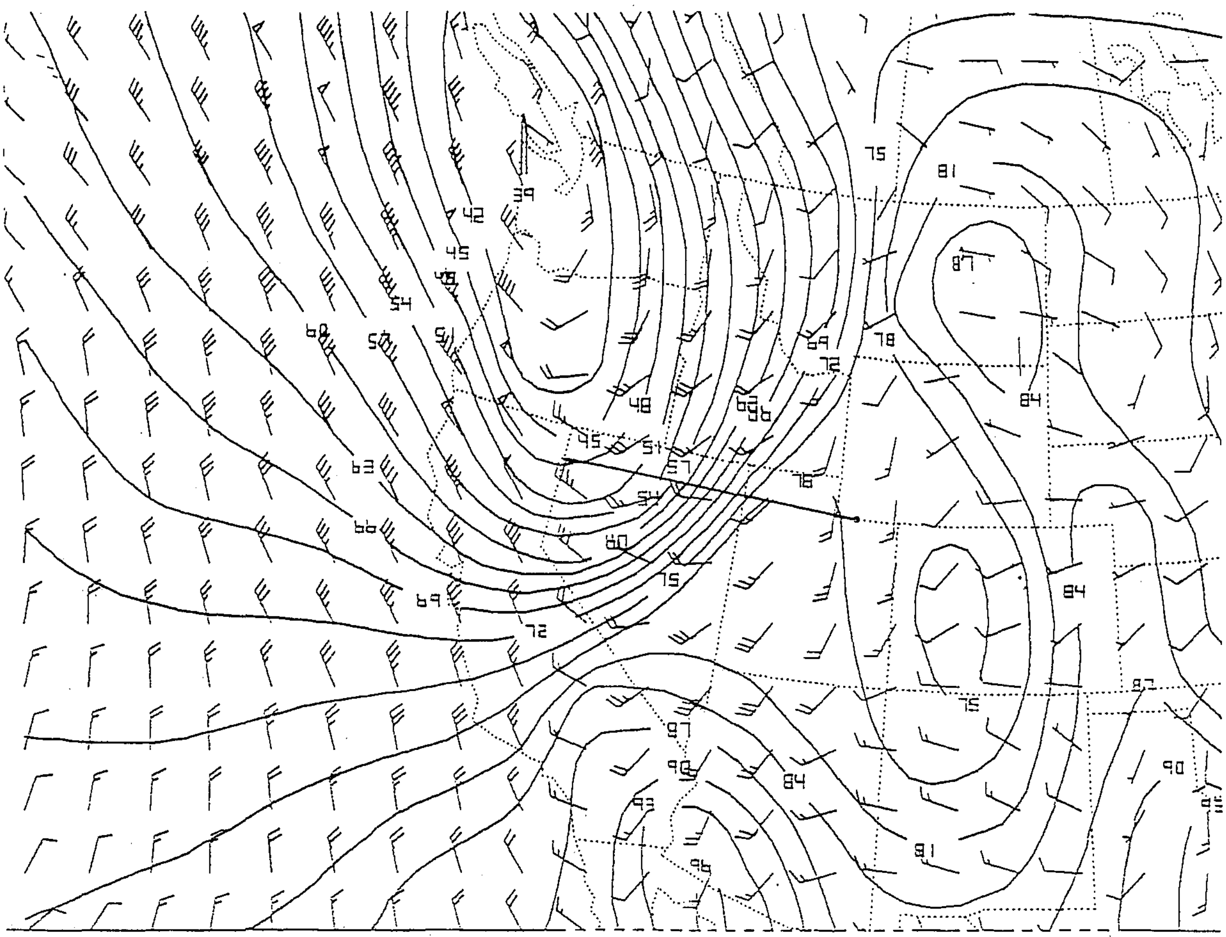

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Fig. 1c. Eta 00 hour forecast for the 305 K surface, isobars (solid lines; contour interval 30 mb) and winds (knots) valid 0000 UTC June 6, 1995.

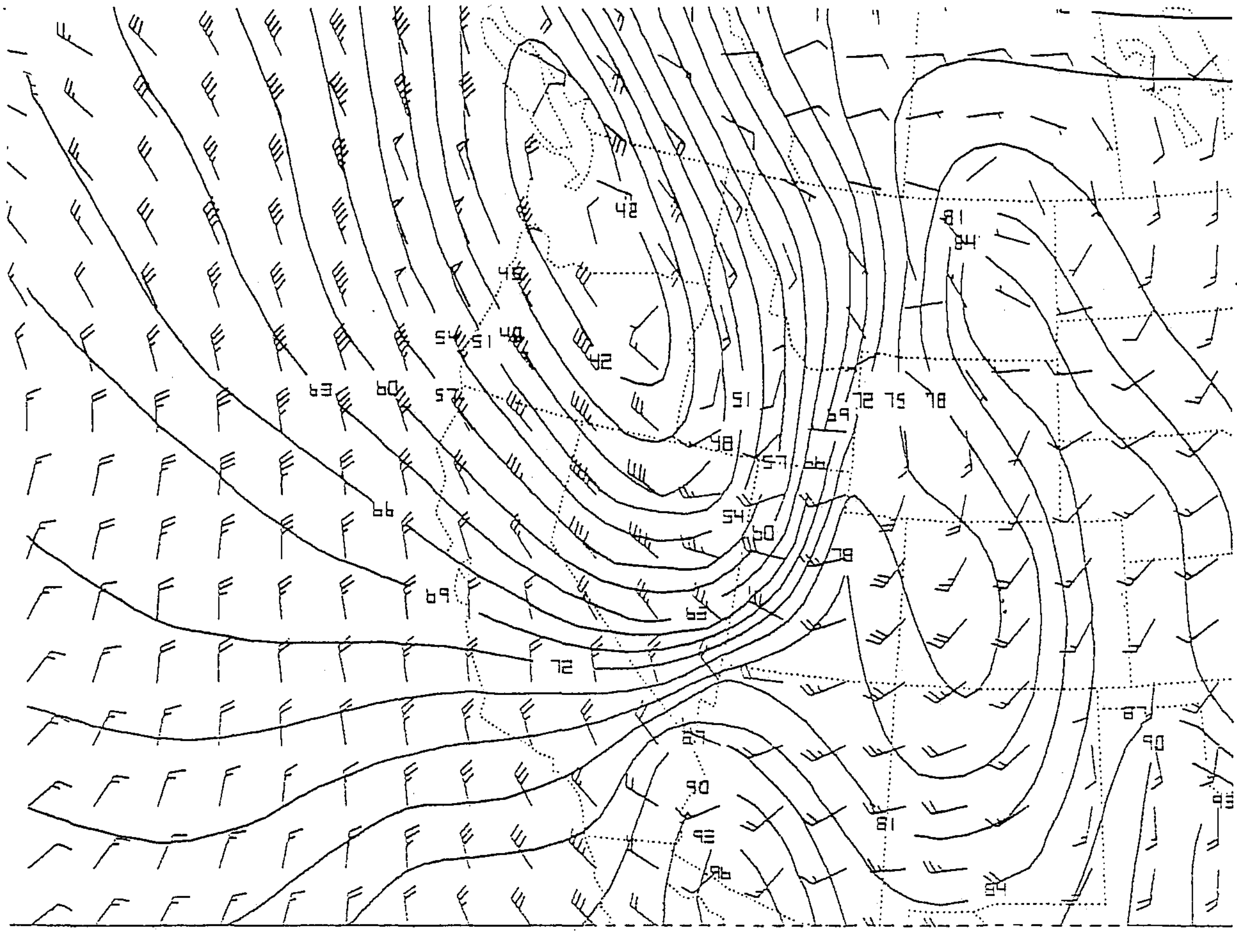

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Fig. 1d. Eta 06 hour forecast for the 305 K surface, isobars (solid lines; contour interval 30 mb) and winds (knots) valid 0600 UTC June 6, 1995.

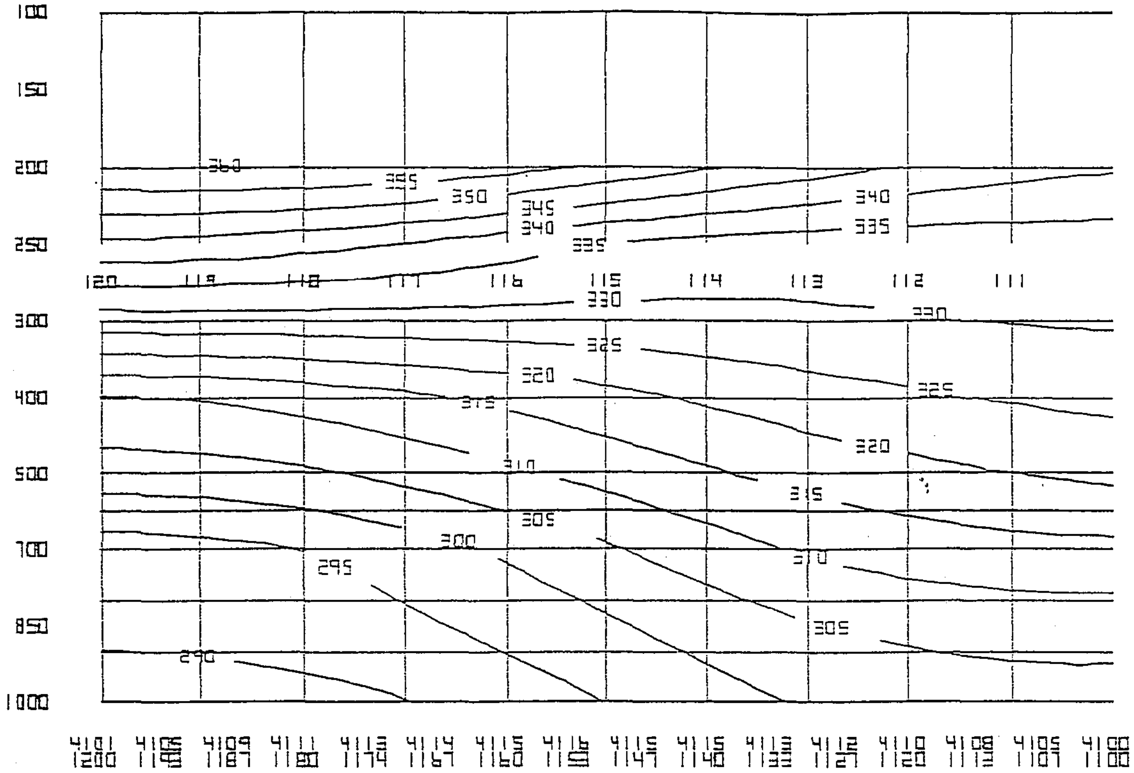

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Fig. 2a. Eta 00 hour forecast of isentropic surfaces (cross section) along 41° N and between 120° W and 110°W valid 0000 UTC June 6, 1995.

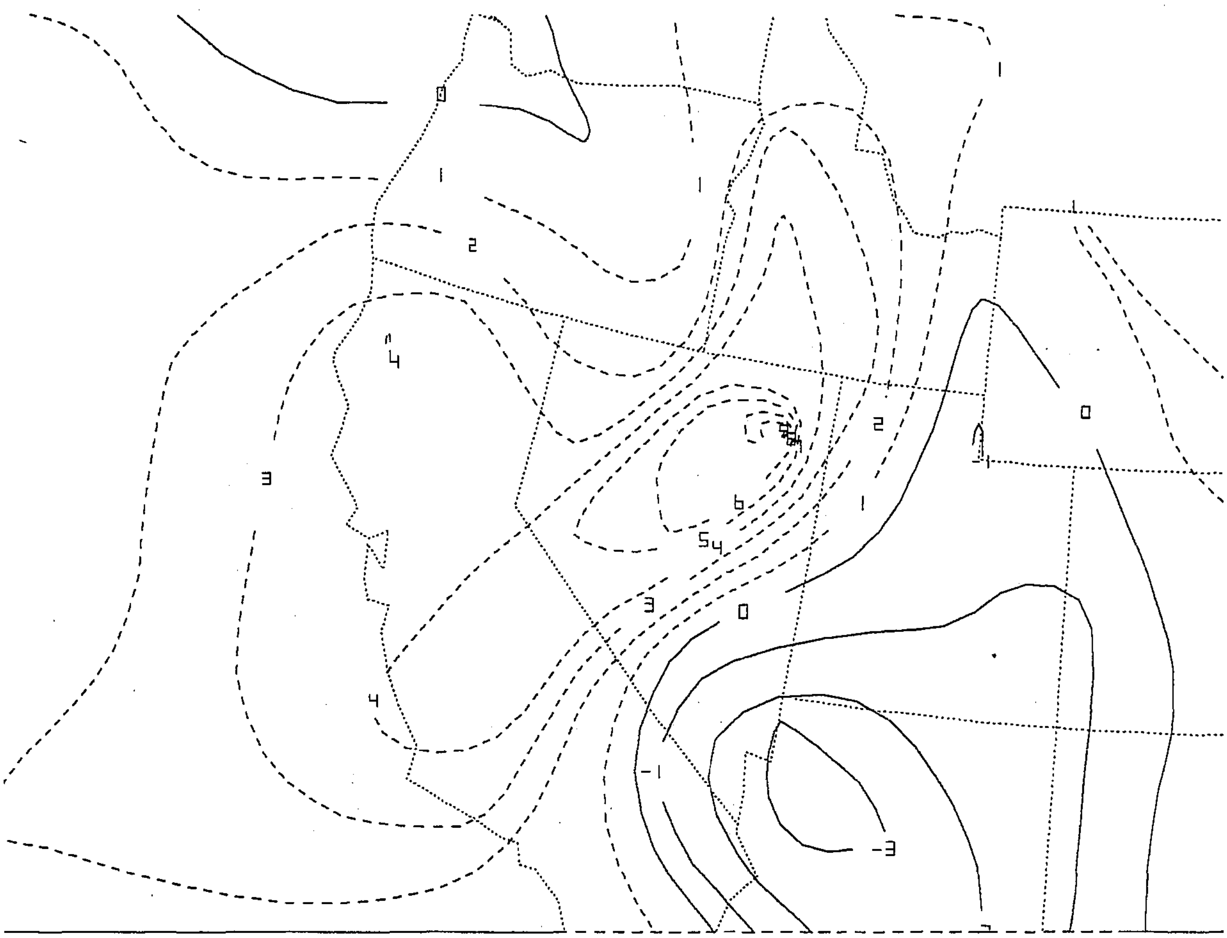

Fig. 2b. Eta 12 hour forecast of pressure advection by the total wind (solid lines with negative values represent -ω and dashed lines with positive values represent +ω) valid 0000 UTC June 6, 1995.

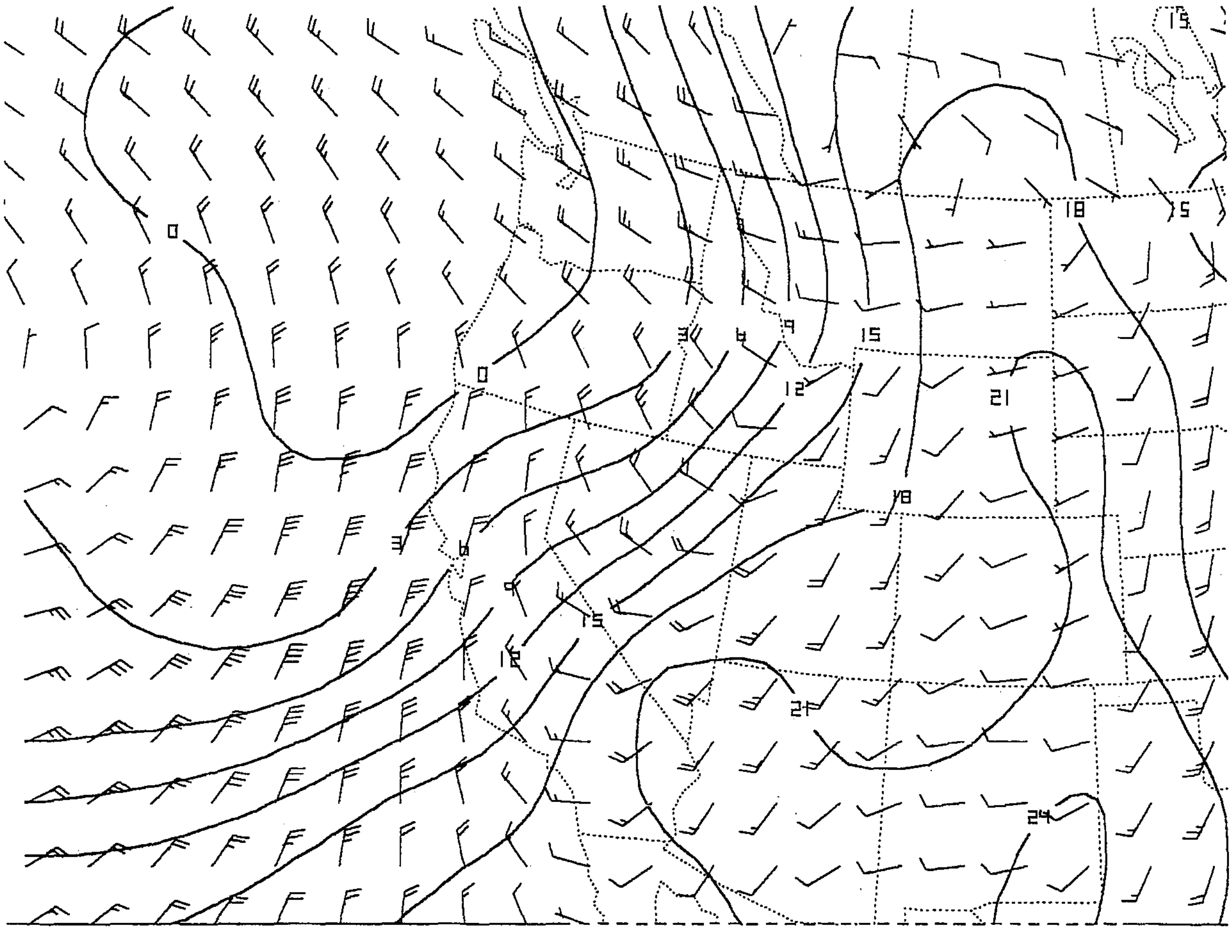

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Fig. 2c. Eta 48 hour forecast 850 mb temperature (solid lines; contour interval 3°C) and winds (knots) valid 0000 UTC June 6, 1995.

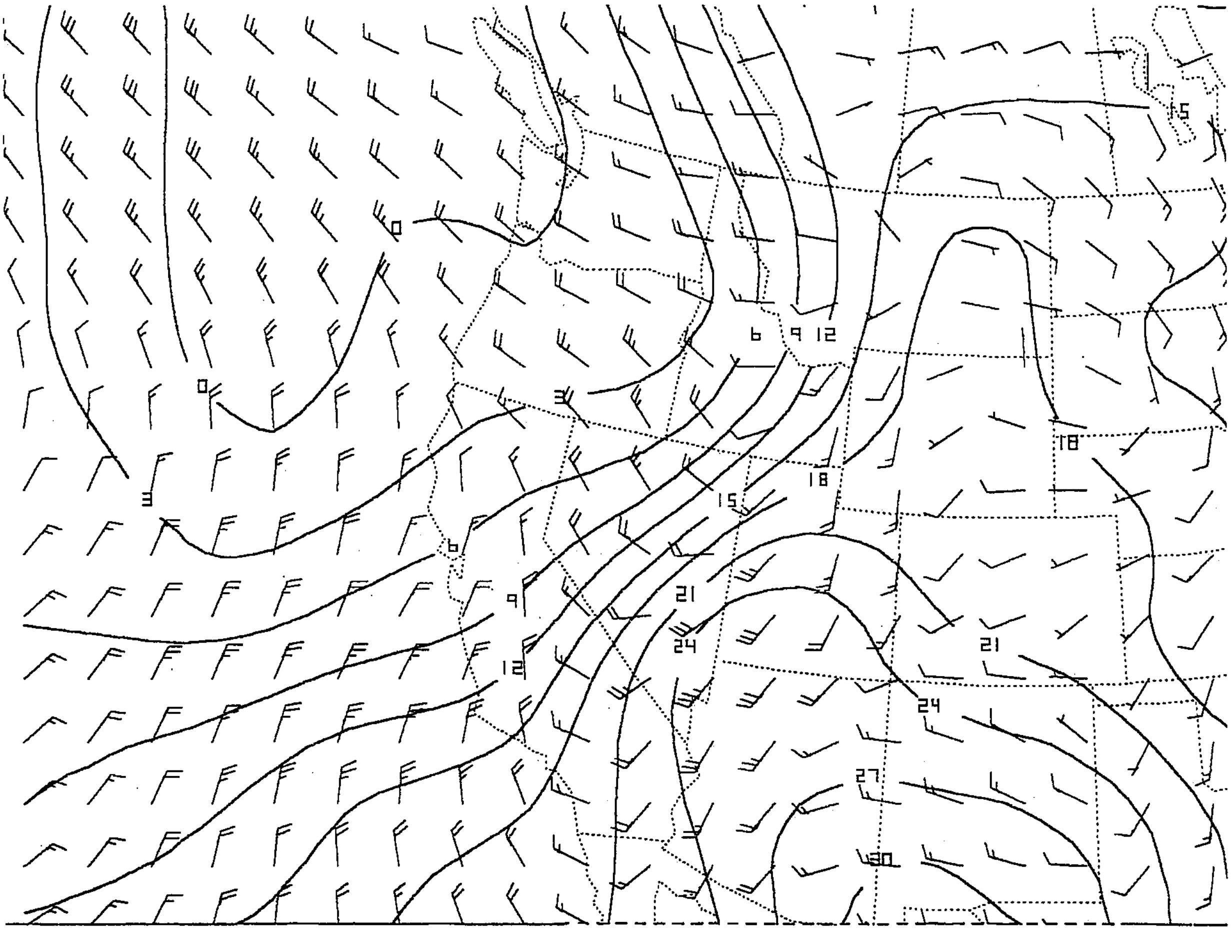

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Fig. 2d. Eta 00 hour forecast 850 mb temperature (solid lines; contour interval 3 °C) and winds (knots) valid 0000 UTC June 6, 1995.

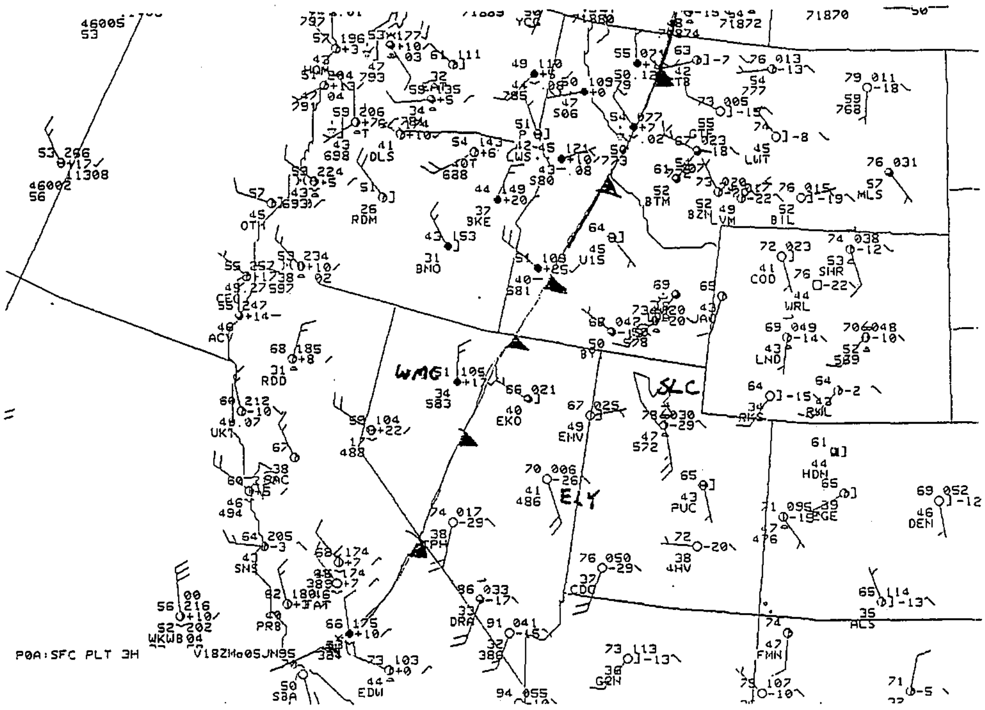

Fig. 3. Surface analysis valid 1800 UTC June 5, 1995.

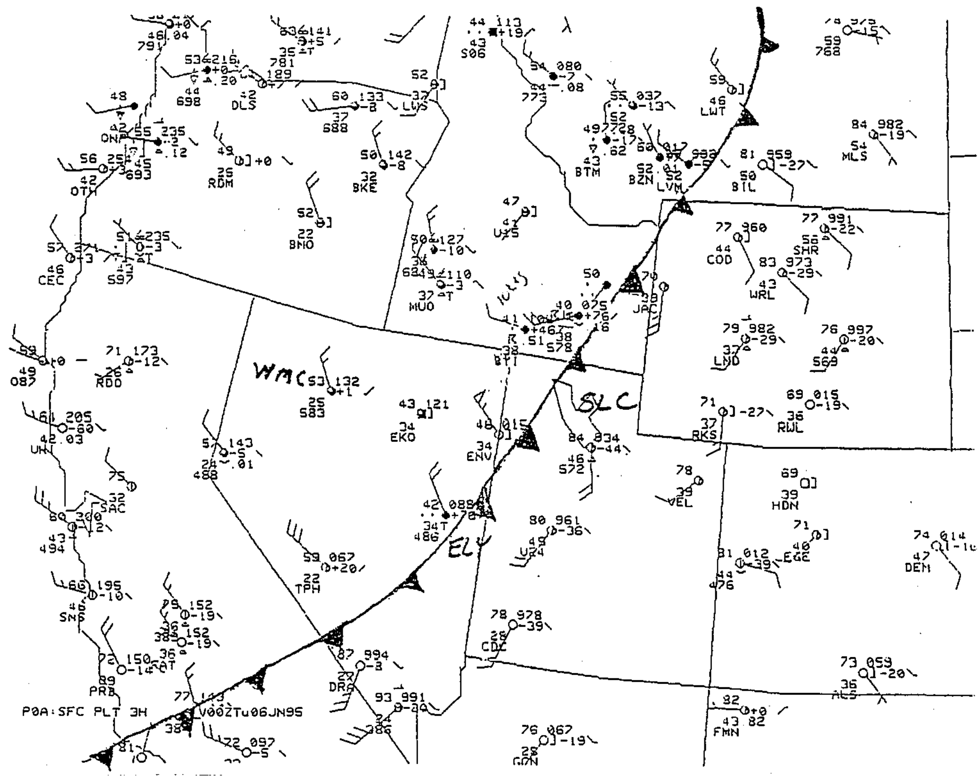

Fig. 4. Surface analysis valid 0000 UTC June 6, 1995.

ENV SA 2055 AWOS CLR BLO 120 10 77/51/2606/951

ENV SA 2115 AWOS CLR BLO 120 10 76/50/2606/949

ENV SA 2135 AWOS CLR BLO 120 10 78/47/2703/948

ENV SA 2155 AWOS CLR BLO 120 10 68/42/3248G56/951

ENV SA 2215 AWOS 110 SCT 61/41/3252G61/952

ENV SA 2235 AWOS 110 SCT 10 56/38/3250G60/954

ENV SA 2315 AWOS M M M/M/3257G65/957

ENV SA 2335 AWOS CLR BLO 120 10 49/32/3245G69/960

ENV SA 2355 AWOS CLR BLO 120 10 46/34/3253G68/962

ENV SA 0035 AWOS M M M/M/3247/968

ENV SA 0055 AWOS 16 SCT 35 SCT 85 SCT 10 43/34/3240G55/974

ENV SA 0115 AWOS M M 42/35/3232G42/977

ENV SA 0135 AWOS 42 SCT 48 SCT 10 42/34/3221G36/980

ENV SA 0155 AWOS 40 SCT 10 43/35/3219G29/982

ENV SA 0215 AWOS CLR BLO 120 10 43/33/3318G41/984

ENV SA 0235 AWOS 29 SCT 10 44/32/2804G15/988

ENV SA 0255 AWOS 29 SCT 10 44/33/3109G14/990

Table 1. Surface observations for Wendover, Utah from 2055 UTC June 5, 1995 to 0255 UTC June 6, 1995.

SEVERE WEATHER REPORTS FOR JUNE 5, 1995 FROM SLC NWSFO

LOCATION/COUNTY	TIME (MDT)	EVENT AND DAMAGE
SALT LAKE	4:00 PM	KEARNS: WIND GUST FROM SW 57 MPH
BOX ELDER	4:32 PM	SNOWVILLE: WIND GUST 62 MPH
BOX ELDER	5:25 PM	LAKESIDE: WIND GUST TO 50 KTS
CACHE	5:52 PM	LEWISTON: WIND GUST FROM N 71 MPH
TOOELE	6:00 PM	SALT PLANT: WIND GUST 55 KTS
CACHE	6:01 PM	TREMONTON: WIND GUST 95 MPH
SALT LAKE	6:28 PM	MAGNA: WIND GUST 58 MPH
WEBER	6:30 PM	FAR WEST CITY: WIND GUST 54 MPH
SALT LAKE	6:34 PM	WEST KEARNS: WIND GUST 84 MPH
SALT LAKE	6:48 PM	KEARNS: WIND GUST 65 MPH
SALT LAKE	6:53 PM	SOUTH JORDAN: WIND GUST FROM WNW 62 MPH
SALT LAKE	6:58 PM	WEST VALLEY: WIND GUST 62 MPH
SALT LAKE	7:27 PM	SOUTH JORDAN: WIND GUST 66 MPH
MILLARD	7:37 PM	DELTA: WIND GUST 50 KTS
SALT LAKE	7:51 PM	PLEASANT GROVE: WIND GUST 65 MPH
SALT LAKE	8:18 PM	KEARNS: WIND GUST 72 MPH

Table 2. Severe weather reports for June 5, 1995 from Salt Lake City, Utah NWSFO.