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CONF-9006111-3

APR 0 5 1990

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LA-UR--90-721

DE90 008965

TITLE: AN ANOMALOUS WIND BETWEEN VALLEYS - ITS CHARACTERISTICS AND A PROPOSED EXPLANATION

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SUBMITTED TO: Mountain Meteorology, June 25-29, 1990  
Boulder, CO

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# An Anomalous Wind Between Valleys— Its Characteristics and a Proposed Explanation

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## 1. Introduction

Beginning in 1986, the US Army engaged the Los Alamos National Laboratory to study meteorological operations at several sites where toxic materials are stored. The main objective of the study was to develop recommendations for a system that could forecast the transport and dispersion of airborne materials in the event of an accident. In the course of that project, detailed meteorological and tracer experiments were conducted at the Army's Tooele Depot, 60 km southwest of Salt Lake City, Utah.

During these investigations we observed that the direction of near-surface flow through low passes connecting two adjacent valleys is often opposite to the prevailing gradient flow. In this sense, the wind was considered "anomalous." In this paper we discuss the statistical properties of this intervalley flow and use a case study to illustrate its vertical structure in relation to the surrounding terrain and the overlying gradient flow. A simplified analysis of the thermal energy changes in the valley atmospheres is used to explain the origin of this local flow.

## 2. Site Description

Early in the design of the field investigations in the Tooele area, attention was given to the possible transport routes for material accidentally released from the South Area in Rush Valley (Fig. 1). Because the prevailing gradient flow over the area often has a westerly component, the low passes extending south of the Oquirrh Mountains were considered a likely transport route. Consequently, a meteorological station was in-

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stalled in Fivemile Pass to document the expected westerly flow. This installation, referred to as station 3, was located 1.5 km west of and 10 m below the divide. Wind and temperature were observed at 10 m above the ground at this well-exposed site from December 1986 to early August 1987.

Terrain and differences in surface characteristics will play a major role in interpreting our observations. West of Fivemile Pass is Rush Valley, a high semiarid basin with a narrow outlet to the north. Most of its floor is 1520 m above sea level (ASL), which is 240 m above the Great Salt Lake and 150 m above Utah Lake. The valley floor is covered mostly with a sparse growth of grease-woods and sagebrush.

East of the pass is Cedar Valley, which we consider part of the great Utah Lake Basin. In contrast to Rush Valley, about 30% of the basin's floor is covered with water, with additional acreage under irrigation. The Wasatch Mountains lie to the east, forming an extensive airshed for katabatic flow into the basin through several large canyons.

### 3. The "Anomalous" Wind

The 700-mb pressure surface is normally found just below the major summits of the region. The wind at this level is considered representative of the large-scale flow, and we refer to it as the gradient wind. The gradient flow over northern Utah often has a westerly component, which lead us to expect channelled westerly flow through Fivemile Pass. However, an 8-month record of winds through the pass shows that the prevailing wind direction is ENE. We will refer to these anomalous winds as easterlies in the discussion that follows.

Attempts to relate wind direction in the pass to the 700-mb pressure gradient were not successful. In our 8-month sample, northern Utah was often under the trailing edge of a 700-mb ridge, and gradient winds were southwesterly. Under such a pressure pattern there is a westerly component to the pressure gradient that might drive ageostrophic easterly surface winds. However, easterlies were also observed when the ridge was upstream of the area and the pressure gradient was easterly. In summary, there seemed to be no way of predicting the surface wind direction in the pass based on 700-mb charts. (In our discussion of pressure gradients here, and in dis-

cussing temperature gradients below, the gradient is in the direction of increasing values of the scalar in question. For example, an easterly, or W-E, gradient means that the scalar increases to the east.)

We conducted a series of kite experiments to more fully document the easterlies in Fivemile and neighboring passes. These investigations, and one month of observations in Twelvemile Pass, established the fact that what we were observing in Fivemile Pass was representative of what was happening in all the passes that span the 20-km gap between the Oquirrh and East Tintic Mountains.

### *3.1 Statistical Properties*

Wind roses for direction for station 3 and adjacent sites are shown in Fig. 2a–d for selected time periods. Figure 2a represents the flow during the early morning hours, when katabatic flow is often well established in the valleys of the region. By late morning (Fig. 2b), katabatic flow weakens and ceases. During this period the frequency of occurrence of the easterlies at station 3 reaches a maximum value of 36%. In the 12–16-MST time period (not shown), the occurrence of easterlies drops to 27%. But by late afternoon (Fig. 2c), when up-valley flow has developed throughout the region, the frequency of occurrence again reaches 36%. [See Stone and Hoard (1990) for a discussion of daytime winds in the region.] In the late evening (Fig. 2d), when katabatic flows are again developing in the valleys, the occurrence easterlies drops to its minimum value of 23%. Overall, easterlies at station 3 occur about 30% of the time.

Probability density functions for wind speed when the wind direction was NE to ENE show that a speed of 3 to 4 m/s is most probable; these winds rarely exceed 5 m/s or are less than 2 m/s. Daytime easterlies average about 3.5 m/s and nighttime easterlies average about 3 m/s.

Histograms for time of onset and cessation of easterlies are shown in Fig. 3. In this analysis, we defined onset as the time the wind direction changed from any value in the SE-to-N sector to values in the NNE-to-ESE sector and remained in that sector for at least 2 h. Similarly, when the wind moved out of the NNE-to-ESE sector and stayed out for at least 2 h, we counted the

event as a cessation.

The most striking features of these distributions are the frequent onsets in the morning hours and the frequent cessations around noon and early in the evening. A less prominent feature is the slight increase in frequency of onsets between 14 and 17 MST. The distributions suggest that surface heating in the morning plays an important role in the development of easterlies at station 3. However, the vertical mixing that accomplishes the heating also imports air with westerly momentum from the gradient flow aloft, and this flux of momentum may cause the frequent cessations observed in late morning. When mixing subsides in the afternoon, easterly flow often resumes for a while and then ceases again in early evening.

### *3.2 A Case Study*

We will use the NE wind event of August 4 and 5 to illustrate many of the features discussed above. Figure 4 presents a record of the the 700-mb wind, the Fivemile Pass wind direction, valley-bottom air temperatures for Rush and Cedar valleys, and the pressure difference between the two valleys.

The 700-mb wind during this event, shown across the top of the figure, was backing from NNW at 6 m/s (at 05 MST, August 4) to WSW at 9 m/s (at 05 MST, August 5).

The wind direction in the pass is SW at the beginning of the record, changing abruptly to NE about 3 h after sunrise on August 4; this is an example of a morning onset as discussed above. In this example, the cessation that often occurs around noon occurs later, after which westerly flow is observed for about 2 h. NE flow resumes later in the afternoon, disappears for a few hours in the early evening, and then develops again in the early morning hours of August 5. The wind record for a station in Twelvemile Pass shows similar behavior, so this easterly flow apparently extended across the whole gap between the Oquirrh and East Tintic Mountains. (The wind speed trace is not shown because it did not reproduce clearly, and it adds little to the interpretation.)

The temperature data in the figure are from 10-m towers located close to the bottoms of Rush and Cedar valleys; the Rush Valley station is 49 m higher than the

one in Cedar valley. The feature of interest here is the rapid relative warming of the Rush Valley atmosphere in the morning hours. This rapid warming of the air in Rush Valley was also noted in a study of NE wind events in March, and we believe that this rapid heating is an important characteristic of the Rush Valley atmosphere.

The pressure difference between the two valleys was measured to help determine the pressure gradient force and to investigate possible phase relations between this force and other variables. Pressure sensors were sited 31.8 km apart along a SW-NE line with station 3 close to the center. The baseline elevation was 1572 m ASL, which is 34 m below Fivemile Pass. One sensor malfunctioned intermittently throughout the experiment and failed completely on August 5. Because of the failure, we were not able to remove possible effects of sensor drift, so the pressure differences reported here may be affected by a small offset. Nevertheless, the trend in the data suggests that there is SW-NE pressure gradient between the valleys, and that the gradient intensifies in phase with surface heating. The gradient reaches a maximum of 0.5 mb/10 km by mid-afternoon. This value is about five times larger than typical synoptic scale pressure gradients but comparable with mesoscale gradients associated with thermally forced wind systems (see, e.g., Atkinson 1981; Ekhardt 1948).

During the first half of the record, the area was under a weak 700-mb high pressure cell with pressure dropping in all directions; across the study area this gradient was less than 0.1 mb/10 km. By 0500 MST on August 5, the high-pressure cell had moved to the SW, and the area was under a weak N-S pressure gradient.

The depth of the NE flow was determined with a series of tethersonde profiles made during the morning of August 5. These observations, and a series of kite experiments earlier in the year, suggest that the easterlies are 300 to 500 m deep. A vertical profile of the E-W component of the wind above the pass is shown in Fig. 5. Here we have superimposed a smoothed profile onto terrain cross-sections to show the relation of the easterlies to the topographic relief and gradient wind.

#### 4. Probable Cause

The cause of the frequent easterly winds through Fivemile Pass has been the subject of much speculation

since they were first observed. Because they are apparently uncorrelated with the 700-mb pressure gradient, they are evidently not driven by dynamic pressure forces arising from the interaction between the mountainous terrain and the large-scale flow. The thesis advanced here explains these winds in terms of locally generated E-W temperature gradients. Considering the daytime easterlies first, we cite topographic reasons why an E-W temperature gradient is expected, give observational evidence for such a gradient, and show analytically how such a gradient might develop and estimate the resulting pressure gradient.

#### *4.1 Topographical Considerations*

There are three reasons why an E-W temperature gradient might develop between the Utah Lake Basin and Rush Valley. First, a large fraction of the Rush Valley floor is 200 m higher than the Utah Lake Basin. Sensible heating of the air above this elevated surface would produce an E-W temperature gradient, and in the absence of strong opposing forces, air would move westward toward the heated region.

Second, as we noted in the site description, 30% of the floor of the Utah Lake Basin is covered with water. Therefore the area-average sensible heat flux for the basin would be less than that over the dry Rush Valley surface. Even if the valley and basin were at the same elevation, we would expect the lake breeze phenomenon to operate.

The third topographic feature that contributes to daytime easterlies is valley geometry. We argue that the net radiative energy load on the valley's surface is proportional to area and that a certain fraction of this energy is dissipated by turbulent sensible heat flux to the valley atmosphere. Therefore, valley top area is a rough measure of the energy input to the valley atmosphere. The ratio of area to volume is then a measure of the amount of heat added per unit volume of the valley atmosphere. We find that on a unit volume, unit time basis, 1.4 times more energy is added to the Rush Valley atmosphere than to that of Utah Lake Basin. (For this analysis, the "top" boundary of the valley is defined by a surface that is horizontal in the E-W direction but whose elevation changes in the N-S direction, taking on the elevation of the lowest ridge line—either the Stans-

bury Mountains on the west or the Wasatch Mountains on the east.)

#### 4.2 *Observational Evidence*

The thesis that rapid heating of the Rush Valley atmosphere in the morning causes the wind is supported by the following observations: (1) easterlies often begin shortly after sunrise; (2) near-surface air temperature in Rush Valley rises faster than that in Cedar Valley; (3) the pressure gradient between the valleys appears to be in phase with the surface heat flux cycle; and (4) the temperature of air entering Rush Valley from the east is colder than the valley air at the same elevation. This last observation was made during a few concurrent tethered flights from central Rush Valley and Fivemile Pass.

#### 4.3 *Analysis*

Further support for the thesis that local differential heating causes the easterlies comes from an analysis of the evolution of the vertical temperature structure in valleys as it develops during the morning. We make the following assumptions:

(1) The thermal energy equation for the valley atmosphere can be expressed simply as a balance between the storage term and the turbulent sensible heat flux term. In other words, we treat the valleys as separate quiescent atmospheres heated from the bottom.

(2) Over land, the sensible heat flux is the same in both valleys.

(3) Over the area covered by Utah Lake, the sensible heat flux is zero night and day.

(4) The energy deficit to the valley atmosphere is proportional to the horizontal extent of its airshed.

The energy input,  $E(t)$ , to the valley atmosphere between sunrise and time  $t$  is given by

$$E(t) = A \int_0^t Q_h dt' \quad (1)$$

where  $A$  is the area of the valley defined by its airshed boundaries, and  $Q_h$  is a representative value of the sensible heat flux density at the surface.

This energy is used first to dissipate the ground-based temperature inversion and then to develop a mixed

layer with a dry adiabatic lapse rate up to elevation  $h$ . The change in the thermal energy storage of the valley atmosphere,  $\Delta S(t)$ , is

$$\Delta S(t) = \overline{\rho c_p} \int_b^h a \Delta T dz \quad (2)$$

where  $\overline{\rho c_p}$  is the layer average product of air density and the specific heat of air at constant pressure;  $\Delta T$  is the change in air temperature of the volume element  $adz$  at height  $z$  above the valley floor between sunrise and time  $t$ ; and  $a$  is the area of the valley at height  $z$ . The limits of integration in  $z$  are from the valley bottom elevation,  $b$ , to the top of the mixed layer at elevation  $h$ .

Equating the right hand sides of (1) and (2), we solve for  $h$ . Above  $h$  the lapse rate is assumed to remain at its presunrise value.

Once the temperature field is known, the pressure at the elevation of interest,  $p(z_1)$ , can be modelled by

$$p(z_1) = p(z_2) \left[ 1 - \frac{\gamma(z_2 - z_1)}{T(z_2)} \right]^{\frac{\gamma_a}{\gamma}} \quad (3)$$

where  $p(z_2)$  and  $T(z_2)$  are a reference pressure and temperature at height  $z_2$ , which is above  $z_1$ .  $\gamma$  is the lapse rate for the layer  $(z_2 - z_1)$ ; and  $\gamma_a$  is the autoconvective lapse rate (Dutton 1976).

Applying the analysis to the Rush Valley atmosphere was straightforward because we had a presunrise temperature profile and a history of the sensible heat flux for a clear day in early August. The integration in (2) was approximated by summing the change in energy in discrete layers of volume  $a\Delta z$ , where  $a$  was area bounded by the valley sides and  $\Delta z = 100$  m. Iterating for increasing values of  $h$  until  $\Delta S(t) = E(t)$  resulted in a mixed layer 1600 m deep at 10 MST.

It was interesting to discover that Eqs. (1) and (2) cannot be applied to a column of unit area. In the center of the valley, where the inversion is particularly strong and deep, the surface flux of sensible heat is insufficient to warm the air in that column at the observed rate. This implies that horizontal fluxes are important in the energy balance of the column and a large-scale redistribution of internal energy occurs within the valley during the heating cycle. However, when the integration is carried out over the entire valley volume, as shown in (1) and (2) the temperature profile evolves in a way

consistent with observed surface temperatures, and the resulting mixing depth is also reasonable.

Using the assumptions mentioned above, we repeated the analysis for the Utah Lake Basin atmosphere. Here we used a temperature profile with the same ambient lapse rate observed high above Rush Valley as a basis for our calculations. The nighttime energy loss was estimated by ratioing the valley top areas. The energy input in the morning was estimated by applying the same heat flux density we observed over Rush Valley to the land surface of the basin. The result is a mixed layer 1400 m deep at 10 MST. This shallower mixed layer with a lower base results in a temperature difference of  $0.7^{\circ}\text{C}$  over a depth of 1100 m above the Fivemile Pass elevation.

The pressure in Rush Valley at the elevation of the pass,  $p(z_1)$ , is evaluated using Eq. (3). Pressure and temperature at the top of the mixed layer are the reference values  $p(z_2)$  and  $T(z_2)$  and  $\gamma$  is set equal to the dry adiabatic value.

In the case of the Utah Lake Basin, the calculation is done in two steps. First, using the same reference parameters, we calculated the pressure at the top of the mixed layer, which is 400 m below the reference elevation. The lapse rate,  $\gamma$ , was set equal to the ambient value over this 400 m layer. Then the pressure and the temperature at this level were used as reference values to estimate the pressure at the Fivemile Pass elevation, 1100 m below in an adiabatic atmosphere. The pressure difference between valleys at height  $z_1$  results in a pressure gradient of 0.13 mb/10 km.

In the absence of friction and large-scale forces, a pressure gradient of 0.13 bm/10 km would accelerate air to 6.5 m/s at the pass. Under the same assumptions, the larger observed pressure gradient (from Fig. 4) would accelerate air to 10 m/s. Unfortunately, there is no simple way of accounting for friction and synoptic forces in this flow, so we cannot proceed further. All we can say is that the observed pressure gradient and the one estimated through an analysis of the temperature fields both produce reasonable velocities for frictionless flow. This analysis suggests that daytime differential heating of the air in the adjacent valleys would lead to pressure gradient forces of sufficient magnitude to drive the observed easterlies.

#### 4.4 Nighttime Easterlies

The cause of the nighttime easterlies through the pass is still a matter of speculation. The topographic considerations discussed in section 4.1 would lead us to expect development of a W-E temperature gradient at night, which would force westerly flow. Two factors, however, work to mitigate the thermal forcing for westerly flow. First, the nighttime sensible heat flux is several times smaller than the daytime flux, so the horizontal variation in the cooling rate is smaller. Second, because the nighttime atmosphere is stable, a large fraction of the energy deficit is concentrated near the valley floor, below the elevation of the passes. Although these factors would mitigate the W-E temperature gradient, they cannot change its sign. Arguments for a change in sign can be made after a closer look at the airsheds for the valley and the basin.

It was recognized from the start of the project that the airshed of the Utah Lake Basin contained a vast source region for cold air drainage at night (Fig. 1). By comparison, the source region for Rush Valley is quite small. (A source region is loosely defined as elevated terrain within the airshed.) A terrain profile along the airshed boundary for the basin shows that Fivemile Pass and its neighbors constitute a major outlet for cold air if it pooled to a height of 300 m or more. Therefore, our hypothesis is that cold air drains off the Watsatch and accumulates in the basin to a height of several hundred meters and results in an E-W gradient that forces easterly flow.

We attempted to test this hypothesis by conducting simultaneous temperature soundings in Cedar and Rush valleys. Unfortunately, none of these dual soundings coincided with periods of well-defined flow, easterly or westerly, through the pass; and no significant differences in temperature were observed. The only evidence we have that the cold air may get extremely deep in the basin is a few observations by Hawkes (1947) that put the katabatic flow depth in the basin at about 970 m, which would be about 700 m above Fivemile Pass.

#### 5. Conclusions

Frequent easterly winds are observed through passes connecting a high, dry basin with a lower basin contain-

ing a large lake. These winds appeared to be anomalous in the sense that they are opposite to the prevailing gradient flow. However, an analysis of the local topography and surface characteristics suggests that, during the daytime, the wind is a response to a pressure gradient resulting from unequal heating of the adjacent valley atmospheres. Factors contributing to the development of an E-W temperature gradient include (1) differences in valley floor elevations, (2) differences in the area-average sensible heating, and (3) differences in the ratio of valley area to volume.

An analysis of mixed-layer growth rates in the two valleys, based on a simplified thermal energy budget approach, show how the pressure gradient might develop. The calculated pressure gradient agrees fairly well with the observed gradient, which is several times greater than synoptic scale gradients.

Nighttime occurrences of the easterlies are more difficult to explain. We hypothesize that the large airshed of Utah Lake Basin causes cold air to pool to great depths and thus sustain the E-W temperature gradient during the night.

Although the region of the atmosphere affected by this kind of flow is small, the emergency response implications are very important. At the Utah site, these near-surface winds might prevent transport in the direction of population centers. At other sites the situation could be reversed. If our thesis concerning the origin of these winds is correct, modeling the flow would require close attention to the topography and the surface energy balance.

## 6. Acknowledgements

We thank J. Archuleta and B. Bourgeois for significant contributions to the field measurements and B. Bowen for reviewing the manuscript. Lawrence Livermore Laboratory provided valuable data from the tower network in the South Area. The project was done under the auspices of the US Department of Energy with support provided by the US Army Nuclear and Chemical Agency.

## 7. References

Atkinson, B.W., 1981: Meso-Scale Atmospheric Cir-

culations. Academic Press, New York.

Dutton, J.A., 1976: *The Ceaseless Wind*, an introduction to the theory of atmospheric motion. McGraw-Hill, New York.

Ekhart, E., 1948: "On the thermal structure of the mountain atmosphere," in *Alpine Meteorology*, Translations of classic contribution by A. Wagner, E. Ekhart and F. Defant, edited by C.D. Whiteman and E. Dreiseitl, Pacific Northwest Laboratory report PNL-5141, ASCOT-84-3, 121 pp.

Stone, G.L. and D.E. Hoard, 1990: The daytime wind in valleys adjacent to the Great Salt Lake. Preprints, Fifth Conference on Mountain Meteorology, June 25-29, Boulder, CO.

#### Figure Captions:

Fig. 1. Map showing the main topographical features and population centers of the study area. Dashed lines are airshed boundaries for Rush Valley and the Utah Lake Basin.

Fig. 2a-d. Frequency wind roses for direction. The length of the spoke represents the percentage of the time, within the time period shown that the wind blows from the indicated direction. Ring interval is 5%. Station 3 is located in Fivemile Pass.

Fig. 3. Histograms for time of onset and cessation of easterlies in Fivemile Pass.

Fig. 4. Time series of wind direction in Fivemile Pass, valley-bottom air temperature for Rush and Cedar valleys, and horizontal pressure difference between the valleys for August 4 and 5, 1987. The 700-mb wind is shown along the top of the figure; long barb represents 10 kn (5 m/s), short barb is 5 kn.

Fig. 5. Vertical profile of the E-W component of the wind above Fivemile Pass, 0500 MST, August 5. The dark heavy line is a west-to-east section of the terrain 5 km south of the pass. The heavy dashed line is a terrain section through the pass, and the lighter dashed lines are sections 5 and 15 km north of the pass. The

vertical scale has been exaggerated 20 times.

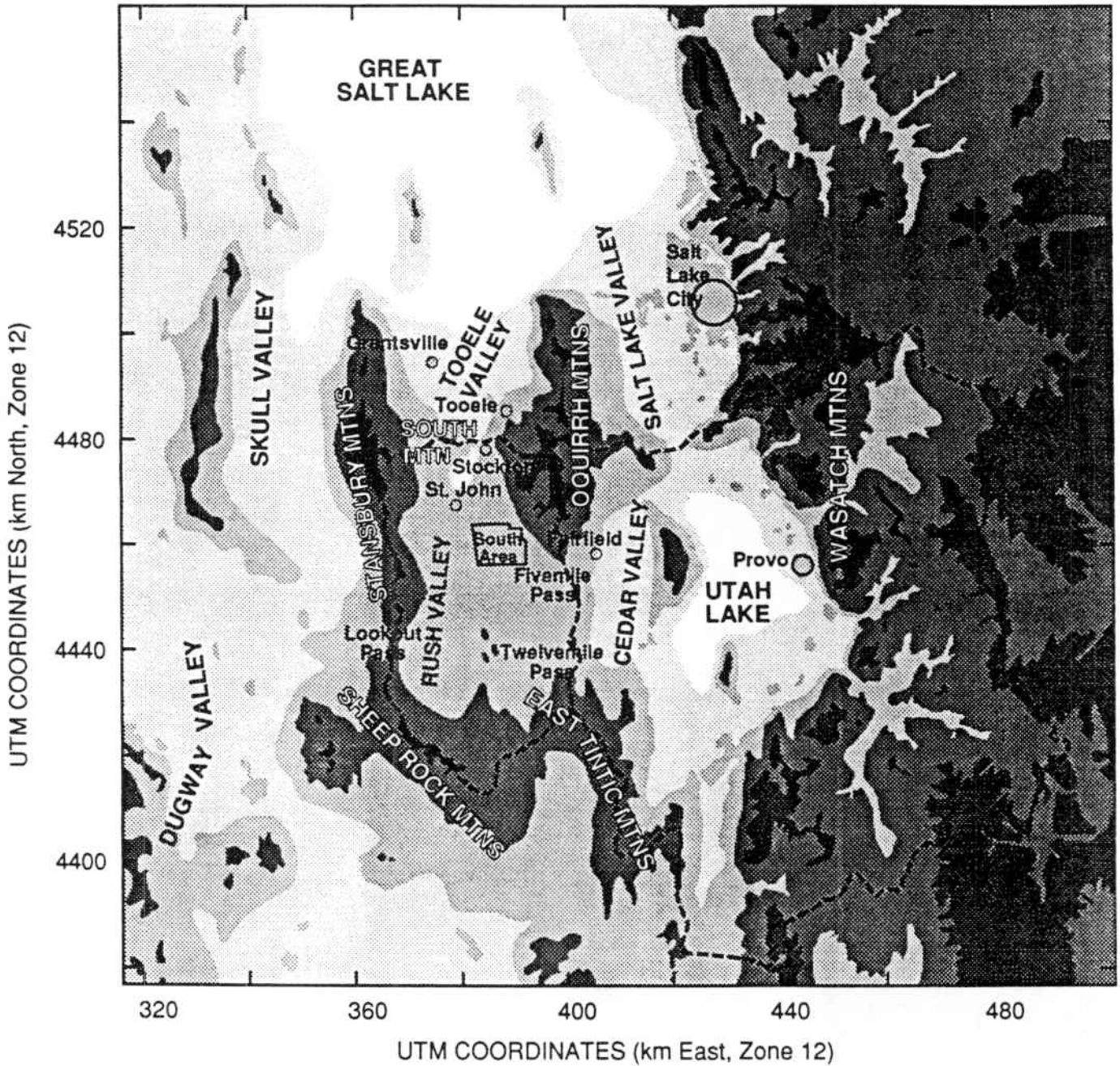


Fig. 1.

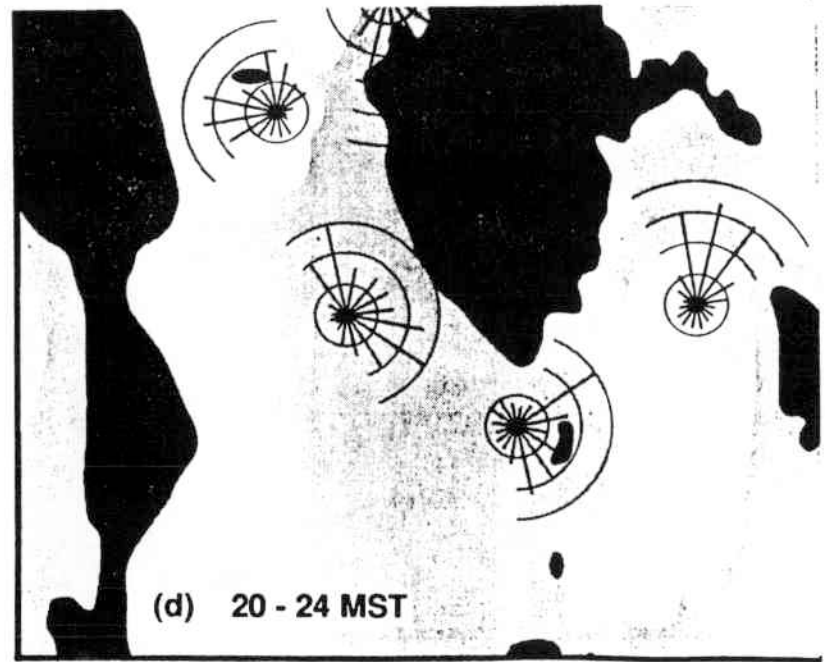
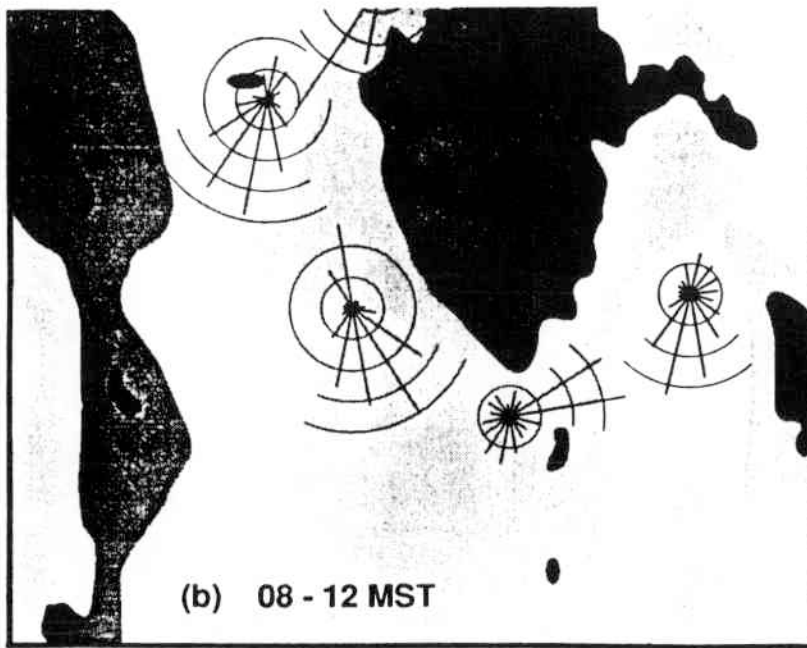
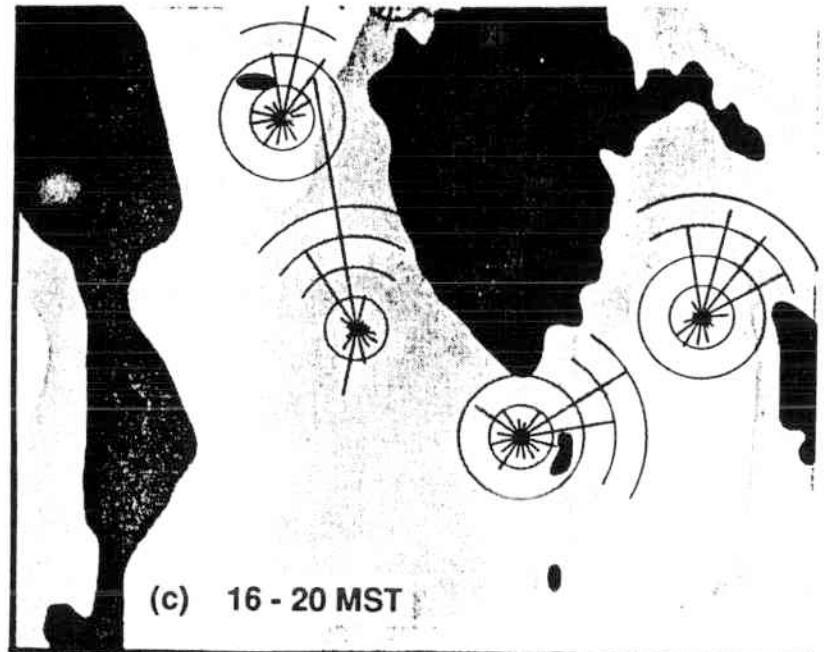
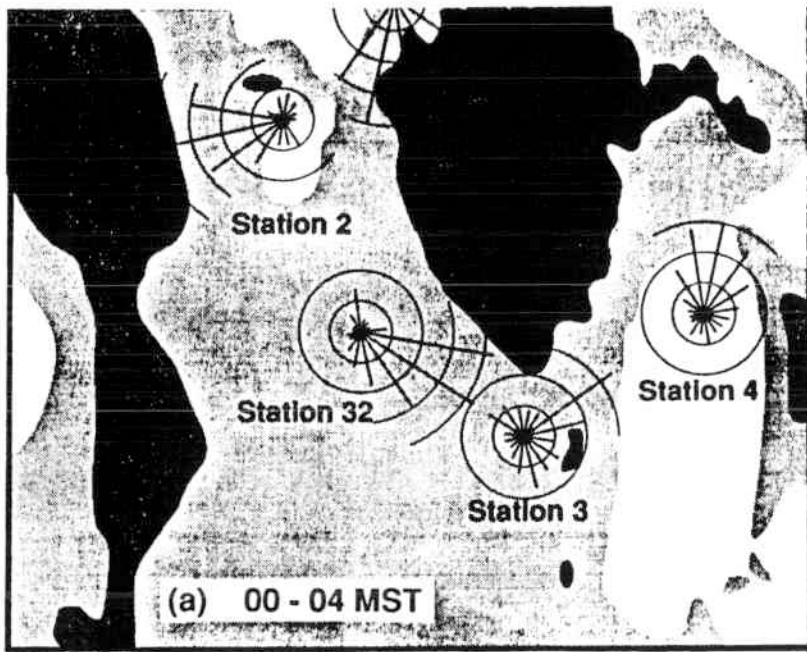


Fig 2

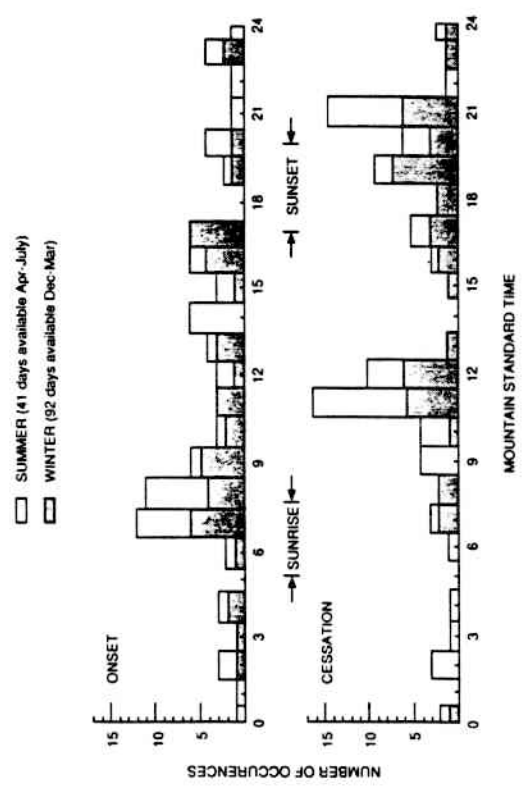


Fig. 3.

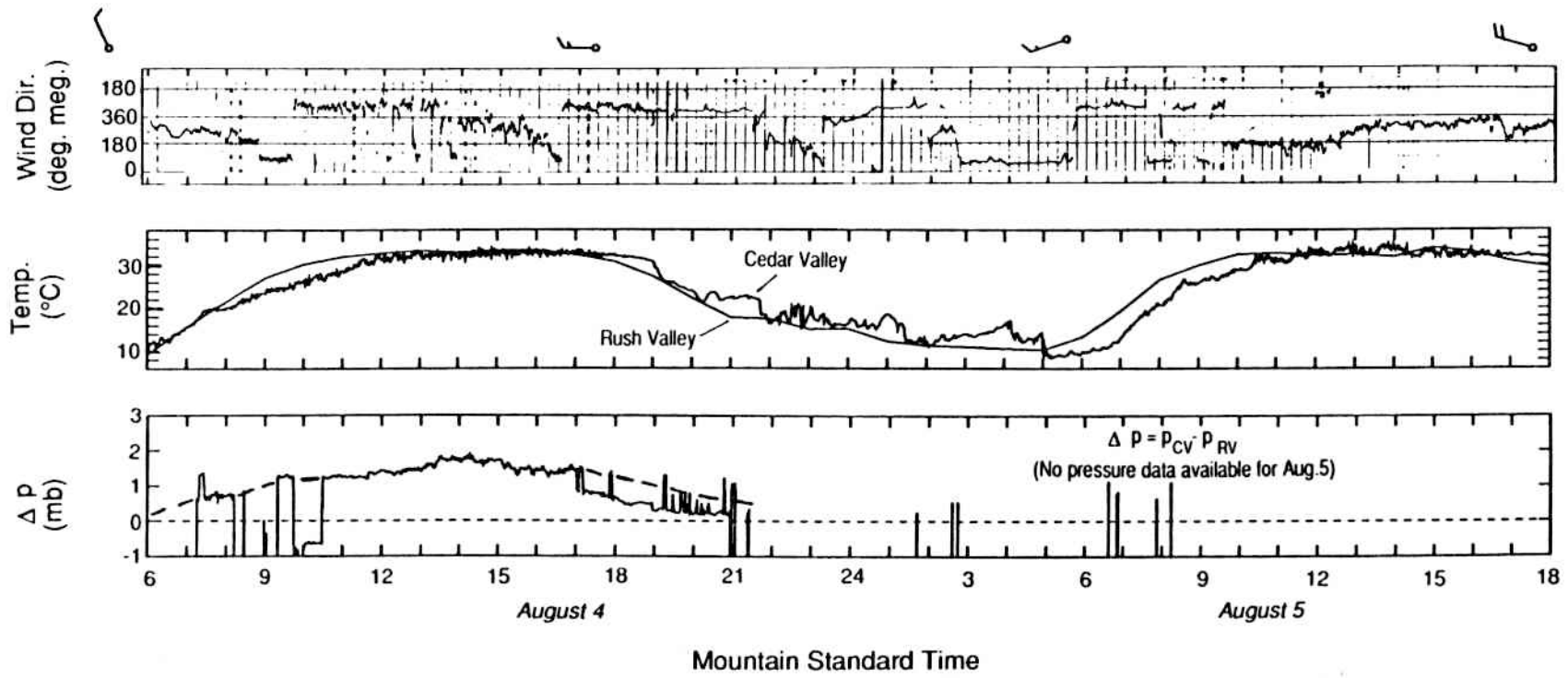


Fig. 4.

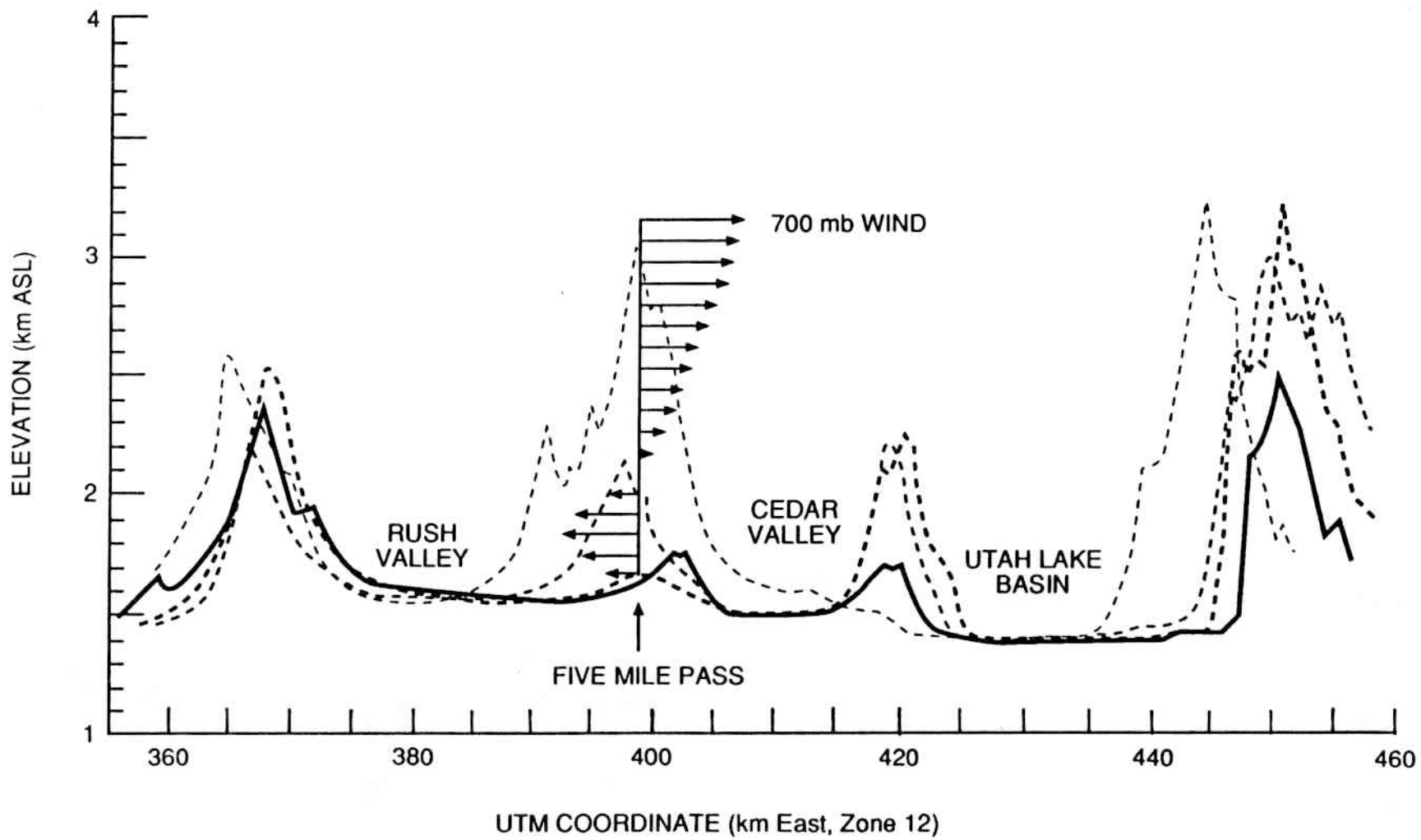


Fig. 5.