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A CLIMATOLOGY AND CASE STUDY OF STRONG LAKE-BREEZE FRONTS IN THE SALT LAKE VALLEY

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## 1. INTRODUCTION

Northerly afternoon winds in the Salt Lake Valley (hereafter Valley) of northern Utah are commonly observed during periods of weak synoptic forcing (Stewart et al. 2002). These up-valley winds develop in response to the aggregate differential heating between the Great Salt Lake Basin (including the Great Salt Lake) to the north of the Valley and the Valley (including the effects of surrounding mountains and Utah Valley to the south).

It is difficult in some cases to determine the causes for the up-valley wind reversal, such as that evident in Fig. 1a. Stivari et al. (2003) and Sturman et al. (2003) investigated the linkages between lake breezes and other thermally driven circulations in complex terrain. Up-valley wind reversals due to the passage of strong lake-breeze fronts occasionally occur in the Valley during the day and are accompanied by sharp discontinuities in moisture and wind speed (Fig. 1b).

The strongest vertical and horizontal winds associated with lake breezes are typically found in the vicinity of lakes located in arid regions (Segal et al. 1997; Shen 1998), such as the Great Salt Lake Basin. Recent drought in the Great Salt Lake Basin, combined with above normal summer temperatures, has led others to suggest that the decreasing lake surface elevation may affect the characteristics of the lake breeze in the Valley.

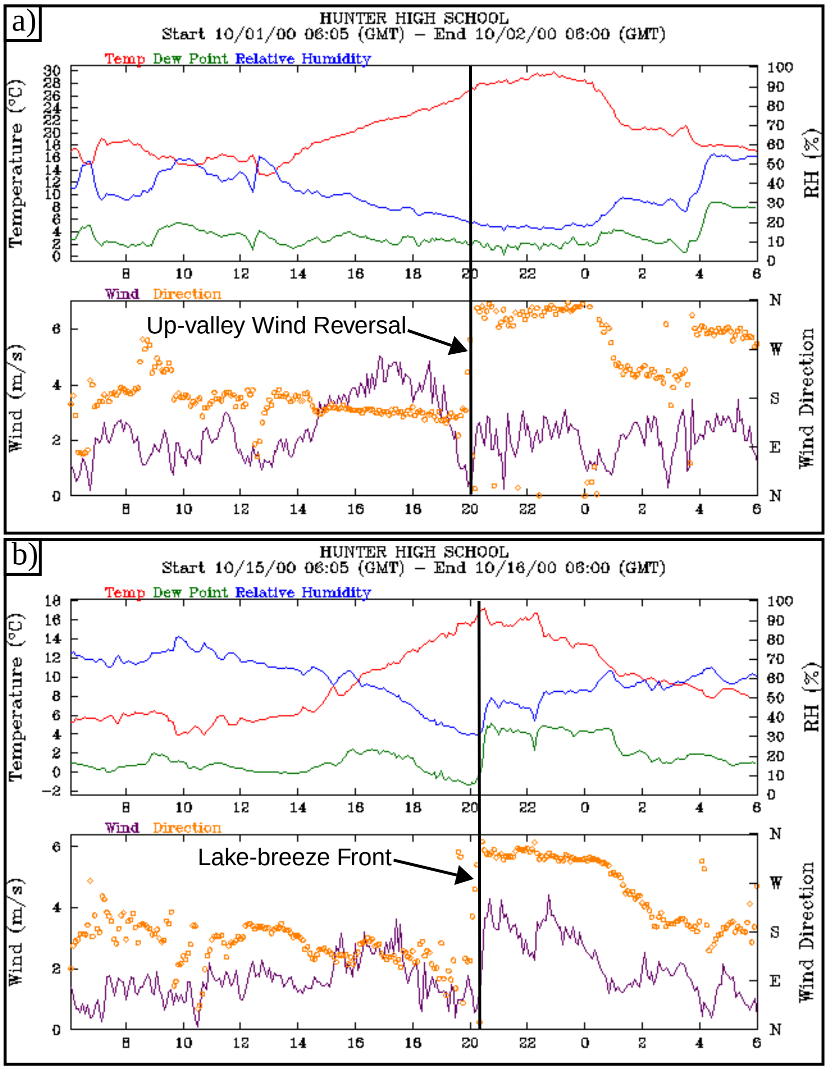


Figure 1. Temperature, dew point temperature, relative humidity, wind speed and direction at a Salt Lake Valley location from (a) 0605 UTC 1 - 0600 UTC 2 October 2000 and (b) 0605 UTC 15 - 0600 UTC 16 October 2000 showing (a) an up-valley wind reversal and (b) a lake-breeze frontal passage.

The objectives of this study were:

•to determine the frequency of northerly wind reversals and strong lake-breeze frontal passages as a function of the average summer Great Salt Lake surface elevation.

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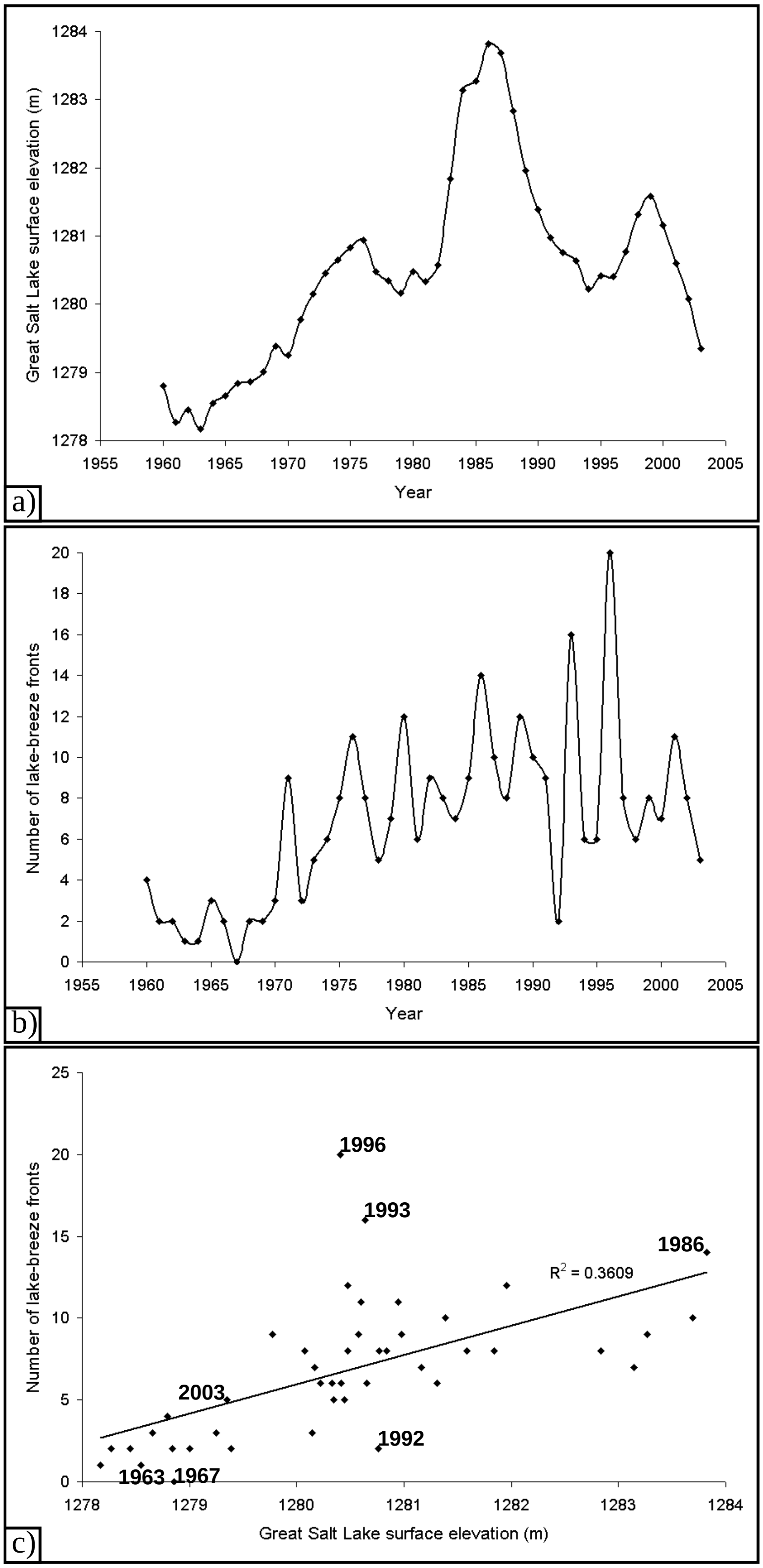


Figure 2. (a) Average summer Great Salt Lake surface elevation (m), (b) number of strong summer lake-breeze frontal passages at SLC, and (c) number of strong summer lake-breeze frontal passages at SLC plotted against average summer Great Salt Lake surface elevation (m) for 1960-2003. Selected years are labelled and the linear fit is shown in (c).

•to study in detail the evolution of a strong lake-breeze front that moved up the Salt Lake Valley on 17 October 2000 in the context of the other thermally driven circulations present on that day.

## 2. SUMMER LAKE-BREEZE FRONT CLIMATOLOGY

The average summer Great Salt Lake surface elevation during the period 1960-2003 ranged from approximately 1278 m in 1963 to 1284 m in 1986 (Fig. 2a). The ongoing drought in the Intermountain West is evident in Fig. 2a by the decrease in lake surface elevation over the past 5 years.

In order to establish the frequency of lake-breeze frontal passages in the Salt Lake Valley, data from the Salt Lake City International Airport (SLC) during the summers from 1960-2003 were used after eliminating days with strong synoptic forcing (precipitation, fronts, etc.). An up-valley wind reversal (i.e., northerly wind-shift) was observed during nearly one-half of all summer days at SLC and the weak summer-to-summer variability in the number of northerly wind reversals bears little resemblance to the interannual variability in lake surface elevation (not shown).

A strong lake-breeze frontal passage was defined here as an up-valley wind reversal accompanied by a dew point temperature increase of at least 2.5°C during peak daytime heating (1500-2200 UTC) on days with weak synoptic forcing. Strong summer lake-breeze frontal passages were observed at SLC during each summer except 1967 (Fig. 2b). In general, the number of strong summer lake-breeze frontal passages increased as the average summer lake surface elevation increased; the linear correlation coefficient between these two is 0.60, which is statistically significant at the 99% confidence level (Fig. 2c). However, other factors such as interannual variations in the seasonal position of the upper-tropospheric anticyclone over the western United States presumably were important as well (e.g., the large variation in the number of lake breeze fronts during the mid-1990's when the lake surface elevation was relatively constant).

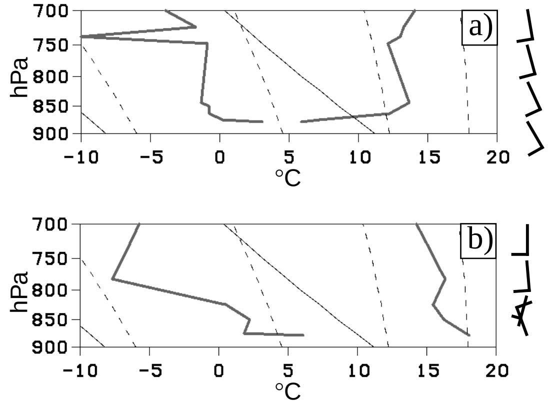


Figure 3. Soundings from the surface to 700 hPa launched from SLC at (a) 1200 UTC and (b) 2100 UTC 17 October 2000. Each half wind barb is 2.5 m $s^{-1}$ and each full wind barb is 5 m $s^{-1}$.

### 3. 17 OCTOBER 2000 CASE STUDY

A case study of a lake-breeze frontal passage on 17 October 2000 during the VTMX (Vertical Transport and Mixing Experiment) field program (Doran et al. 2002) was performed to investigate the interactions between the lake-breeze front and mountain-valley winds in the Valley. The field program provided an unprecedented amount of surface, rawinsonde, radar, sodar, and lidar data collected by commercial, military, government, and educational institutions, including the Department of Meteorology at the University of Utah.

A strong 500 hPa ridge resided over the western United States with the axis extending from western Utah to southern British Columbia at 1200 UTC 17 October 2000 (not shown). Clear skies and weak synoptic-scale forcing allowed a temperature inversion and down-valley and land breeze winds to develop prior to sunrise in the Valley (Fig. 3a). Downslope winds were also observed at this time on the slopes of the Wasatch and Oquirrh Mountains located east and west of the Valley respectively.

As summarized in Fig. 4, up-slope and up-canyon surface winds developed in the eastern third of the Valley from 1400-1700 UTC while an up-valley wind reversal in the western two-thirds of the Valley appeared to propagate southward between 1900 and 2230 UTC. The lake-breeze front moved up the Valley between 1900 and 2330 UTC at an average speed of 3 m $s^{-1}$ (Fig. 5). The lake-breeze front was superimposed upon the up-valley flow in the western Valley and the up-slope and up-canyon flow in the eastern Valley.

The lake-breeze frontal passage was associated with dew point temperature increases at Valley surface observation sites (Fig. 6). Most sites observed an hourly dew point temperature increase of 2.5°C or more across the lake-breeze front, satisfying the criteria used to define the lake-breeze fronts as described in the previous section. The lake-breeze front was evident as a wave of dew point temperature increase, with mostly negative or near-zero hourly dew point temperature changes following the frontal passage. Hour-to-hour increases in dew point temperatures of 1–2°C were used to help define the lake-breeze frontal movement shown in Fig. 5.

A variety of data resources were used to diagnose the three-dimensional structure of the boundary layer before and after the lake-breeze frontal passage. The lake breeze boundary layer was clearly evident in the northern Valley by 2100 UTC (Fig. 3). This sounding (launched at 2033 UTC from SLC) showed a large dew point temperature gradient between the surface and the top of the lake breeze boundary layer at roughly 825 hPa with 850 hPa winds from the north-northwest at 5 m $s^{-1}$. Winds aloft above roughly 750 hPa (2500 m) remained southerly throughout the day and opposed the lake-breeze front.

At Wheeler Farm, located in the eastern Valley, rawinsondes were launched at the outset of an Intensive

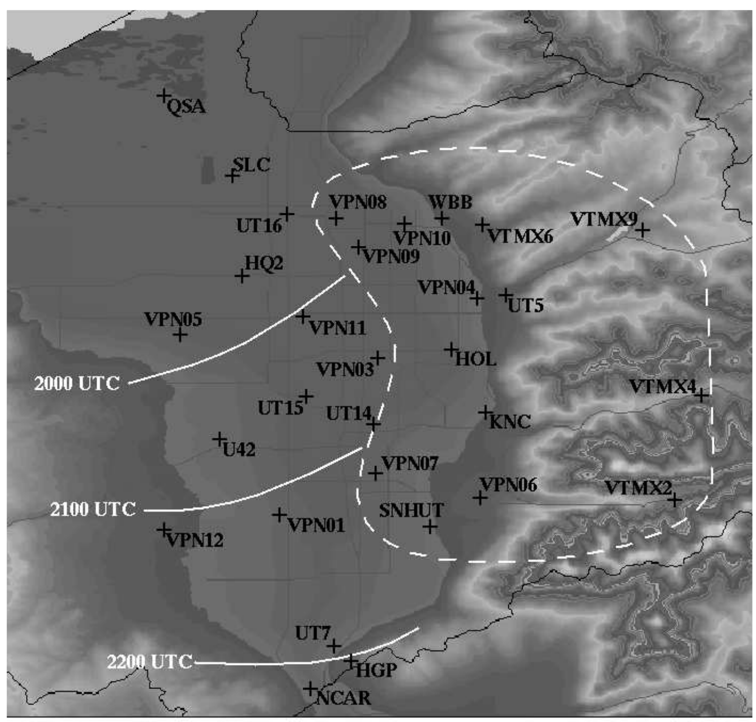


Figure 4. Onset time isochrones of up-valley (solid white lines) and area of up-slope and up-canyon flows (within dashed white line) at the surface that preceeded the 17 October 2000 lake-breeze front in the Salt Lake Valley.

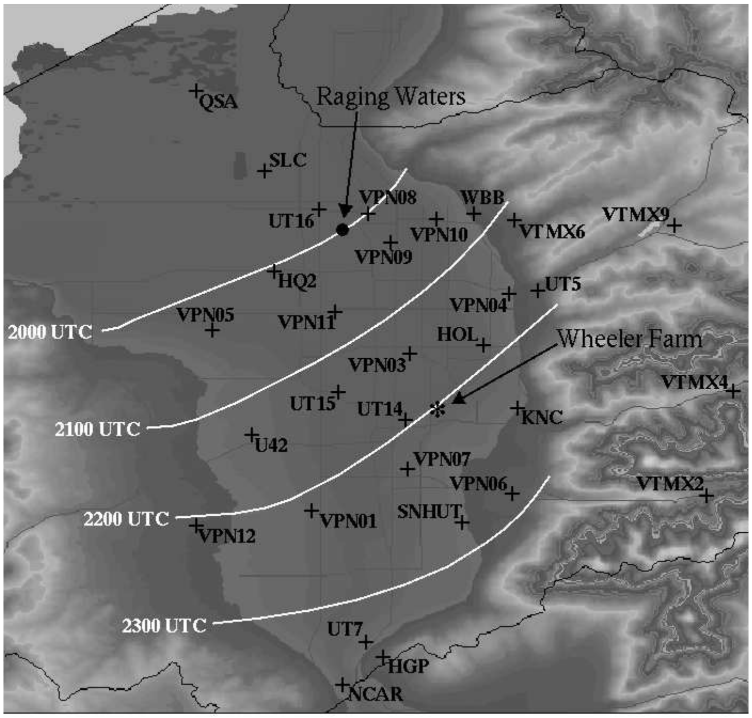


Figure 5. Summary isochrones of the lake-breeze front passing observation sites in the Salt Lake Valley during 17 October 2000.

Observing Period (IOP-7) beginning at 2152 UTC (Fig. 7). Fortunately, this launch appeared to be slightly ahead of the lake-breeze front and after the up-valley wind reversal. The winds were initially light northwesterly from the surface to 500 m agl and there was little evidence of strong vertical mixing (i.e., a superadiabatic layer existed at the surface). By the time of the next launch (2250 UTC), the wind speed had increased significantly and potential temperature was nearly constant with height in the lowest 600 m agl. By 0000 UTC 18 October, a surface inversion began to form while the lake breeze persisted aloft.

A backscatter lidar located at the NCAR (National Centers for Atmospheric Research) data collection site in the southern end of the Valley showed increased aerosol mixing before and after the lake-breeze frontal passage at 2325 UTC 17 October (not shown). Two distinct waves at the top of the boundary layer were evident at this time, suggesting that gravity waves were excited along and ahead of the lake-breeze front with vertical displacements around 150 m.

The lake breeze weakened after 0000 UTC 18 October as the land breeze, down-valley, down-slope, and down-canyon flow resumed Valley-wide by 0300 UTC. The land breeze and down-valley flow was 1-1.5 km deep by this time as indicated by the NOAA (National Oceanic and Atmospheric Administration) lidar located at Salt Lake Airport #2 (U42-not shown).

## 4. SUMMARY

This study of lake-breeze fronts in the Salt Lake Valley was motivated in part by the ongoing drought in the Intermountain West and the possible modulation of the occurrence and intensity of lake breezes by changes in the Great Salt Lake surface elevation. A statistically significant relationship was evident between lake surface elevation and the occurrence of strong summer lake-breeze fronts during the 1960-2003 period such that more lake-breeze fronts would be expected during summers with higher lake surface elevation. However, lake surface elevation alone would not be a successful predictor for the number of strong lake-breeze fronts during a summer chosen at random. For example, there were summers during the 1990's with nearly identical lake surface elevation and widely different numbers of lake-breeze frontal passages, presumably as a result of summer-to-summer variations in the large-scale atmospheric circulation.

A case study of a strong lake-breeze front moving up the Salt Lake Valley on 17 October 2000 was performed. Figure 4 summarizes several of the salient features of the thermally driven flows prior to the passage of the lake-breeze front. The down-slope and down-valley flows in the eastern third of the Valley reversed to up-slope from 1400-1700 UTC. In contrast, down-valley winds in the central and western portions of the Valley continued through the morning and actually increased in magnitude. Ultimately, the wind reversed to a northerly direction in the western two-thirds of the Valley and this reversal appeared to propagate up the Valley faster than the advective speed of the wind. The apparent propagation of the up-valley wind reversal along the Valley axis observed in this case study appeared to reflect interactions between the thermally forced up-valley wind and the opposing synoptically forced down-valley wind aloft.

The lake-breeze front moved up the Valley beginning after 1900 UTC at approximately the rate of the mean wind in the boundary layer behind the front, i.e., roughly 3 m $s^{-1}$ (Fig. 5). The front was accompanied by a strong moisture gradient within a 3-4 km band, superimposed upon the prevailing up-valley wind in the western two-thirds of the Valley and the prevailing up-slope and up-canyon flow in the eastern third. The lake breeze collapsed Valley-wide by 0300 UTC 18 October.

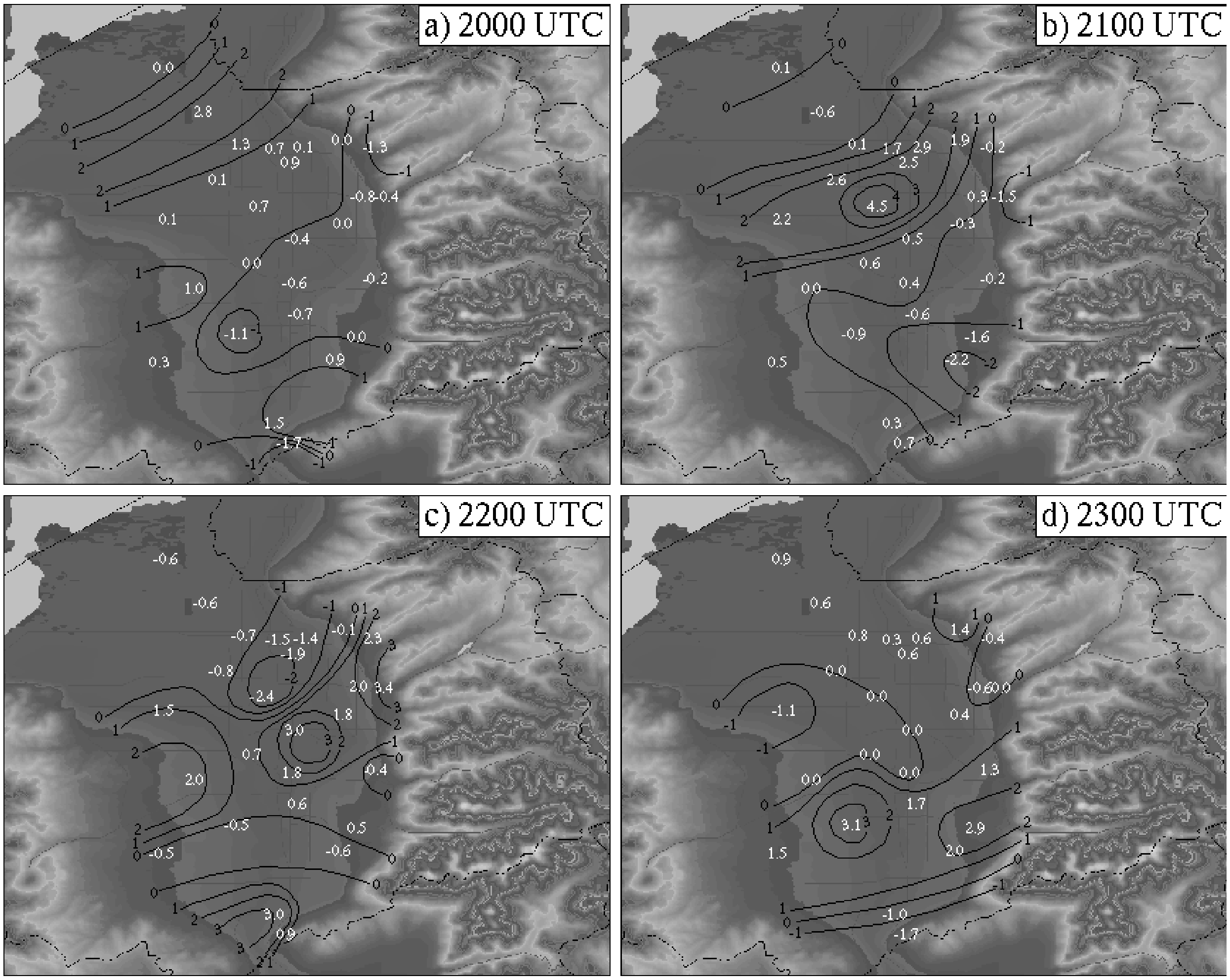


Figure 6. Hourly dew point temperature changes (°C) at Salt Lake Valley surface observation sites (a) 1900-2000 UTC, (b) 2000-2100 UTC, (c) 2100-2200 UTC, and (d) 2200-2300 UTC during 17 October 2000.

## 5. REFERENCES


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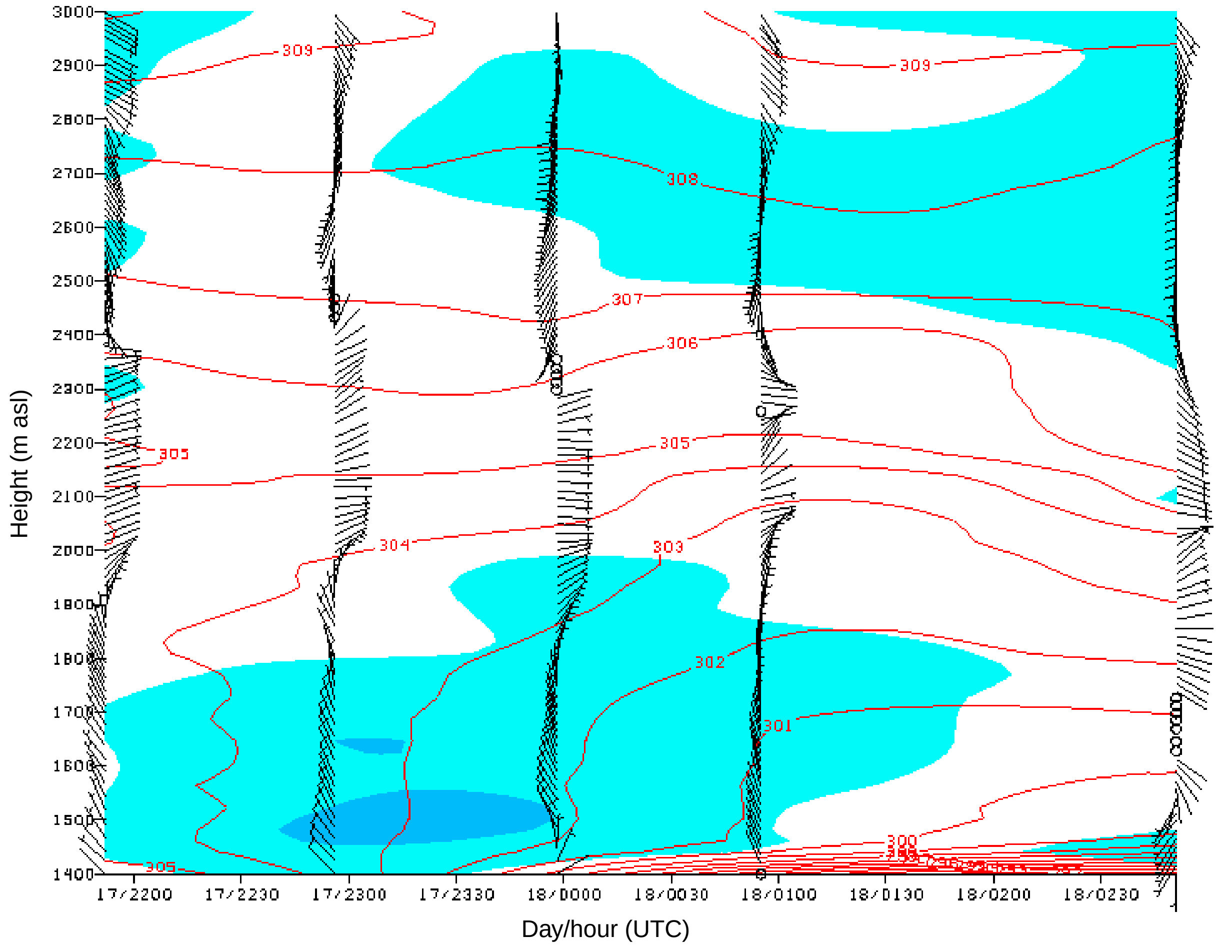


Figure 7. Time-height cross section of soundings launched at Wheeler Farm from 2152 UTC 17 - 0251 UTC 18 October 2000. Solid red lines indicate potential temperature (K) and the y-axis is height above sea level (m asl). Each half barb is 2.5 m $s^{-1}$, each full barb is 5 m $s^{-1}$, and no barb indicates wind less than 1.25 m $s^{-1}$. Blue shading indicates wind speed equal to or greater than 5 m $s^{-1}$, turquoise shading indicates wind speed 2.5-5 m $s^{-1}$, and no shading indicates wind speed less than 2.5 m $s^{-1}$.