Lake-Breeze Fronts in the Salt Lake Valley

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Abstract

Winds at the Salt Lake International Airport (SLC) have been observed during the April-October period from 1948-2003 to shift to the north (up-valley direction) between late morning and afternoon on over 70% of the days without precipitation. Lake-breeze fronts that develop as a result of the differential heating between the air over the nearby Great Salt Lake and that over the Lake's surroundings are observed at SLC only a few times each month. Fewer lake-breeze fronts are observed during late July-early September than before or after that period. Interannual fluctuations in the areal extent of the shallow Great Salt Lake contribute to year-to-year variations in the number of lake-breeze frontal passages at SLC.

Data collected during the Vertical Transport and Mixing Experiment (VTMX) of October 2000 are used to examine the structure and evolution of a lake-breeze front that moved through the Salt Lake Valley on 17 October. The onset of up-slope and up-valley winds occurred within the Valley prior to the passage of the lake-breeze front. The lake-breeze front moved at roughly 3 m s^{-1} up the Valley and was characterized near the surface by an abrupt increase in wind speed and dew point temperature over a distance of 3-4 km. Rapid vertical mixing of aerosols at the top of the 600-800 m deep boundary layer was evident as the front passed.

1. Introduction

Thermally driven flows often dominate the local surface wind field in the Salt Lake Valley (Valley hereafter) of northern Utah. The Valley is approximately 40 km long, 25 km wide, and bordered by the Wasatch Mountains to the east, the Oquirrh Mountains to the west, the Traverse Range and Jordan Narrows to the south, and the Great Salt Lake (Lake hereafter) to the north (Fig. 1). The Lake is approximately 120 km long, 45 km wide, oriented northwest to southeast, and has a maximum depth of 10 m when its surface elevation is 1280 m.

Hawkes (1947), Stewart et al. (2002), and Ludwig et al. (2004) investigated how the surface winds in the Valley are affected by the contrasts in surface heating within and external to the Valley. Such contrasts develop over a wide range of scales in regions of complex terrain (Whiteman 2000). The local thermally driven surface wind circulations in the Valley are shown schematically in Fig. 1 and are defined as follows:

- up- and down-slope flows within the Valley that develop primarily on its flanks in response to horizontal temperature contrasts between the slopes and the air at the same elevation over the center of the Valley
- up- and down-canyon flows (e.g., those occurring within the Wasatch Mountain canyons to the east) that develop in response to the aggregate of the local slope flows within those canyons combined with temperature contrasts between those canyon complexes and the Valley
- up- and down-valley flows that develop in response to the aggregate differential heating between the Great Salt Lake Basin (including the Lake) and the Valley (including the cumulative drainage effects of the surrounding terrain and the higher elevation Utah Valley to the south).

The cumulative effects of these thermally driven flows are quite apparent in the wind rose in Fig. 1 determined from wind direction observations from 1948-2003 at the Salt Lake City (SLC) International Airport. On days from April-October without precipitation (roughly 65% of the time) during which thermally driven flows are likely to be more common, the wind direction tends to be either down valley (53% of the time from the south or southeast) or up valley (29% of the time from the north or northwest).

The onshore penetration of well-defined sea- and lake-breeze fronts are commonly observed near major water bodies (e.g., Biggs and Graves 1962; Pielke 1984; Laird et al. 2001). Occasionally, the onset of up-valley flow during the afternoon in the Valley is accompanied by obvious signatures of a lake-breeze front, including abrupt increases in wind speed and moisture and decreases in temperature (or temperature change). As discussed by Segal et al. (1997) and Shen (1998), intense lake breezes are often found in the vicinity of lakes located in arid regions such as the Great Salt Lake Basin. However, the development and intensity of the lake breeze in mountain basins can be affected significantly by interactions with the ambient large-scale flow and other thermally driven flows (Rife et al. 2002; Stivari et al. 2003; Sturman et al. 2003; Cox 2006). Although sea- and lake-breeze fronts elsewhere are frequently accompanied by precipitation, most lake-breeze fronts in the Valley are not (a noticeable exception is the tornadic environment on 11 August 1999, Dunn and Vasiloff 2001).

The purpose of this paper is to illustrate the interactions of thermally driven flows in regions of complex terrain such as the Valley. As summarized by Horel (2003), the inherent predictability of terrain-induced circulations is often presumed to be high because the forcing is tied to geographically-fixed features of the underlying surface. However, a relatively novel aspect of the thermal forcing in the Valley is that the areal extent of the shallow Lake has varied from roughly 2000 to 8500 km^2 during the past 40 years in response to regional climate variations in precipitation, evaporation, and runoff within its watershed. The decrease in areal extent of the Lake during recent years has heightened interest in determining whether the occurrence of local weather phenomena, such as lake-breeze fronts, are affected by interannual changes in the differential heating between the Lake and surrounding land areas.

The surface and upper-air observations routinely available in the Valley are insufficient to assess in detail the structure or evolution of lake-breeze fronts. Hence, our study consists of two complementary parts: a brief climatological investigation in the next section that uses the long-term record at SLC to estimate seasonal and interannual variations in the occurrence of lake-breeze fronts and a case study in Section 3 that examines the temporal and spatial evolution of a lake-breeze front in the Valley on 17 October 2000. The climatological analysis provides context for the case study by identifying the times of year when lake-breeze fronts are most common and addresses the hypothesis that lake-breeze fronts are more likely during years when the Lake's areal extent is large. The case study relies upon data collected during the Vertical Transport and Mixing Experiment (VTMX) and URBAN 2000 (Doran et al. 2002; Allwine et al. 2002) field programs during October 2000 as well as subsequent analysis of the data and model simulations undertaken by participating scientists (Monti et al. 2002; Zhong and Fast 2003; Fast and Darby 2004; Chen et al. 2004; Ludwig et al. 2004; Banta et al. 2004; Berg and Zhong 2005; Cox 2006). It should be noted that the deployment of instrumentation and sampling strategies for these field projects were optimized for studies of the nocturnal boundary layer in the core of the Valley. Hence, the formative stages of the lake-breeze front in the vicinity of the Lake are not observed in the available data and will not be addressed in this study.

2. Seasonal and Interannual Variations in Lake-breeze Fronts

Hourly aviation reports at SLC for the period from 1948-2003 have been used to estimate the frequency of lake-breeze frontal passages in the Valley and to investigate the possible effects of the variations in the Lake surface area upon their occurrence. SLC is both the default choice for this analysis (since it is the only observing site in the Valley that has a long record of hourly observations) as well as an optimal choice, because of its location roughly 10 km to the south and east of the Lake during those years when the Lake is near its 1280 m average level (see Fig. 1).

As discussed by Zumpfe (2004), our goal is to identify conservatively the days on which lake-breeze fronts are most likely to have been observed at SLC using the following four criteria:

(1) snow cover is absent,

(2) no precipitation (and presumably accompanying extensive cloudiness) is observed,

(3) a wind shift to the up-valley direction is observed at SLC between 1500 UTC and 2200 UTC[1], and

(4) the northerly wind reversal is accompanied by an increase in dew point temperature of at least 2.5°C during a 1-hour period.

The first two criteria are used to limit our analysis to those days when thermally-driven flows are likely to dominate. Snow cover inhibits the development of up-valley flows and widespread cloudiness (as inferred by the occurrence of precipitation) tends to reduce differential heating between the lake and surrounding land. For convenience, we will refer to the days satisfying the first two criteria as "dry" days and they are most common during the period from April through October (roughly 65% of the time during those months). The subset of dry days that meet the additional wind shift criterion are referred to as "northerly wind reversal" days. These up-val-

1. Coordinated universal time (UTC), which is 7 h ahead of local mountain standard time (MST), is used in this study.

ley flows may develop in the late morning or afternoon for a number of reasons, but commonly arise as a result of the aggregate differential heating between the Great Salt Lake Basin (including the Lake) and the Valley. The precipitation and snowpack criteria help eliminate some northerly wind reversals associated with synoptic-scale weather events; however, it is entirely possible that a few dry cold fronts accompanied by northerly wind shifts in the afternoon may remain in this sample. The dew point temperature criterion defines those days when the onset of the up-valley wind is accompanied by a sharp increase in moisture that is likely associated with a lake-breeze front.

Considerable effort was spent assessing additional temperature, pressure, or wind criteria on lake-breeze fronts identified subjectively during October 2000 and the summer months of 2003. We found that applying additional criteria to the SLC record led to missing some well-defined lake-breeze fronts. For example, since temperature at SLC is reported to the nearest ^{o}F at hourly intervals only, the often subtle, brief temperature drop or flattening of the rate of afternoon heating accompanying most lake-breeze fronts was often missed if a temperature criterion was used. The dew point temperature criterion was varied over the range from 0.5-4.5°C and the results shown below were found to be insensitive to criterion changes of order 1°C (the 2.5°C criterion is also supported by the results from the case study in the next section, see Fig. 8).

The occurrence of dry days depends on the absence of precipitation-bearing storms, which happens on over 50% of the days from late March through early November (not shown). Northerly wind reversals on dry days are common from April through October at SLC, peaking in early October (Fig. 2a). As a fraction of the total number of dry days, northerly wind reversals occur over 60% of the time throughout most of the year (Fig. 2b). As shown in Fig. 2c, the number of lake-breeze frontal passages as defined in this study is quite variable throughout the year: the peak occurrence is in early July with other maxima during early October and May. The May peak in the number of lake-breeze fronts is noteworthy because there are more synoptic-scale weather systems during that time of year and, hence, fewer dry days (Fig. 2d). According to Fig. 2d, lake-breeze fronts occur on slightly less than 10% of the dry days.

We do not have a definitive explanation for the sharp decline in lake-breeze frontal passages that is evident in mid-July in Figs. 2c and 2d. The occurrence of lake breezes in other regions generally peaks during the summer months (e.g., Laird et al. 2001). The timing of this abrupt decline at SLC is roughly concurrent with the average onset date of the North American Monsoon season in Utah (Adams and Comrie 1997; Anderson et al. 2004; Gutzler et al. 2005). The daily average dewpoint temperature at SLC increases sharply from 5°C in June to a peak of nearly 9°C by 1 August before dropping back to below 5°C in early September. Although there is no substantive change in the occurrence of up-valley flow reversals during the monsoon season (Fig. 2b), changes in moisture and stability in the boundary layer and increased cloudiness and precipitation may contribute to the smaller number of lake-breeze fronts during the monsoon season.

Interannual variations in the occurrence of lake-breeze fronts are now examined relative to the areal extent of the Lake. We will also relate the year-to-year variations in Lake level to those in the number of northerly wind reversal days. We hypothesize that periods with broader areal extent of the Lake are associated with enhanced differential heating between the Lake and Valley that would lead to an increase in the number of lake-breeze fronts at SLC. Since the Lake is shallow, we use observations of Lake surface elevation as a proxy for changes in the areal extent of the Lake as a whole. Since shorelines are present both to the west and north of SLC as well as levees and ponds nearby, it is not possible to specify a linear distance between SLC and the Lake as a function of Lake elevation. Hence, we can not assess whether our count of lake-breeze fronts depends on the distance the lake-breeze front propagates prior to reaching SLC.

Monthly Lake surface elevation observations are available from the United States Geological Survey and the values from April through October of each year were averaged to obtain annual values for the period 1948-2003 (Fig. 3a). The lowest Lake elevations were observed in the 1960's. Above normal precipitation over nearby drainages raised the lake surface elevation rapidly from approximately 1280 m in 1980 to 1284 m in 1986. The Lake surface elevation declined rapidly back to 1280 m by 1994 and has further declined to 1279 m in recent years. As mentioned in the Introduction, the Lake area increased roughly by a factor of 4 from the 1960's to its peak in 1986.

As shown in Fig. 3b, northerly wind reversals were observed at SLC on average more than 70% of the time on days without precipitation (i.e., roughly 100 days during each April-October period). Northerly wind reversals were less frequent during the mid-1950's yet occurred on more than 85% of the dry days during 1987 (a total of 124 days from April to October). No strong relationship is evident between the interannual variations in the number of northerly wind reversals and Lake surface elevation. Hence, northerly wind reversals in the afternoon at SLC might be expected to take place as a result of the thermally-driven mountain-valley circulations even if the Lake disappeared entirely. Rife et al. (2002) found that a daytime northerly wind shift was simulated in the Valley even when the Lake was removed. We also note that no relationship exists between interannual variations in the number of dry days and Lake elevation since the number of dry days depends on the frequency of synoptic scale and mesoscale precipitation-bearing storms, which is independent of the Lake state. Not surprisingly, the fewest number of dry days occurred during 1984 when frequent storms contributed to the rapid rise in Lake level.

The number of lake-breeze frontal passages during each April-October period ranged from 1 in 1949 and 1967 to 34 in 1986, which was 26% of the total number of dry days that season (Fig. 3c). Fewer lake-breeze frontal passages were found before the early 70's while the highest average number of lake-breeze frontal passages was found during the mid 1980's. The linear correlation between the number of lake-breeze frontal passages during each April-October period and Lake surface elevation is 0.75, which is significant at the 99% confidence level even if only 9 degrees of freedom are assumed in order to reflect the long-term trends in the Lake surface elevation[2].

Based on Fig. 3, the number of lake-breeze frontal passages and the fraction of dry days during the season with lake-breeze fronts increases as the average Lake surface elevation (and, hence, areal extent) increases. However, there is more year-to-year variability in the frequency of occurrence of lake-breeze frontal passages than in the Lake surface elevation. Hence, other factors, such as interannual variations in the seasonal position of the upper-tropospheric anticyclone over the western United States, may affect the occurrence of lake-breeze fronts. For example, abnormally persistent ridging over the West during much of the 1996 season (when Lake level was near normal) led to the highest number (149) of dry days in the 56-year record and, hence, favorable conditions and increased opportunities for lake-breeze fronts.

2. In addition, the Spearman rank correlation (a measure of nonlinear monotonic association between two variates) between Lake elevation and the number of lake-breeze fronts is 0.76, which is significant at the 99% confidence level. Further, linear and Spearman rank correlations between Lake level and the fraction of dry days with lake-breeze fronts are slightly higher (0.76 and 0.77 respectively). In contrast, the linear or Spearman rank correlations between the number of northerly wind reversals and Lake level are roughly 0.35, which is not significant at the 99% confidence level.

3. 17 October 2000 Lake-Breeze Front

a. Data

The VTMX field program during October 2000 was designed to investigate and improve simulations of stable nocturnal boundary layers over urban basins such as the Valley (Doran et al. 2002) while the companion URBAN 2000 field effort focused on the flow and dispersion of tracer material within Salt Lake City (Allwine et al. 2002). Intensive Observing Periods (IOPs) typically began during the late afternoon and continued overnight[3]. This case study on 17 October takes advantage of special observations collected during the last hours of IOP-6 and the first hours of IOP-7. Because of the goals of the VTMX and URBAN 2000 field programs, the timing of IOPs and location of equipment are not ideal for examining the complete evolution of lake-breeze fronts in the Valley, particularly the initial development of the front on 17 October.

Figure 4 shows where data were collected routinely throughout the Valley and where supplemental observations were collected during specific IOPs. Surface stations were installed for the field program by the Pacific Northwest National Laboratory (PNNL), the National Center for Atmospheric Research Atmospheric Technology Division (NCAR-ATD), and the University of Utah to supplement permanent sites maintained by a number of local data providers (Horel et al. 2002). Special rawinsondes were launched by National Weather Service staff from SLC and University of Utah students from Wheeler Farm. Radar wind profilers operated by the National Oceanic and Atmospheric Administration Field Research Division (NOAA-FRD) at Raging Waters (INEL in Fig. 4) and at the PNNL site in the central Valley provided hourly averaged wind observations in the lowest 2 km AGL. A doppler lidar operated by the NOAA Environmental Technology Laboratory (NOAA-ETL) located at Salt Lake Airport #2 (U42 in Fig. 4) scanned radially

3. UTC was the official time for the field programs. The times of sunrise and sunset on 17 October were 1341 and 0043 UTC (0641 and 1743 MST) respectively.

and in range-height cross sections at various intervals during each IOP (Banta et al. 2004). A spectral aerosol backscatter lidar (SABL) was placed in the Jordan Narrows by NCAR-ATD to measure the backscatter reflectivity of particles within the lowest 2 km during VTMX. The Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR), located 22 km north of SLC was also used to analyze the near-surface wind field.

b. Synoptic setting and overview

Based on Rapid Update Cycle analyses at 1200 UTC 17 October 2000 produced by the National Centers for Environmental Prediction, a longwave 500 hPa ridge resided over the western United States with a ridge axis that extended from extreme western Utah to British Columbia. The 1200 UTC sounding at SLC (Fig. 5a) indicated southeasterly winds from 4-5 m s^{-1} between the surface (878 hPa) and the crest level of the mountains to the west and east of the Valley (near 700 hPa). Further aloft, the wind veered from southerly at 5 m s^{-1} at 700 mb to westerly at 9 m s^{-1} at the tropopause near 200 hPa (not shown). Clear skies and light winds prior to sunrise allowed a shallow near-surface inversion to form at SLC.

The lake-breeze boundary layer was clearly evident at SLC by 2100 UTC (Fig. 5b). This sounding (launched at 2033 UTC) showed a large dew point temperature gradient between the surface and the top of the lake-breeze boundary layer at roughly 825 hPa. 850 hPa winds within the lake-breeze boundary layer were 5 m s^{-1} from the north-northwest with southerly opposing winds above 800 mb. The sounding launched from SLC three hours later (not shown) did not differ significantly from this afternoon sounding.

As discussed by Banta et al. (2004), the synoptic-scale ridge and a near-surface south-to-north pressure gradient provided the large-scale conditions favorable for down-valley, down-slope, and down-canyon flows in the early morning hours of 17 October (see also Zhong and Fast 2003; Fast and Darby 2004; and Chen et al. 2004). The intensity and vertical extent of the down-valley flow was evident in the radial velocity data from the NOAA-ETL lidar located at U42 (see Fig. 9c Banta et al. 2004). The down-valley flow was 2-8 m s^{-1} to a depth of 1-1.5 km with the peak winds in the lowest 200 m.

Strong thermal forcing existed during the early morning on 17 October from land to Lake that reversed in the afternoon from Lake to land. The conditions over the Lake on this day can be characterized by the water and air temperature at Hat Island, located near the center of the Lake and roughly 60 km to the WNW of SLC[4]. The water temperature, observed in the shallows adjacent to Hat Island, ranged from 12-15°C; the air temperature increased from 11-14°C during the day. In contrast to these relatively constant temperatures over the Lake, the surface air temperature over the Valley was considerably lower than that over the Lake in the early morning (as cool as 2°C) and much higher in the afternoon (as warm as 25°C).

The dashed white boundary in Fig. 6 denotes the portions of the Valley where thermally driven up-slope and up-canyon wind reversals occurred between 1400-1900 UTC. Monti et al. (2002) examine in detail the upslope flow reversal in the morning on the east side of the Valley (see their Figs. 7 and 8). Fast (2003) also illustrates the morning flow reversal in this area. The isochrones in the western Valley represent the onset of thermally driven up-valley flow from north to south. This flow reversal moved faster than the up-valley wind speed. The up-valley transition began in the northern Valley at roughly 1900 UTC and reached the Traverse Range to the south by 2230 UTC. This non-simultaneous up-valley wind reversal was similar to that observed in the Alpine foothills of central Switzerland by Richner and Griesser (1993).

4. Due to falling Lake levels, the water temperature sensor placed offshore Hat Island in 1998 by the second author is now several km from the lake shore.

As shown spatially by the isochrones in Fig. 7, the lake-breeze front traveled southward through the Valley from 1900-2330 UTC at an average speed of 3 m s^{-1}. These isochrones were determined by integrating all of the available data assets, including reflectivity images from the TDWR. (The reflectivity signature of the lake-breeze front was difficult to follow near the Traverse Range after 2225 UTC because the TDWR beam was above the top of the lake-breeze airmass.) Initially, the front traveled faster in the western Valley and became oriented from southwest to northeast, presumably as a result of the relatively open exposure and close proximity to the Lake on the west side of the Valley. The onset of the lake breeze was evident at SLC by 1955 UTC when the wind shifted to northerly and increased to 4 m s^{-1}. The criteria applied in the previous section for a lake-breeze frontal passage was satisfied at SLC as the dew point temperature at SLC increased from 2.8°C to 5.6°C during the period 1855-1955 UTC. The lake-breeze front became oriented nearly east-west in the western two-thirds of the Valley by 2100 UTC. Comparing Figs. 6 and 7 it is evident that locations in the Valley experienced a surface wind shift to the up-slope, up-canyon, and/or up-valley direction prior to the passage of the lake-breeze front.

The lake-breeze frontal passage was associated with dew point temperature increases at most Valley sites (Fig. 8). Several sites indicated an hourly dew point temperature increase of 2.5°C or more across the lake-breeze front, satisfying the criteria used in the lake-breeze front climatology presented in Section 2. The lake-breeze front is represented here by dew point temperature increases over a distance of 3-4 km, with mostly negative or near-zero dew point temperature changes after the frontal passage.

c. Near-surface evolution

Hodographs for selected surface sites are shown in Fig. 9 in order to document the often abrupt changes in wind direction as a result of changes in thermal forcing. Central Valley sites VPN05 (Fig. 9b), VPN11 (Fig. 9c), and VPN01 (Fig. 9g) were dominated by south-southeasterly down-valley flow overnight and during the early part of the day. An abrupt increase in wind speed associated with the lake-breeze front is evident at these stations between 2010 and 2200 UTC. VPN12 (Fig. 9f), located on the western slope of the Valley, had westerly down-slope winds prior to sunrise that transitioned to east-southeasterly up-slope winds by 1440 UTC. Eastern Valley sites VPN04 (Fig. 9d) and VPN06 (Fig. 9h) had easterly down-slope and down-canyon winds that transitioned to westerly up-slope and up-canyon winds after sunrise. At Wasatch Mountain canyon sites VTMX2 (Fig. 9i) and VTMX9 (Fig. 9e), easterly down-canyon winds were evident through the morning and shifted to westerly up-canyon winds during the afternoon.

Figs. 6 and 7 show that the lag between the onset of the up-valley winds and the lake-breeze front grew larger as they moved up the Valley. The lag was largest at sites in the south (e.g., VPN01 and HGP). Figure 10a shows that the wind veered at VPN01 from a southerly down-valley and land breeze direction to a northerly up-valley direction between 2000 UTC and 2100 UTC, maintaining an average wind speed of 1 m s^{-1}. The lake-breeze front passed at 2210 UTC when wind speed increased by 2 m s^{-1} and the dew point temperature rose by 3.3°C across the front. At HGP (Fig. 10b), wind decreased from 4 m s^{-1} at 1930 UTC to 1 m s^{-1} at 2200 UTC, as the direction went from a south-southeasterly down-valley direction to a north-northwesterly up-valley direction. The lake-breeze front did not pass HGP until 2335 UTC. Wind speed increased to 7 m s^{-1} by 0005 UTC 18 October and there was a 3.7°C dew point temperature increase across the front. After 0005 UTC, wind speeds at HGP gradually decreased to calm after the transition to the down-valley and land breeze winds shortly after 0400 UTC.

d. Three-dimensional structure

As shown in Fig. 11, the leading edge of the lake-breeze front passed the NOAA-FRD wind profiler located at INEL in the northern Valley before 2000 UTC and was roughly 400 m deep; by 0000 UTC 18 October, the depth increased to roughly 700 m (see also Fig. 9b of Zhong and Fast 2003 and Fig. 6a of Fast 2003). The lake breeze began to erode rapidly near the surface at 0200 UTC with complete flow reversal by 0300 UTC. The vertical extent of the lake breeze diminished by 0200 UTC and gave way to down-valley flow. Based on lidar retrievals in the central portion of the Valley in the vicinity of U42, Banta et al. (2004) showed that the evolution of the winds within the lake-breeze boundary layer after 0000 UTC 18 October was similar to that observed at INEL (see their Fig. 9c). Northerly winds were confined within 700 m of the surface at 0000 UTC with the maximum northerly winds observed in the 100-200 m AGL layer.

Figure 12 is a time-height section of winds and potential temperature above Wheeler Farm in the east central Valley. Rawinsondes were launched at the outset of IOP-7 beginning at 2152 UTC (Fig. 12) and the first launch appears to have been slightly ahead of the lake-breeze front because the winds were initially light northwesterly from the surface to 500 m AGL and there was little evidence of strong vertical mixing (e.g., a superadiabatic layer was found near the surface). By the time of the next launch (2250 UTC), wind speeds had increased significantly and potential temperature was nearly constant with height in the lowest 600 m. Sonic anemometer and wind profiler observations at PNNL also revealed an abrupt increase in wind speed after 2100 UTC associated with the lake-breeze front (Zhong and Fast 2003; Chen et al. 2004). By 0000 UTC 18

October (near sunset), a surface inversion had begun to form below the lake breeze as a result of surface radiative cooling. Both the NOAA-ETL lidar located at U42 (Banta et al. 2004) and Wheeler Farm rawinsondes in Fig. 12 indicated light winds from the east reversing to down-valley above 1000 m AGL.

High-resolution NCAR-ATD SABL data were collected at the NCAR site in the Jordan Narrows (Fig. 13). They define several important characteristics of the lake-breeze front around 2325 UTC and the earlier up-valley wind reversal. After 2130 UTC, there were intermittent pulses of aerosols rising to as high as 800 m AGL, although mixing was most evident below 600 m AGL. The vertical transport of aerosols became more regular after 2230 UTC when up-valley flow at that location began. Beginning at 2325 UTC, three distinct features at the top of the boundary layer were evident with vertical displacements around 150 m. A small pressure increase after the lake-breeze frontal passage coincided with the turbulent mixing seen in Fig. 13 (not shown). Higher concentrations of aerosols up to 800 m AGL were observed by the SABL for several hours after the lake-breeze frontal passage.

4. Summary

A long record of hourly surface observations at SLC was examined objectively in order to estimate when lake-breeze fronts may have penetrated into the Valley. The hourly aviation report data combined with the criteria used to identify the lake-breeze fronts (northerly wind reversal in the late morning or afternoon accompanied by a sharp increase in dew point temperature on days without precipitation and snow cover) provide a conservative estimate of their occurrence. It is likely that some lake-breeze frontal passages at SLC are not included in our sample (e.g., ones accompanied by dew point temperature increases from the top of one hour to the next of less than

2.5^{o}C at SLC) while a few false positives may be included (e.g., dry afternoon cold fronts). Given these caveats, lake-breeze fronts are limited to about 10% of the April-October period and occur most frequently in early summer and fall with a pronounced drop in events roughly coincident with the North American monsoon season in Utah.

A goal of this study was to determine the extent to which fluctuations in the areal extent of the Great Salt Lake affect the frequency of occurrence of lake-breeze fronts in the Salt Lake Valley. Our results suggest that the number of northerly wind reversals from April-October appears insensitive to interannual changes in Lake surface area. Hence, it is likely that up-valley wind shifts on many days without precipitation are caused by the aggregate effects of differential heating between the Great Salt Lake Basin with the Valley and its surrounding mountains rather than simply by differential heating between the Lake and its surroundings. This conclusion is supported by the modeling study by Rife et al. (2002) that showed a northerly afternoon wind reversal in the Valley in a model simulation in which the Lake was removed.

There is a stronger relationship between low-frequency variations in Lake surface elevation and the occurrence of lake-breeze fronts at SLC: more lake-breeze fronts occurred during the high water years after the early 1970's than during the low water years prior to that time. However, year-to-year variations in the number of lake-breeze fronts during periods of nearly equal Lake surface elevation suggest that interannual variations in the regional atmospheric circulation also play a role. For example, periods of abnormally persistent ridging over the Western United States (such as during 1996) favor more frequent development of thermally-driven flows irrespective of the Lake state. In addition, interannual variations in other aspects of the Lake state (e.g., surface temperature and salinity) may be important as well; Crosman (2005) documents year-to-year variations in Lake surface temperature of several ^{o}C based on satellite observations.

The case study on 17 October 2000 documents the structure and temporal evolution of a lake-breeze front and its interactions with other thermally driven flows. Figure 6 summarizes salient features of the thermally driven flows prior to the passage of the lake-breeze front on 17 October 2000. The movement of the up-valley wind reversal along the Valley axis was unexpected and requires further examination. It may reflect interactions between the thermally driven up-valley wind and the opposing large-scale southerly wind.

The lake-breeze front progressed up the Valley from 1900-2330 UTC at roughly 3 m s^{-1} (Fig. 7) and was characterized near the surface by an abrupt increase in moisture over a distance of 3-4 km (Fig. 8). Consistent with previous modeling and observational studies (e.g., Segal et al. 1997), winds aloft in the Valley that oppose the lake breeze may have strengthened the lake-breeze front. However, as a result of the preexisting up-slope and up-valley flows, the near-surface winds do not change direction with the passage of the front.

Segal et al. (1997) presented a conceptual model generally accepted for thermally driven circulations that arise from differential heating of adjacent land and water surfaces (e.g., lake breezes). Building on that conceptual model, Fig. 14 is an idealized schematic of the pre- and post-frontal atmospheric conditions over the Lake and Valley on 17 October 2000. It is based on all available data, including the SLC and Wheeler Farm soundings, and wind profiler and lidar observations at several sites within the Valley. Prior to the lake-breeze frontal passage, a superadiabatic layer forms in the lowest 100 m beneath a nearly adiabatic layer extending upwards to 600-800 m AGL. There are light winds throughout both layers. The lake-breeze frontal passage is marked by a sharp increase in wind speed to 3-5 m s^{-1} in the lowest 200-300 m and increased mixing to 600-800 m AGL. The front is shallow (approximately 600-800 m) in comparison to the depth of the southerly flow overnight (approximately 1-1.5 km). Recent high-resolution modeling simulations of the boundary layer flow in the Valley during VTMX support this schematic structure of lake-breeze fronts in the Valley (Cox 2006).

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Figure Captions

Figure 1. Physiographic features in the vicinity of the Salt Lake Valley and schematic depiction of thermally driven slope (dashed black arrows), canyon (solid black arrows), and valley (solid white arrows) flows. A schematic lake-breeze front is also shown. Frequency (%) of hourly wind direction in each of the eight cardinal directions during days without precipitation at SLC from April-October 1948-2003 (upper right corner). Terrain elevation varies from approximately 1200 m (darkest shading) near the Great Salt Lake to 3300 m (lightest shading) in the Wasatch Mountains.

Figure 2. (a) Number of northerly wind reversals at SLC by day of year during 1948-2003, (b) fraction of dry days with northerly wind reversals, (c) as in (a) except for lake-breeze fronts, and (d) as in (b) except for lake-breeze fronts. The values have been smoothed by 14-day running means.

Figure 3. (a) The average Great Salt Lake surface elevation, (b) fraction of dry days with northerly wind reversals, and (c) fraction of dry days with lake-breeze fronts for each April-October from 1948-2003. Dashed lines represent average values and 5-year running means are depicted by heavy solid lines in the lower two panels.

Figure 4. Locations of observation sites.

Figure 5. 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}.

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Figure 11. Radar wind profiler observations from 0600 UTC 17 - 0500 18 October 2000 at INEL (courtesy NOAA-FRD). 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}. The heavy black line encloses the lake-breeze boundary layer.

Figure 12. Time-height cross section of soundings launched at Wheeler Farm 2152 UTC 17 - 0251 UTC 18 October 2000. Solid lines indicate potential temperature (K). 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}. Darker shading indicates wind speeds equal to or greater than 5 m s^{-1}, lighter shading indicates wind speeds of 2.5 m s^{-1}, and no shading indicates wind speeds less than 1.25 m s^{-1}.

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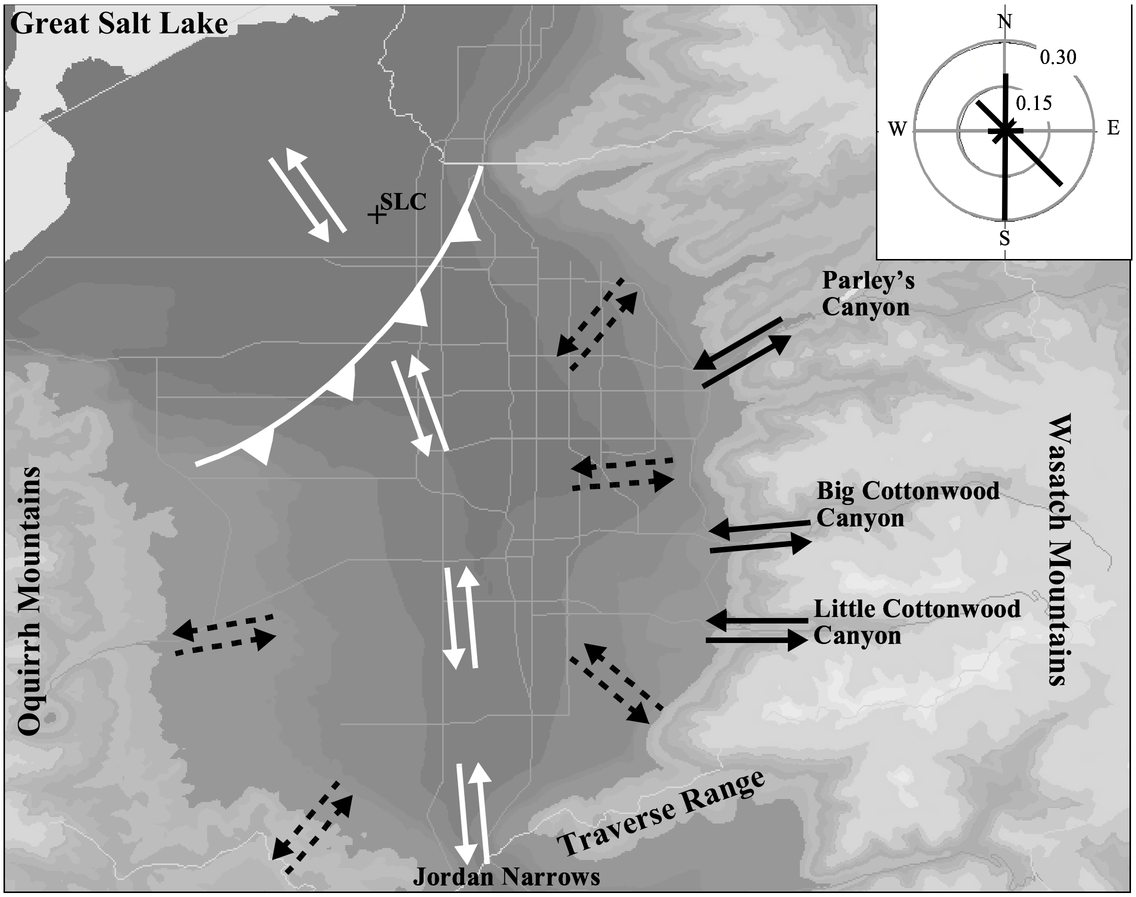

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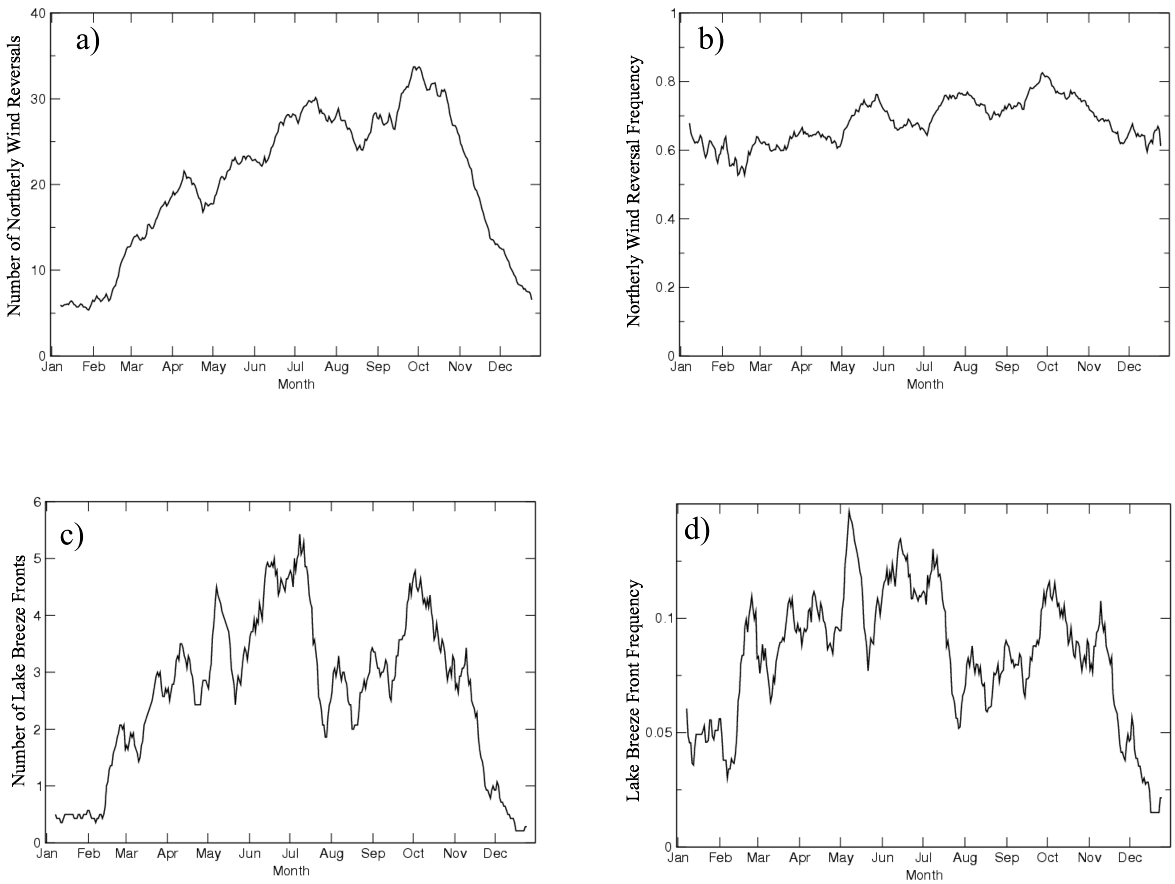

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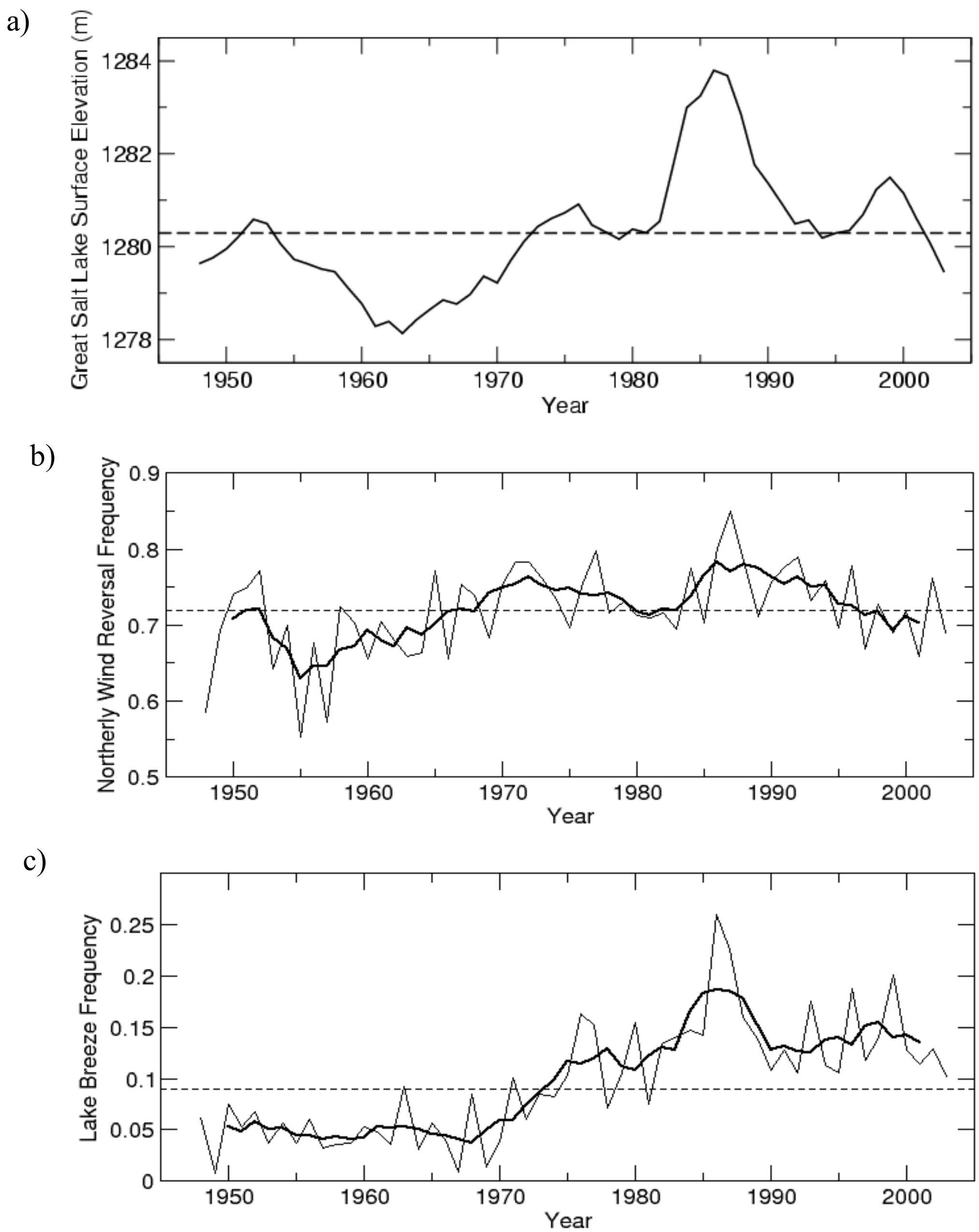

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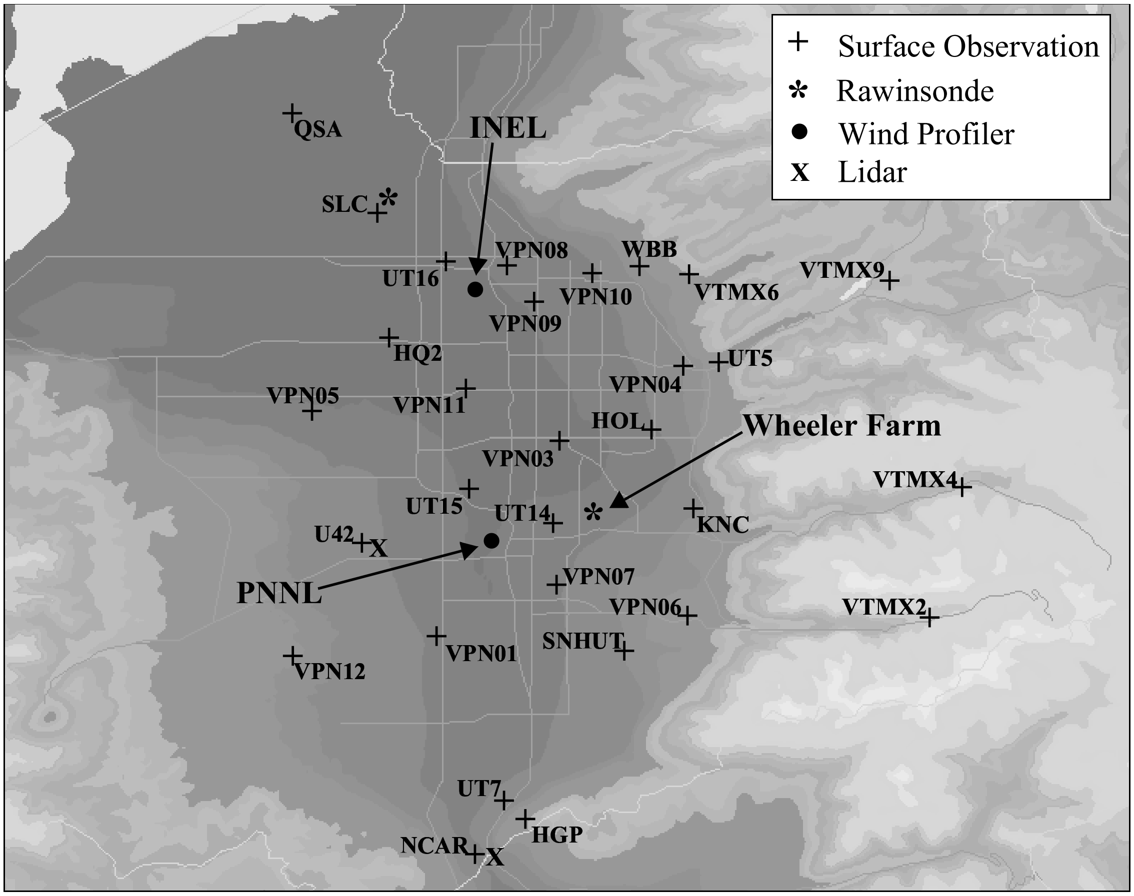

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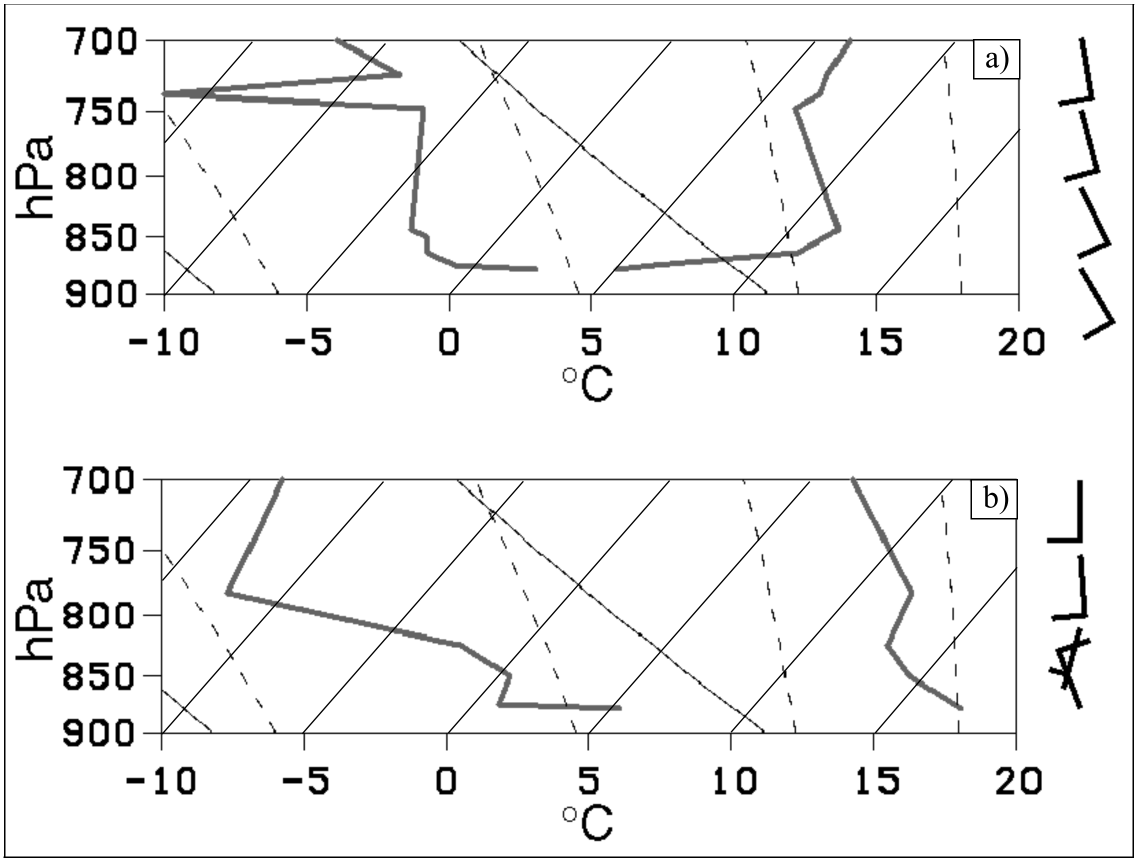

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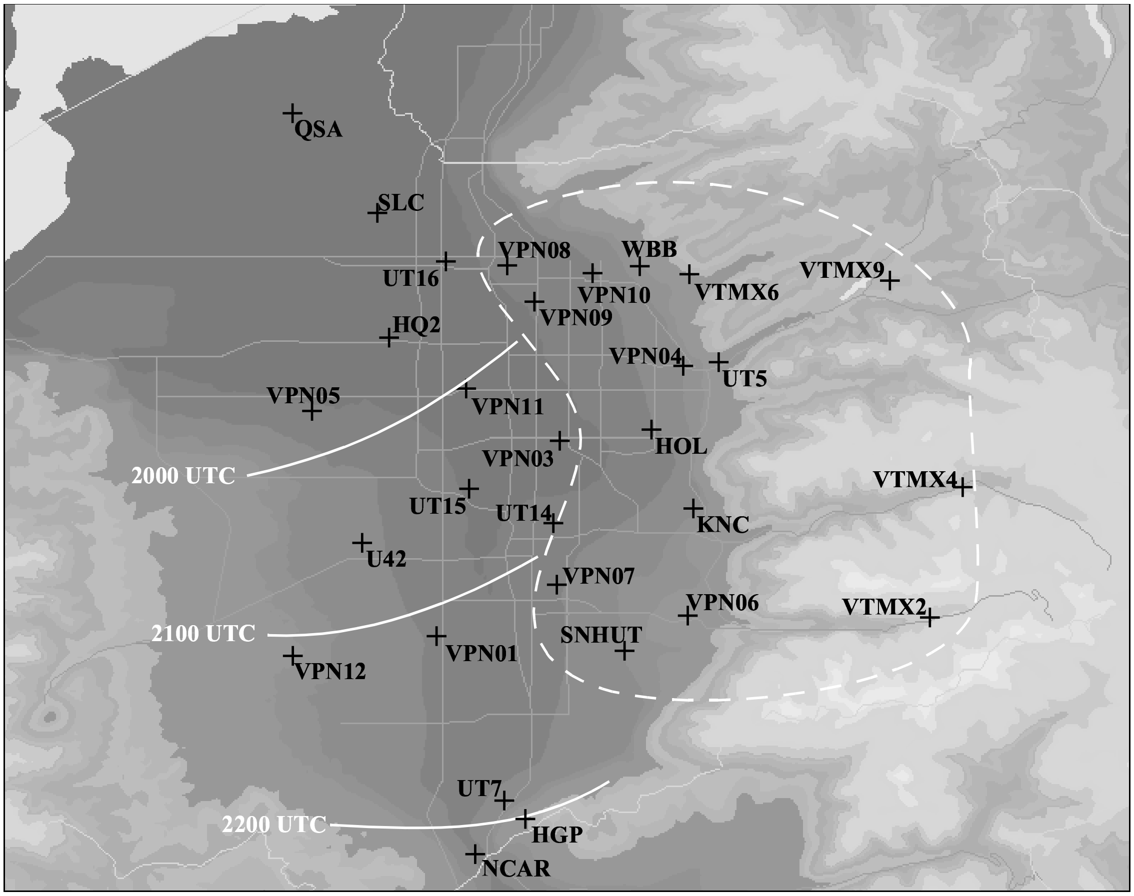

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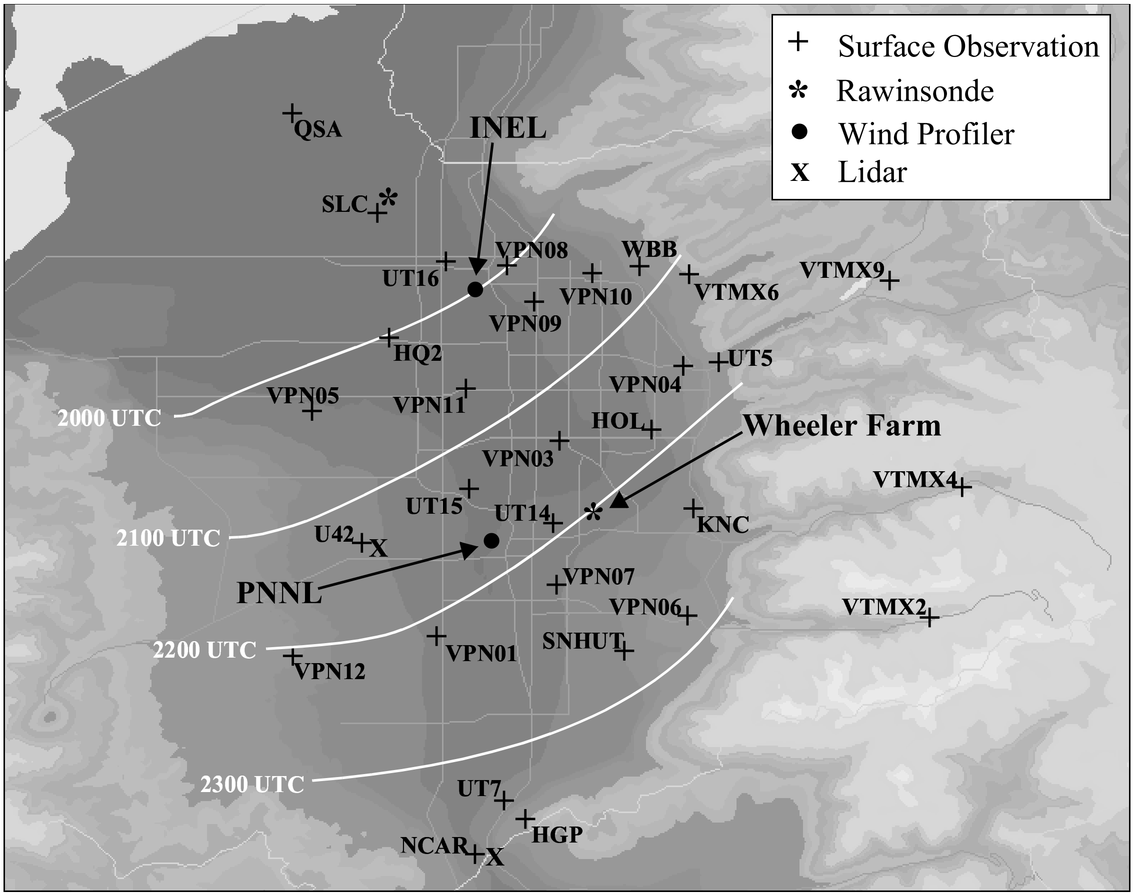

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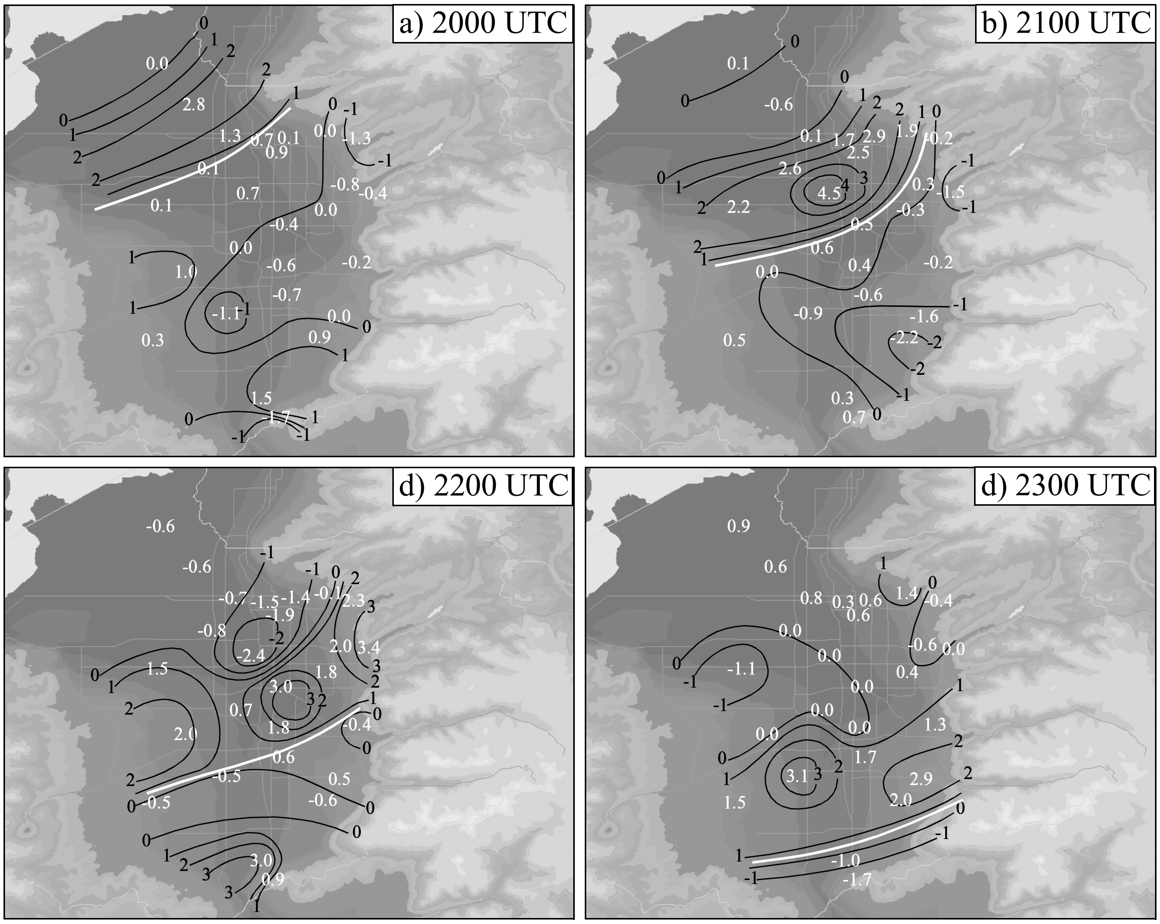

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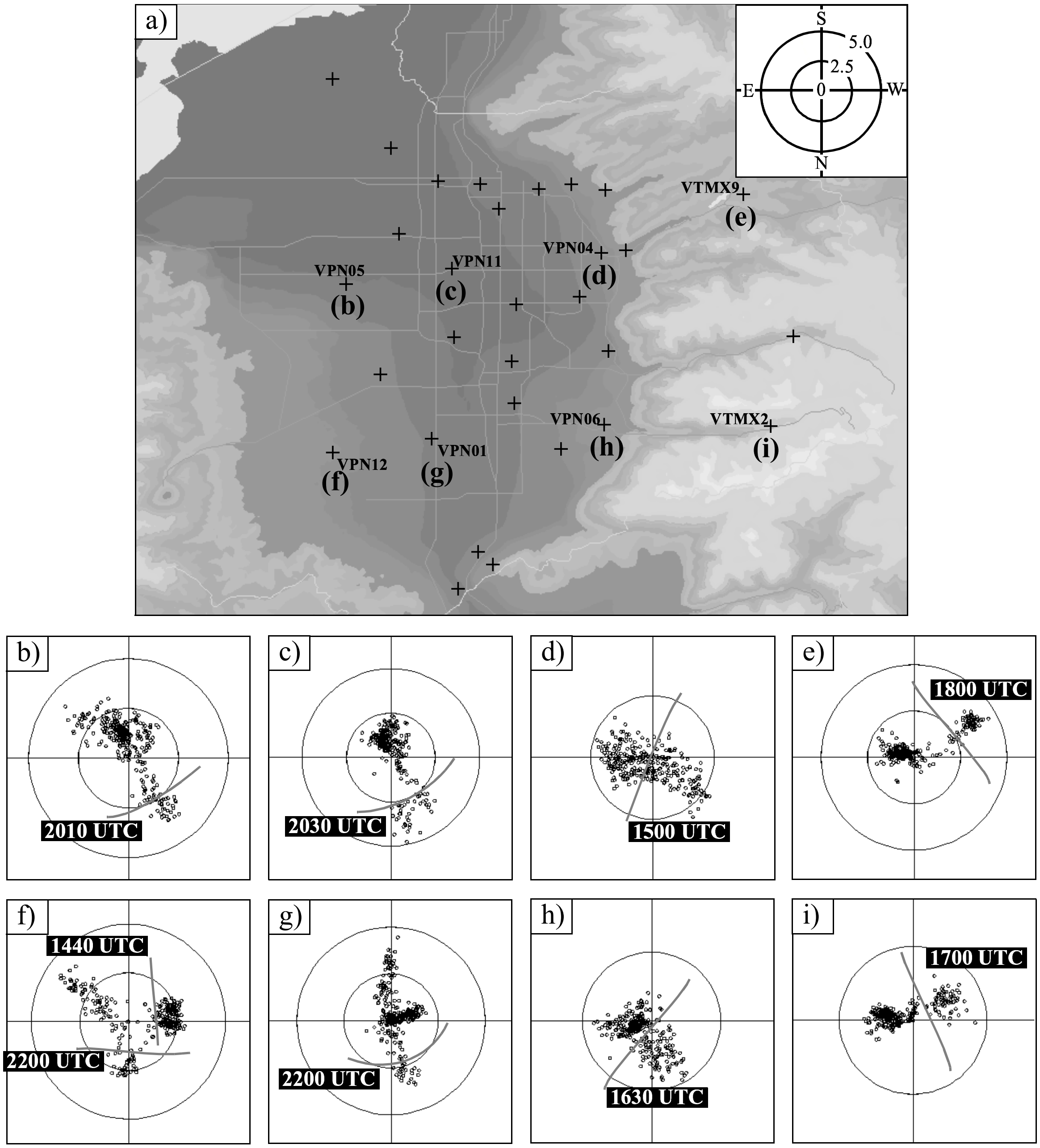

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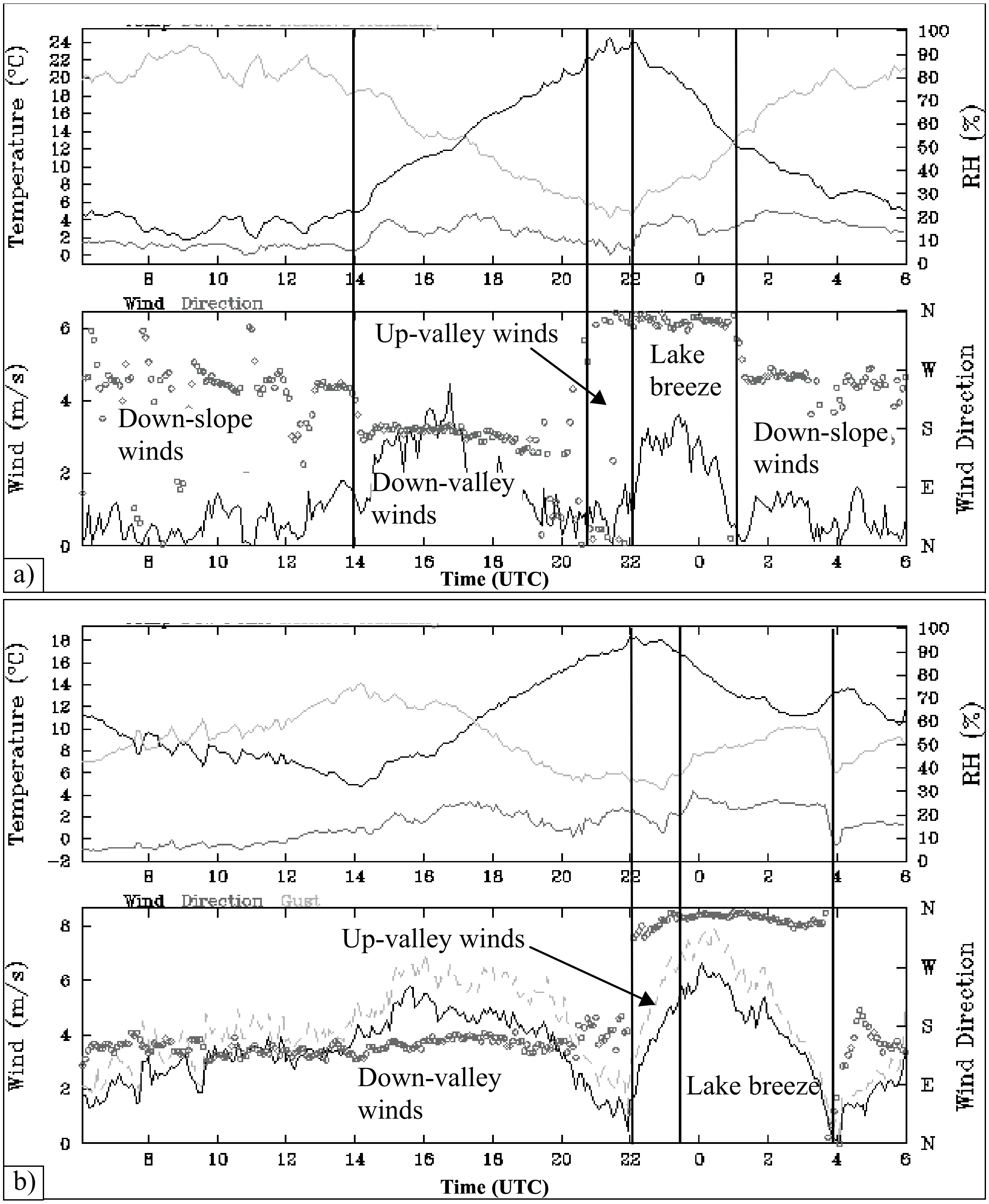

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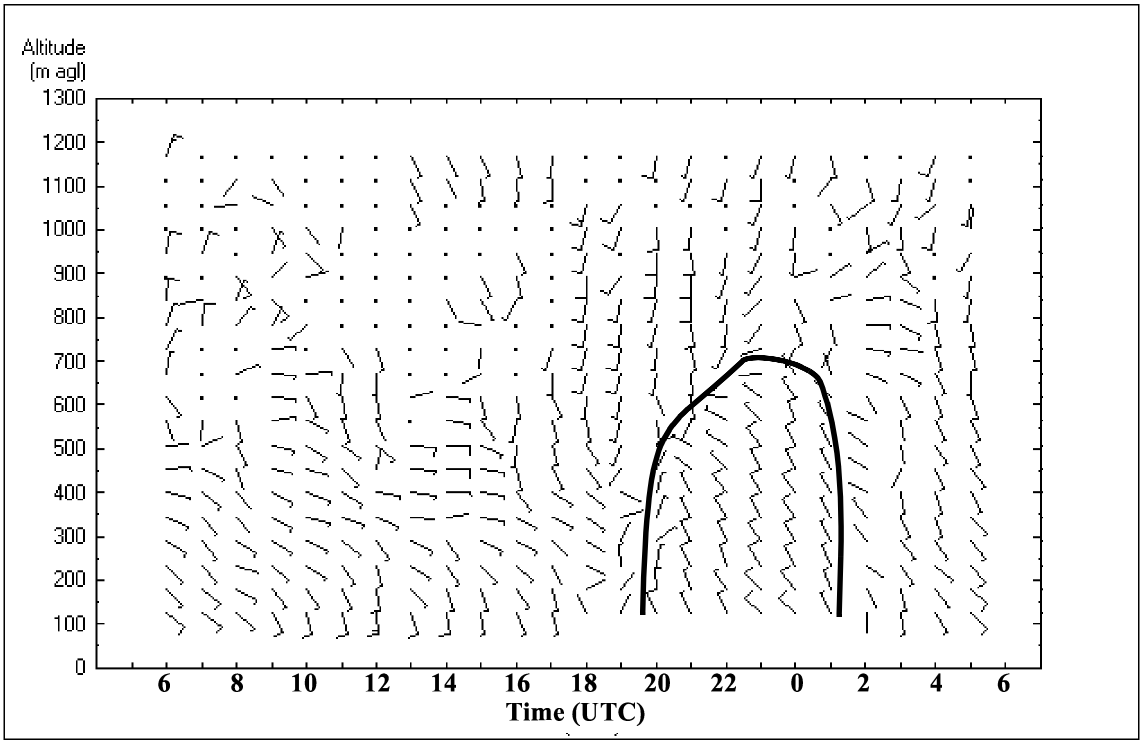

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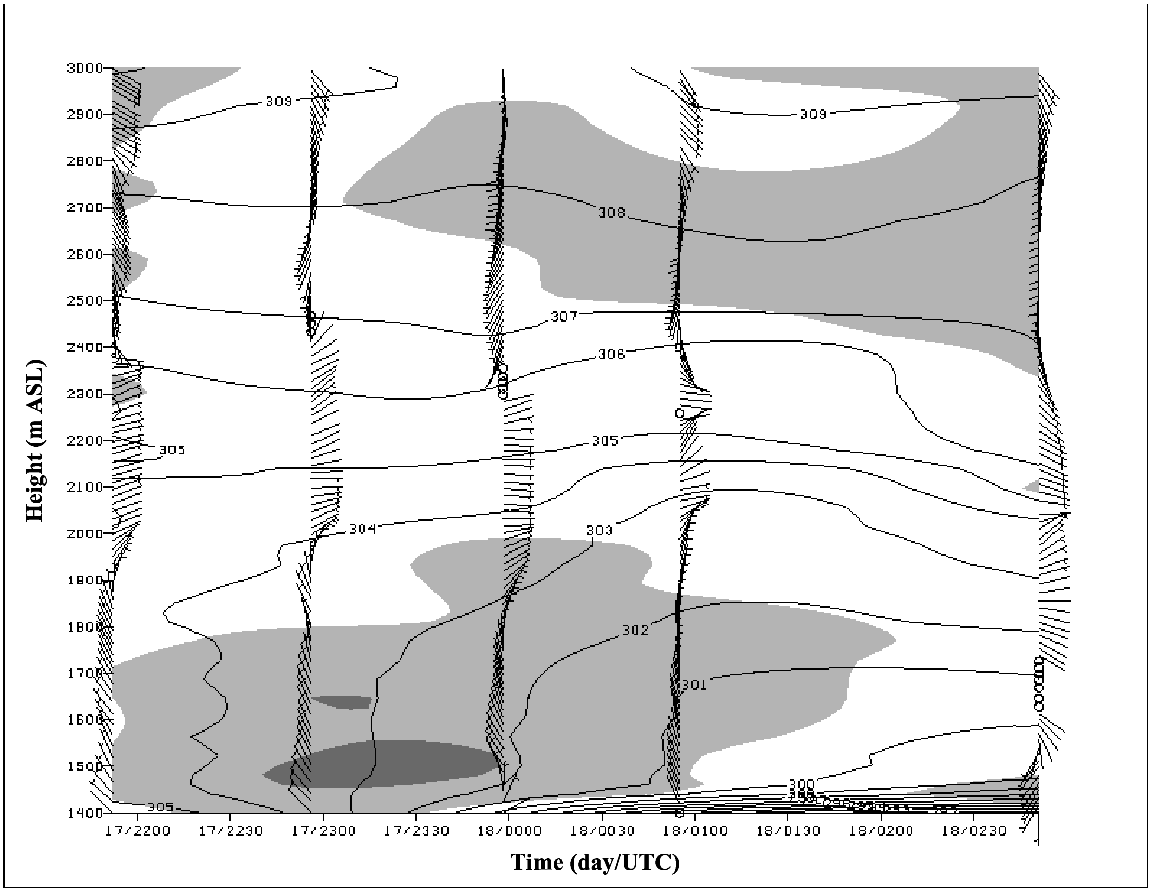

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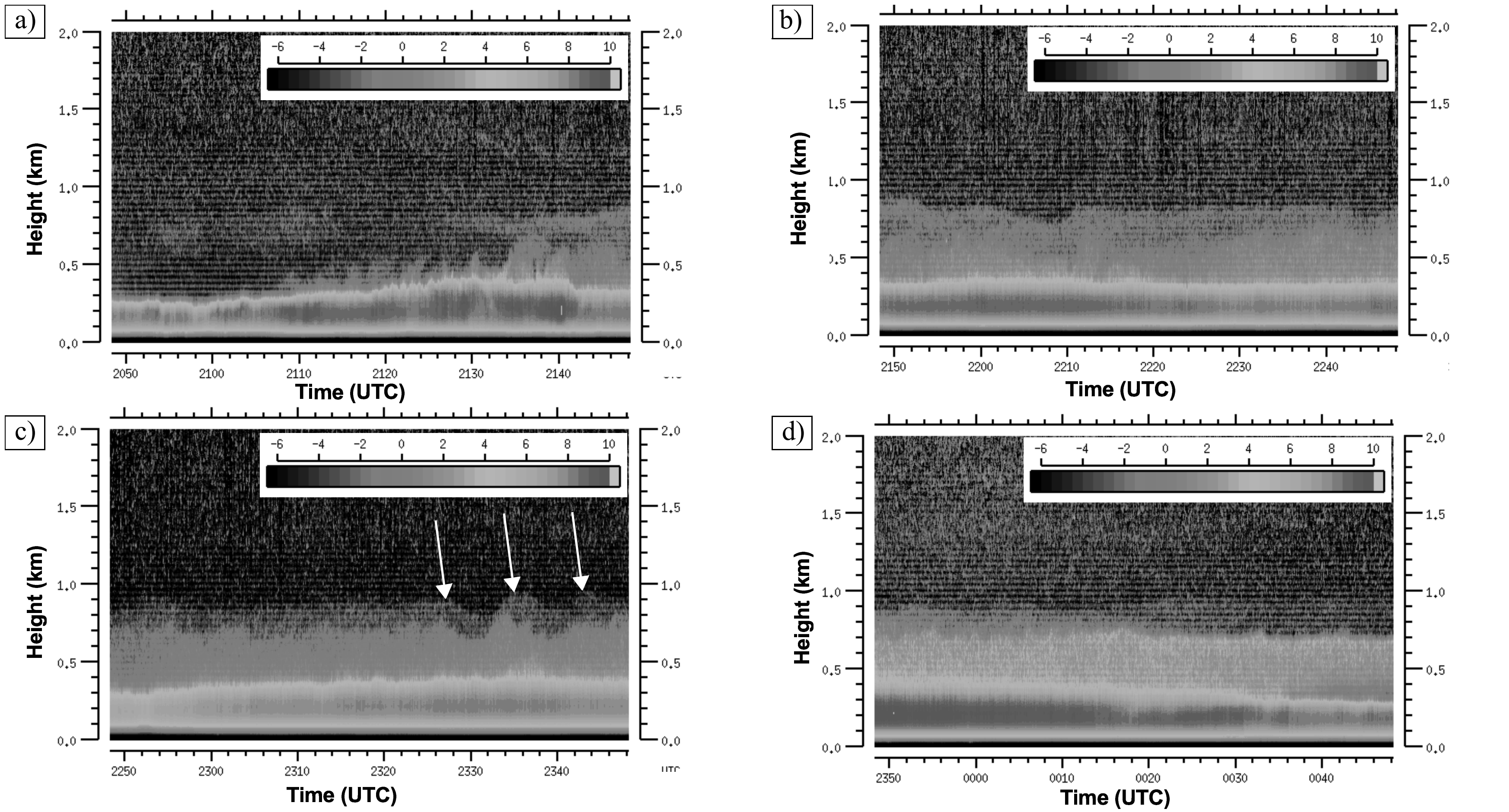

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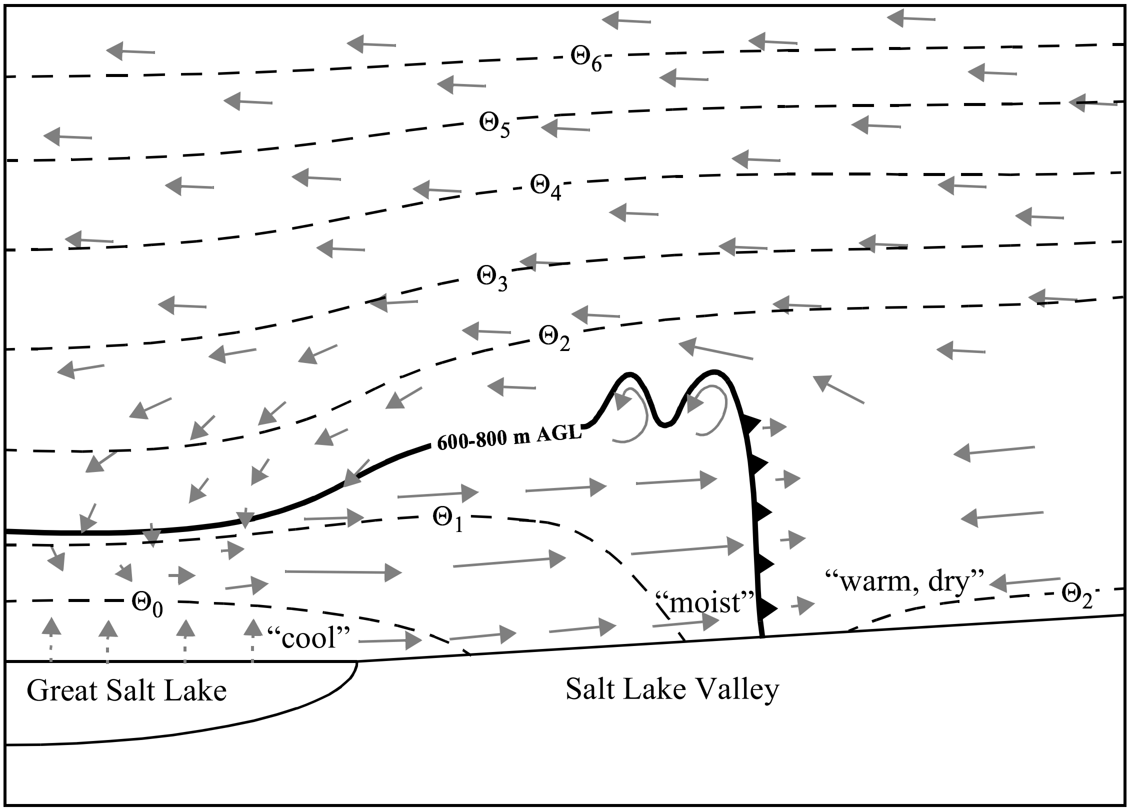

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