ABSTRACT

A strong lake-breeze front arising from differential heating between the Great Salt Lake and its surroundings moved southward through the Salt Lake Valley during the afternoon of 17 October 2000. A climatology of northerly wind reversals and lake-breeze fronts at the Salt Lake City International Airport (SLC) during each April through October period from 1948-2003 is used to place this lake-breeze front in context. Winds at SLC shift to the up-valley direction (from the north) during the late morning or afternoon during nearly one-half of all days during each April through October period. However, strong lake-breeze fronts (defined by a northerly wind shift and increase in dewpoint temperature on days without precipitation or synoptic-scale frontal passages) develop only a few times each month during each April through October period.

Data collected as part of the Vertical Transport and Mixing Experiment and URBAN 2000 field programs during October 2000 provided an unprecedented opportunity to contrast the movement of the lake-breeze front to the diurnal evolution of thermally driven flows within the Salt Lake Valley on a variety of spatial scales. Analysis of surface observations indicates that the lake-breeze front was preceded by wind shifts to up-slope and up-valley directions that reflect the effects of the differential heating along slopes and between mountains and valleys, as well as the differential heating between the Great Salt Lake and its surroundings. The narrow lake-breeze front (3-4 km wide) moved at a speed of approximately 3 m $s^{-1}$ up the entire length of the Valley and was characterized near the surface by an abrupt increase in wind speed and dew point temperature. Rapid vertical mixing of aerosols in wave-like features at the top of the lake breeze boundary layer were evident as the front passed through the southern end of the Valley. Rawinsonde, profiler, and lidar observations at several locations in the Valley documented that the lake-modified air behind the front was roughly 600-800 m deep and that the lake breeze weakened rapidly throughout the Valley between 0100 UTC and 0200 UTC 18 October.

## 1. Introduction

Weak synoptic-scale forcing allows thermally driven flows to dominate local wind circulations in the vicinity of complex terrain (Whiteman 1990) such as those found in the vicinity of the Salt Lake Valley (Valley hereafter) of northern Utah (Stewart et al. 2002). These thermally driven flows may be superimposed upon one another and are defined here as follows. Up- and down-slope flows develop primarily on the flanks of mountain ranges that surround the Valley. Up- and down-canyon flows (e.g., those occurring within the Wasatch Mountain canyons to the east) develop in response to the aggregate of the local slope flow within these canyons combined with differential heating between those canyon complexes and the Valley. Up- and down-valley flows develop in response to the aggregate differential heating between the Great Salt Lake Basin (including the Great Salt Lake) and the Valley (including the effects of surrounding terrain and the Utah Valley to the south).

It is difficult to distinguish between up-valley or down-valley flow arising solely as a result of differential heating between the Great Salt Lake (Lake hereafter) and nearby land from that arising from differential heating of the Valley and adjacent terrain. However, one of the purposes of this study is to examine the differences between northerly (up-valley) wind reversals that occur during the late morning and afternoon in the Valley from the occasional development of lake-breeze fronts, which can be characterized by northerly wind reversals combined with sharp discontinuities in moisture and wind speed (and to a lesser degree the reduction in the rate at which temperature increases during the afternoon).

Past studies such as Hawkes (1947), Stewart et al. (2002), and Ludwig et al. (2004) focused on how the wind field in the Valley is typically affected by the Lake while others such as Stivari et al. (2003) and Sturman et al. (2003) investigated the linkages between lake breezes and other thermally driven circulations in other areas of complex terrain. Studies in the Great Lakes Region have utilized changes in surface winds and temperature to detect lake-breeze frontal passages during summer (JJA) months (e.g., Biggs and Graves 1962; Laird et al. 2001). 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 some to suggest that the decreasing lake surface elevation may affect the characteristics and frequency of lake-breeze frontal passages in the Valley.

The Valley is approximately 40 km long, 25 km wide, and oriented north to south in the southern part and northwest to southeast in the northern part. The Valley is 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 Lake to the north (Fig. 1). Major canyons in the Wasatch Mountains include Parley's, Big Cottonwood, and Little Cottonwood Canyon. The Lake has high salinity, no outlet, and is sustained mostly by runoff precipitation over its watershed. The Lake is approximately 120 km long, 45 km wide, oriented northwest to southeast, and has a maximum depth of 10 m when its lake surface elevation is 1280 m. The historic Lake surface elevation measurements, from 1875 to the present, have varied between approximately 1278 m and 1284 m (not shown).

To illustrate the differences between northerly (up-valley) wind reversals and lake-breeze frontal passages, data collected during the VTMX (Vertical Transport and Mixing Experiment) field program of October 2000 are evaluated. Northerly wind reversals were observed at a northern Valley surface observation site (VPN05) during all 13 of the days in October 2000 with weak synoptic forcing (i.e., days without synoptic fronts, precipitation, etc.) including 1 October and 15 October (Fig. 2). A south-southeasterly wind in excess of 3 m $s^{-1}$ was observed at VPN05 from 1500-1900 UTC 1 October (Fig. 2a). By 2000 UTC, wind speed decreased to less than 1 m $s^{-1}$ as the wind reversed to north-northwesterly (up-valley direction). The wind then increased to 2-3 m $s^{-1}$ and remained north-northwesterly until a down-valley wind reversal occurred at approximately 0000 UTC 2 October. Little change in temperature or dew point temperature was evident before or after the up-valley wind reversal.

The up-valley wind reversal on 1 October (Fig. 2a) differs from the wind reversals that occurred each day during the period 15-19 October when well-defined lake-breeze fronts were superimposed upon the thermally driven mountain-valley winds. For example, weak synoptic forcing and differential heating between the land and lake surfaces resulted in a lake-breeze front that traveled up the Valley on 15 October 2000 (Fig. 2b). The lake-modified airmass can be characterized by the lake and air temperature near the center of the Great Salt Lake at Hat Island (60 km north-northwest of the Salt Lake City

International Airport). The lake temperature, observed in the shallows near Hat Island, varied between 12°C and 14°C while the air temperature varied between 9°C and 11°C on this day (not shown). In contrast, the surface air temperature over the Valley ranged from roughly 5–20°C on this day. At VPN05, winds became light and variable after 1800 UTC as solar insolation continued to increase, breaking down the southeasterly down-valley and land breeze winds (Fig. 2b). A lake-breeze front passed VPN05 at roughly 2045 UTC, evidenced by: (1) a wind speed increase to more than 5 m $s^{-1}$, (2) a dew point temperature increase of more than 6°C, and (3) a decrease in temperature by 2°C. The highest wind speeds and dew point temperatures occurred immediately following the lake-breeze frontal passage.

In order to establish the frequency of lake-breeze frontal passages with similar strength to that observed on 15 October 2000 and to investigate the possible effects of the recent decrease in the Lake surface elevation on above normal summer temperatures in the Valley, a preliminary study of strong lake-breeze frontal passages at the Salt Lake City International Airport observation site was performed. This climatology shows the frequency of strong lake-breeze frontal passages, frequency of northerly wind reversals, and the effect of the Lake surface elevation upon the frequency of strong lake-breeze frontal passages.

### *a. Lake-breeze Front Climatology*

The passage of strong lake-breeze fronts at the Salt Lake City International Airport observation site (SLC) has been determined. This brief study contrasts the number of strong lake-breeze frontal passages at SLC with the total number of northerly wind reversals at SLC and the average Lake surface elevation, measured at the Boat Harbor (southern end of the Lake) for each year 1948-2003. The criteria used to identify strong lake-breeze frontal passages relative to up-valley wind reversals are discussed further by Zumpfe (2004). Briefly, northerly wind reversals included all days where a strong lake-breeze front passed or an up-valley wind reversal occurred at SLC between 1500 UTC and 2200 UTC. Strong lake-breeze frontal passages were accompanied by an increase in dew point temperature of at least 2.5°C as well as a northerly wind-shift. During the period 1948-2003, northerly wind reversals were most common April through October at SLC with the peak of occurrence in early October (Fig. 3). The number of strong lake-breeze frontal passages for each day of the year was quite variable throughout the record with the peak of occurrence in early July and lesser maxima in early October and May (Fig. 4). This climatology focused primarily on the time of year when northerly wind reversals and lake-breeze frontal passages were most frequent at SLC (April through October).

It was hypothesized that periods with high average Lake surface elevation would have more lake-breeze frontal passages at SLC than periods with low average Lake surface elevation. In other words, as the Lake surface elevation increases, the areal extent of the Lake increases and the proximity of the Lake to SLC decreases, both of which might lead to increased differential heating between the Lake and Valley.

For each April through October period between 1948 and 2003, the average Lake surface elevation ranged from approximately 1278 m in 1963 to 1284 m in 1986 (Fig. 5). The Lake surface elevation was around 1280 from the late 1940's through the 1950's while decreasing to less than 1279 m during the mid 1960s. During the 1980's, above normal precipitation for Great Salt Lake drainages caused the lake surface elevation to rapidly increase from approximately 1280 m in 1980 to 1284 m in 1986. After 1987, the Lake surface elevation declined rapidly back to 1280 m by 1994. During the last 10 years, the average summer Lake surface elevation peaked at approximately 1282 m in 1999 and declined to approximately 1279 m by 2003 as the result of below normal precipitation over Lake drainages.

A northerly wind reversal was observed on nearly one-half of all days at SLC during each April through October period 1948-2003 (not shown). The number of days where a northerly wind reversal was observed at SLC varied between 71 days in 1957 and 123 days in 1988, averaging approximately 100 days per April through October period. Although there was some interannual variability in the number of northerly wind reversal days, there does not appear to be a relation to the average Lake surface elevation.

Strong lake-breeze frontal passages were observed at SLC each April through October period 1948-2003 (Fig. 6). The number of lake-breeze passages ranged from 1 in 1949 and 1967 to 33 in 1987. The lowest average number of lake-breeze frontal passages were found during the late 1960’s while the highest average number of lake-breeze frontal passages were found during the mid 1980’s. The number of strong lake-breeze frontal passages at SLC was correlated with the average summer Lake surface elevation. Hence, the linear correlation coefficient between the Lake surface elevation and the number of lake-breeze frontal passages for this study period is 0.75, which is significant at the 99% confidence level. In general, the annual number of strong lake-breeze frontal passages increased as the average Lake surface elevation increased. 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. For example, the variation in wind reversals from year-to-year depended in part on the number of synoptic-scale weather features that occurred. The summer (JJA) of 1996 was among the summers with the fewest days with precipitation on record and hence the number of northerly wind reversals and strong lake-breeze frontal passages were the highest for summer during the 56-year period.

*b. Objectives*

The climatology in the previous subsection suggests that northerly wind reversals between 1500 UTC and 2200 UTC occur on nearly one-half of all days from April through October at SLC. Strong lake-breeze fronts, as defined in this study from the SLC record, occur on roughly one-tenth of all days from April through October. In part, the relatively low number of lake-breeze frontal passages reflects the stringent requirements applied and hence may represent an underestimate of these occurrences. For example, the strong lake-breeze front observed on 15 October 2000 (Fig. 2b) did not meet these criteria since no large dew point temperature increase was observed at SLC even though an increase was evident at other locations such as VPN05.

While lake-breeze fronts may be observed occasionally during the summer, the VTMX (Vertical Transport and Mixing Experiment) and URBAN 2000 field programs conducted during October 2000 provided an unprecedented opportunity to investigate lake breezes and their interactions with other thermally driven flows in the vicinity of the Valley as already shown in several earlier figures. It is expected that, even if there was no Lake, a northerly (up-valley) flow would be present during the afternoon in the Valley as a result of differential heating between the Great Salt Lake Basin and surrounding mountains (Rife et al. 2002). However, of interest in this study is how the Lake superimposes further thermal forcing arising from differential heating between the Lake surface and surrounding dry soils upon the terrain-driven flows.

The specific purpose of this paper is to improve understanding of strong lake-breeze fronts that move from the vicinity of the Lake through the Valley and the interaction of the lake breeze with other thermally driven flows in the Valley. The spatial and temporal characteristics of a strong lake-breeze front and its interactions with the synoptic environment and thermally driven mountain-valley circulations in the Valley is presented using data collected during VTMX (Doran et al. 2002) and URBAN 2000 (Allwine et al. 2002) on 17 October 2000. The 17th was selected over the other 4 days (15-19 October) with lake-breeze frontal passages during this month because of the amount of specialized data available between two Intensive Observation Periods (IOP's 6 and 7).

Section 2 describes the data used to evaluate the case study of the lake-breeze front. The lake-breeze front case study is presented in Section 3. Section 4 will summarize the results of this study and conclude with suggestions concerning future research.

## 2. Data

Two field programs took place in the Valley during October 2000, providing an unprecedented amount of boundary layer observational data. The VTMX field program primarily investigated stable nocturnal boundary layer characteristics and processes in the Valley (Doran et al. 2002) while URBAN 2000 was concerned with flow and dispersion of tracer material through and near an urban setting such as downtown Salt Lake City (Allwine et al. 2002). Those directly involved in the two field programs included commercial, military, government, and educational institutions including the Department of Meteorology at the University of Utah (UUtah).

Automated observational systems were utilized throughout the Valley and nearby mountain canyons during the VTMX and URBAN 2000 field programs and were available for the 17 October 2000 lake breeze case study. Surface observations were provided by the Pacific Northwest National Laboratories (PNNL), the National Center for Atmospheric Research Atmospheric Technology Division (NCAR-ATD), and UUtah that measured temperature, dew point temperature, pressure, relative humidity, and wind direction, gust, and speed in 5-minute intervals (see Fig. 1). These automated field observations were supplemented with observations from permanent sites maintained by mesonet providers in the UUtah MesoWest surface observation network (Horel et al. 2002). Only data that consistently passed data quality checks made by MesoWest are included in this study.

Special rawinsondes were used by many of the organizations to measure atmospheric profiles overnight during VTMX. The routine 1200 UTC 17 October and 0000 UTC 18 October soundings, supplemented by a rare afternoon 2100 UTC 17 October sounding preceding IOP-7, were launched by the National Weather Service (NWS) at Salt Lake City International Airport (see Fig. 1). Rawinsondes were also launched at Wheeler Farm by UUtah students during IOP-7 beginning on the afternoon of 17 October (see Fig. 1). This high-resolution sounding data helps to show the effects of the lake-breeze frontal passage on the vertical wind and temperature profiles over the central Valley.

A radar wind profiler that was located at Raging Waters measured the three dimensional wind field, in 1-hour averages and 60 m intervals, from 100-2000 m agl (see Fig. 1).

This profiler was operated by the National Oceanic and Atmospheric Administration Field Research Division (NOAA-FRD).

A doppler lidar operated by the National Oceanic and Atmospheric Administration Environmental Technology Laboratory (NOAA-ETL) (located at U42 during VTMX) scanned radially and in range-height cross sections at various intervals during the morning (end of IOP-6) while resuming operations later during the afternoon on 17 October (beginning of IOP-7) (see Banta et al. 2004).

A vertically pointed lidar was placed in the Jordan Narrows by NCAR-ATD to measure the backscatter reflectivity of particles within the lowest 2 km (see Fig. 1). This lidar operated continuously during VTMX for the purpose of identifying the atmospheric aerosol structure and making quantitative aerosol measurements.

The Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR), located 22 km north the Salt Lake City International Airport, was also used to determine the lake-breeze frontal movement on 17 October 2000.

## 3. Case Study

### *a. Synoptic setting and overview*

A strong 500 hPa ridge resided over the western US with the axis extending from extreme western Utah to British Columbia at 1200 UTC 17 October 2000 (not shown). The 1200 UTC sounding at SLC indicated southeasterly winds from 4-5 m $s^{-1}$ between the surface (878 hPa) and crest level (near 700 hPa), veering just above crest level from southerly at 5 m $s^{-1}$ to westerly near the tropopause (200 hPa) at 9 m $s^{-1}$ (Fig. 7). Clear skies and light winds prior to sunrise allowed a shallow near-surface inversion to form at SLC.

The synoptic-scale ridging provided the large-scale conditions favorable for down-valley, down-slope, and down-canyon flows that contributed to the formation of a land breeze directed toward the Lake. The intensity and vertical extent of the down-valley flow and land breeze were evident in the radial velocity data from the NOAA-ETL lidar located at U42 (not shown). The down-valley flow was 3-6 m $s^{-1}$ to a depth of 1-1.5 km with the peak winds in the lowest 200 m.

As a means to summarize the complex evolution of the lake-breeze front in the context of the other thermally driven flows present in the vicinity of the Valley, summary diagrams are presented in Figs. 7 and 8. Throughout the Valley and Wasatch Mountain canyons, wind reversals occurred prior to the lake-breeze frontal passage (Fig. 8). Eastern Valley and Wasatch Mountain canyon sites within the dashed white boundary indicate the area where thermally driven up-slope and up-canyon wind reversals occurred during the period 1400-1900 UTC. The isochrones in the western Valley represent an apparent propagation of the thermally driven up-valley flow from north to south. As will be discussed later, the up-valley flow transition was seen in the time-series of many surface sites yet the apparent propagation speed is much faster than can be explained by an advective process. The up-valley transition began in the northern Valley at roughly 1900 UTC, reaching the Traverse Range to the south by 2230 UTC.

The lake-breeze front traveled southward through the Valley from 1900-2330 UTC at an average speed of 3 m $s^{-1}$ as shown spatially by the isochrones in Fig. 9. The lake-breeze front became superimposed upon the up-valley flow in the western Valley and the up-slope and up-canyon flows in the eastern Valley. There was some evidence of the lake-breeze front superimposed upon up-canyon flow at VTMX9 in Parley's Canyon during the period 2200-2300 UTC (not shown).

As a representation of the fine-line spatial structure of the lake-breeze front, insects, dust, and other scatterers were concentrated along the front as it moved southward through the Valley (not shown). Although both the reflectivity and radial velocity channels showed some anomalous echoes, the lake-breeze front was initially evident from the TDWR returns at 1940 UTC. The lake-breeze front initially traveled faster into the western Valley and became oriented from southwest to northeast as summarized in Fig. 9. As the lake-breeze front evolved, it became oriented more zonally in the western two-thirds of the Valley by 2059 UTC and 2225 UTC. The lake-breeze front reflectivity signature became difficult to follow as it approached the Traverse Range after 2225 UTC when the radar beam began to overshoot the depth of the lake breeze airmass.

The lake-breeze frontal passage was associated with dew point temperature increases at most Valley sites (Fig. 10). 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 strong lake-breeze front climatology presented in Section 1. The lake-breeze front is represented here as a wave of dew point temperature increase, with mostly negative or near-zero hourly dew point temperature changes following frontal passage. Hour-to-hour increases in dew point temperatures of 1–2°C were used to help define the evolution of the lake-breeze front as shown in Fig. 10.

*b. Near-surface evolution*

The evolution of surface wind, temperature, and moisture within the Valley is now presented. Pressure changes associated with the lake-breeze frontal passage were found to be minimal and will not be discussed further in this section. Hodographs for selected surface sites are shown in Fig. 11. Down-valley, down-slope, down-canyon and land breeze winds were evident at sites in the Valley and Wasatch Mountain canyons from 0605-2230 UTC as will be documented in greater detail later. Central Valley sites VPN05 (Fig. 11b), VPN11 (Fig. 11c), and VPN01 (Fig. 11g) were dominated by south-southeasterly down-valley and land breeze winds overnight and during the early part of the day. VPN12 (Fig. 11f), located on the western slope of the Valley, had west-northwesterly down-slope winds prior to sunrise (1341 UTC) that transitioned to east-southeasterly up-slope winds thereafter. Eastern Valley sites VPN04 (Fig. 11d) and VPN06 (Fig. 11h) had easterly down-slope and down-canyon winds, transitioning to westerly up-slope and up-canyon winds after sunrise. An abrupt increase in wind speed associated with the lake-breeze front is delineated for VPN05 (Fig. 11b), VPN11 (Fig. 11c), VPN12 (Fig. 11f), and VPN01 (Fig. 11g). At Wasatch Mountain canyon sites VTMX2 (Fig. 11i) and VTMX9 (Fig. 11e), easterly down-canyon winds were evident through the morning, transitioning to westerly up-canyon winds during the afternoon.

The lake-modified airmass on this day can be characterized by the lake and air temperature near the center of the Lake at Hat Island. The lake temperature, observed in the shallows near Hat Island, ranged from 12-15°C while the air temperature ranged from 11-14°C on this day (not shown). In contrast, the surface air temperature over the Valley exhibited a diurnal range of roughly 2-25°C.

The onset of the lake breeze was evident near the shore of the Lake. Wind at SLC was southeasterly at 3-4 m $s^{-1}$ from sunrise (1341 UTC) through 1555 UTC and then calm thereafter through 1855 UTC (not shown). The dew point temperature at SLC ranged between 2°C and 3°C from sunrise through 1855 UTC. At 1955 UTC, the lake-breeze frontal passage was seen at SLC as the wind shifted to northerly and increased to 4 m $s^{-1}$. The criteria for a strong lake-breeze frontal passage, as applied to the lake-breeze front climatology in Section 1, was satisfied as the dew point temperature at SLC increased from 2.8–5.6°C during the period 1855-1955 UTC. The exact timing of the lake-breeze frontal passage at SLC was unclear due to the hourly temporal resolution of observations. The rate of temperature increase prior to the lake-breeze frontal passage at SLC was higher than after the frontal passage. Wind speed decreased as the lake breeze transitioned to the land breeze after 0100 UTC 18 October.

The lag between the onset of the up-valley winds and the lake-breeze front grew progressively larger with time as a function of up-valley distance (see Figs. 8 and 9). This lag was largest at sites in the south part of the Valley including VPN01 and HGP (Fig. 12). At VPN01, the wind veered from a southerly down-valley and land breeze direction to a northerly up-valley direction between 2000 UTC and 2100 UTC, with wind speed averaging 1 m $s^{-1}$ throughout the up-valley transition (Fig. 12a). The lake-breeze front passed at 2210 UTC as wind speed increased by 2 m $s^{-1}$ and dew point temperature by 3.3°C across the front. At HGP, wind decreased from 4 m $s^{-1}$ at 1930 UTC to 1 m $s^{-1}$ at 2200 UTC, accompanied by the transition from a south-southeasterly down-valley and land breeze direction to a north-northwesterly up-valley direction after 2200 UTC (Fig. 12b). The lake-breeze front passed HGP at 2335 UTC, accompanied by an increase in wind speed to 7 m $s^{-1}$ by 0005 UTC 18 October and a 3.7°C dew point temperature increase across the front. After 0005 UTC, wind speeds at HGP gradually decreased to calm as the transition to the down-valley and land breeze wind occurred after 0400 UTC.

Thermally driven up-slope and up-valley wind interactions with the lake-breeze front were evident at the western Valley site VPN12 (not shown). VPN12 was located on a gradual slope of the Oquirrh Mountains in the western Valley (the Whiteman Slope). The transition from down-slope wind to up-slope wind coincided with a temperature increase from 3.6–10.4°C between 1405 UTC and 1505 UTC at VPN12. The rate of temperature increase slowed thereafter and remained constant from 1505-2110 UTC. Through the transition to the up-slope direction, wind speed decreased from 2 m $s^{-1}$ to calm and increased to 4 m $s^{-1}$ after 1600 UTC. After 2110 UTC, west-southwesterly up-slope wind decreased to 1 m $s^{-1}$ and temperature increases became negligible as wind transitioned to the north-northeasterly up-valley direction. Wind speed at VPN12 remained light from the onset of up-valley winds until the lake-breeze frontal passage at 2205 UTC. Then, the wind speed increased to 2.5 m $s^{-1}$ and dew point temperature increased by 2.7°C across the front. Wind transitioned from the northerly lake breeze direction to the west-southwesterly down-slope direction and decreased to an average of 2 m $s^{-1}$ from 0030-0100 UTC 18 October.

### *c. Three-dimensional Structure*

A variety of data resources are now used to diagnose the three-dimensional structure of the lake-breeze front and the boundary layer ahead of and behind the front. The lake breeze boundary layer was clearly evident in the northern Valley by 2100 UTC (Fig. 13). 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. The sounding launched from SLC three hours later (not shown) did not differ significantly from the afternoon sounding.

The time-height evolution of the lake-breeze front and associated boundary layer was indicated by the NOAA-FRD wind profiler located at Raging Waters (not shown). The leading edge of the lake-breeze front passed Raging Waters at 2000 UTC and was roughly 400 m deep; by 0000 UTC 18 October, the depth increased to roughly 700 m. 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 and land breeze winds.

At Wheeler Farm in the east central Valley, rawinsondes were launched at the outset of IOP-7 beginning at 2152 UTC (Fig. 13). Fortunately, the first launch appears to have been slightly ahead of the lake-breeze front as the winds were initially light northwesterly from the surface to 500 m agl and there was less evidence of strong vertical mixing (i.e., a superadiabatic layer was found near the surface). By the time of the next launch (2250 UTC), wind speeds increased significantly and potential temperature was nearly constant with height in the lowest 600 m. By 0000 UTC 18 October, a surface inversion began to form while the lake breeze persisted aloft. Both the NOAA-ETL lidar located at U42 (not shown) and Wheeler Farm rawinsondes (Fig. 13) indicated light winds from the east reversing to down-valley above 1000 m agl (above the lake breeze).

The high-resolution NCAR-ATD lidar data collected at the NCAR site in the Jordan Narrows defined several critical characteristics of the lake-breeze front around 2325 UTC and the earlier up-valley wind reversal (Fig. 14). After 2130 UTC, aerosols began to be transported in bursts to as high as 800 m agl, although mixing is most evident below

600 m agl. When the thermally driven up-valley flow became evident at the southern end of the Valley after 2230 UTC, the vertical transport of aerosols became somewhat more regular. Beginning at 2325 UTC, three distinct waves at the top of the boundary layer were evident, suggesting that gravity waves had been excited at the leading edge of the lake-breeze front with vertical displacements around 150 m. A small pressure increase after the lake-breeze frontal passage was evident at the NCAR surface site (not shown) coinciding with the turbulent mixing seen in Fig. 14. Observational and modeling studies have shown similar turbulent mixing associated with gravity waves, Kelvin-Helmholtz billows, and internal bores coinciding with other types of mesoscale discontinuities such as sea-breeze fronts (Sha et al. 1991, 1993) and gust fronts from dissipating thunderstorms (Koch et al. 1991). Higher concentrations of aerosols up to 800 m agl were observed by the NCAR-ATD lidar for several hours after the lake-breeze frontal passage.

## 4. Summary and conclusions

The goal of this study was to determine the extent to which variations in the areal coverage and surface elevation of the Great Salt Lake affected the frequency of occurrence and characteristics of lake breezes in the Salt Lake Valley. Objective criteria were used to discriminate between up-valley wind reversals and strong lake-breeze frontal passages that occurred at SLC during summers from 1948-2003. This preliminary study suggested that the frequency of occurrence of northerly wind reversals between late morning and early afternoon during summer was insensitive to Lake surface elevation while a statistically significant relationship was evident between Lake surface elevation and the occurrence of strong lake-breeze fronts 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 given summer as there was large summer-to-summer variability in lake breeze occurrences, presumably due to variability in upper-level height patterns.

Figure 8 summarizes a couple of the salient features of the thermally driven flows prior to the passage of the lake-breeze front on 17 October 2000. The down-slope and down-valley flows in the eastern third of the Valley shifted to up-slope during the period 1400-1700 UTC while down-canyon flow reversed to up-canyon in the nearby Wasatch Mountains by 1900 UTC. In contrast, southerly (down-valley and land breeze) winds present through a depth of 1-1.5 km in the western two-thirds of the Valley increased in magnitude during the morning. Ultimately, the wind reversed to an up-valley 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 appears to reflect interactions between the thermally driven up-valley wind and the opposing large-scale southerly wind. This propagating wind reversal was similar to that observed in the Alpine foothills of central Switzerland by Richner and Griesser (1993).

The lake-breeze front progressed up the Valley from 1900-2330 UTC at roughly 3 m $s^{-1}$ (Fig. 9) and was accompanied by a 3-4 km band of moisture (Fig. 10). Consistent with previous modeling and observational studies (e.g., Segal et al. 1997), large-scale winds in the Valley opposing the lake breeze appeared to strengthen the lake-breeze front. The front became 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.

There were indications that the lake-breeze front extended up Parley's Canyon with a 2.5°C dew point temperature increase at 2215 UTC (not shown).

The SLC and Wheeler Farm soundings, combined with profiler and lidar observations at several sites within the Valley, provided a unique opportunity to diagnose the structure of the boundary layer on 17 October. Pre- and post-frontal atmospheric conditions over the Lake and Valley are summarized in Fig. 15. Prior to the lake-breeze frontal passage, a superadiabatic layer was evident in the lowest 100 m beneath a nearly adiabatic layer through 600-800 m agl with light winds throughout both layers. The lake-breeze frontal passage was characterized 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 gravity waves observed at the top of the lake-breeze front by the NCAR-ATD lidar helped to explain this increased mixing aloft. Due to the lower heat capacity of the Valley surface compared to that of the Lake surface, the higher heating rate (expansion) of air over the Valley during the daytime would have resulted in a deeper boundary layer than that over the Lake even after the lake-breeze frontal passage (see Segal et al. 1997). The front was shallow (order 600-800 m) in comparison to the depth of the southerly flow overnight (order 1-1.5 km).

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Figure 1. Key observation sites in the Salt Lake Valley during October 2000.

Figure 2. Time-series at VPN05 showing (a) an up-valley wind reversal on 1 October and (b) a lake-breeze frontal passage on 15 October. In each time-series, the top graph shows temperature (°C, dark line), dew point temperature (°C, medium dark line), and relative humidity (%, faint line) while the bottom graph shows wind direction (open dots) and speed (m $s^{-1}$, dark line).

Figure 3. Number of northerly wind reversals at SLC by day of year 1948-2003 represented by a 14-day running mean.

Figure 4. Number of strong lake-breeze frontal passages at SLC by day of year 1948-2003 represented by a 14-day running mean.

Figure 5. The average Great Salt Lake surface elevation per April through October period 1948-2003.

Figure 6. Number of strong lake-breeze frontal passages at SLC per April through October period 1948-2003.

Figure 7. 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 $s^{-1}$.

Figure 8. Onset time isochrones of up-valley and area of slope flows preceding the lake-breeze front on 17 October 2000. Up-slope and up-canyon flow dominated eastern Salt Lake Valley and Wasatch Mountain canyon sites respectively (area within dashed white lines) while up-valley flow dominated western Salt Lake Valley locations (apparent propagation of up-valley wind reversal indicated by solid white lines).

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Figure 11. Plan view map (a) and hodographs for Salt Lake Valley observation sites (b) VPN05, (c) VPN11, (d) VPN04, (e) VTMX9, (f) VPN12, (g) VPN01, (h) VPN06, and (i) VTMX2 from 0605 UTC 17 - 0600 UTC 18 October 2000. All wind observations beneath the gray lines in (b), (c), (f), and (g) were taken after the passage of the lake-breeze front. The legend in the upper right corner of (a) shows wind directions with a wind speed increment of 2.5 m $s^{-1}$ for each ring.

Figure 12. Time series of observations at (a) VPN01 and (b) HGP from 0605 UTC 17 - 0600 18 October 2000. The top graph shows temperature (°C, dark line), dew point temperature (°C, medium dark line), and relative humidity (%, faint line) while the bottom graph shows wind direction (open dots), speed (m $s^{-1}$, dark line), and gust (m $s^{-1}$, faint dashed line) for (b) only.

Figure 13. Time-height cross section of soundings launched at Wheeler Farm 2152 UTC 17 - 0251 UTC 18 October. Solid lines indicate potential temperature (K) and the y-axis is height (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 $s^{-1}$. Darker shading indicates wind speeds equal to or greater than 5 m $s^{-1}$, lighter shading indicates wind speeds between 2.5 m $s^{-1}$, and no shading indicates wind speeds less than 2.5 m $s^{-1}$.

Figure 14. Time-height cross sections of lidar relative backscatter (ranging between -6 and 10 dBZ) above the Jordan Narrows from (a) 2048-2148 UTC 17, (b) 2148-2248 UTC 17, (c) 2248-2348 UTC 17, and (d) 2348 UTC 17 - 0048 UTC 18 October 2000. The crests of three wave-like structures are annotated by arrows in (c) (courtesy NCAR-ATD).

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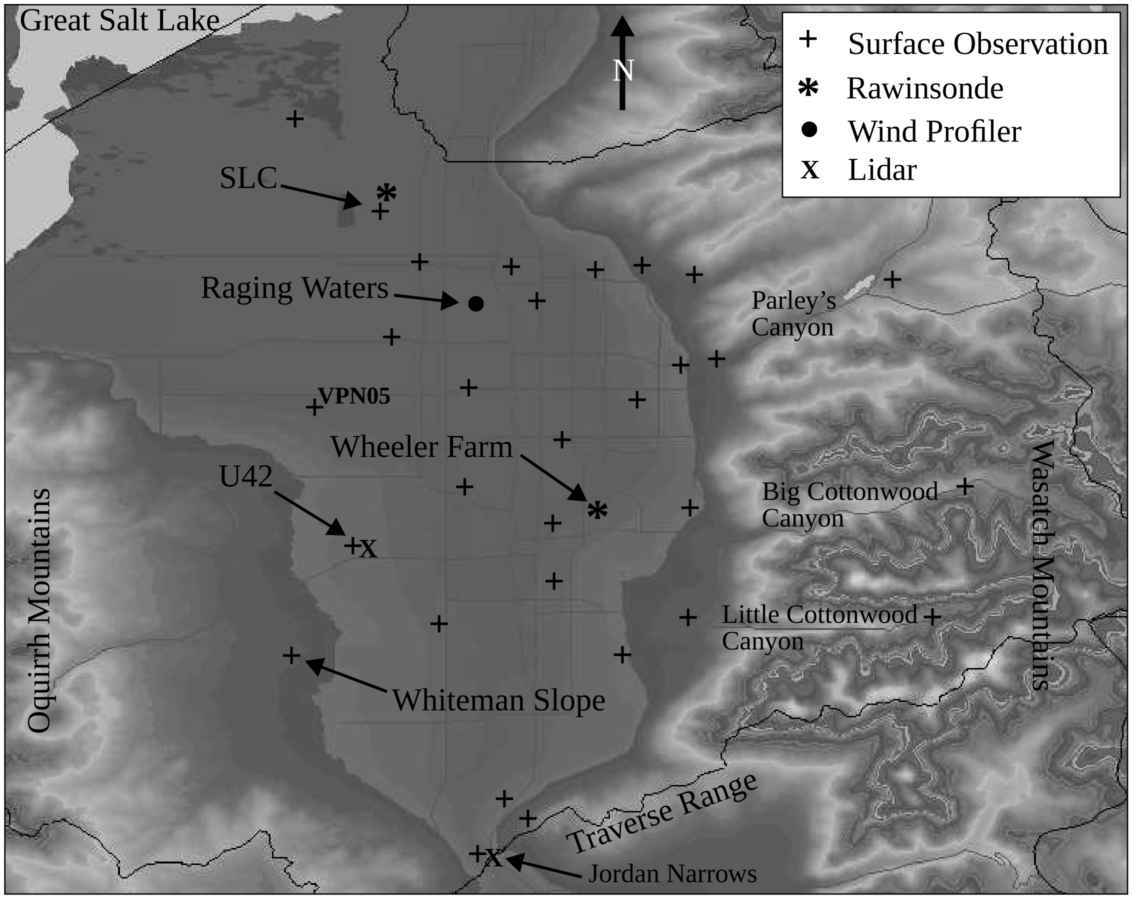


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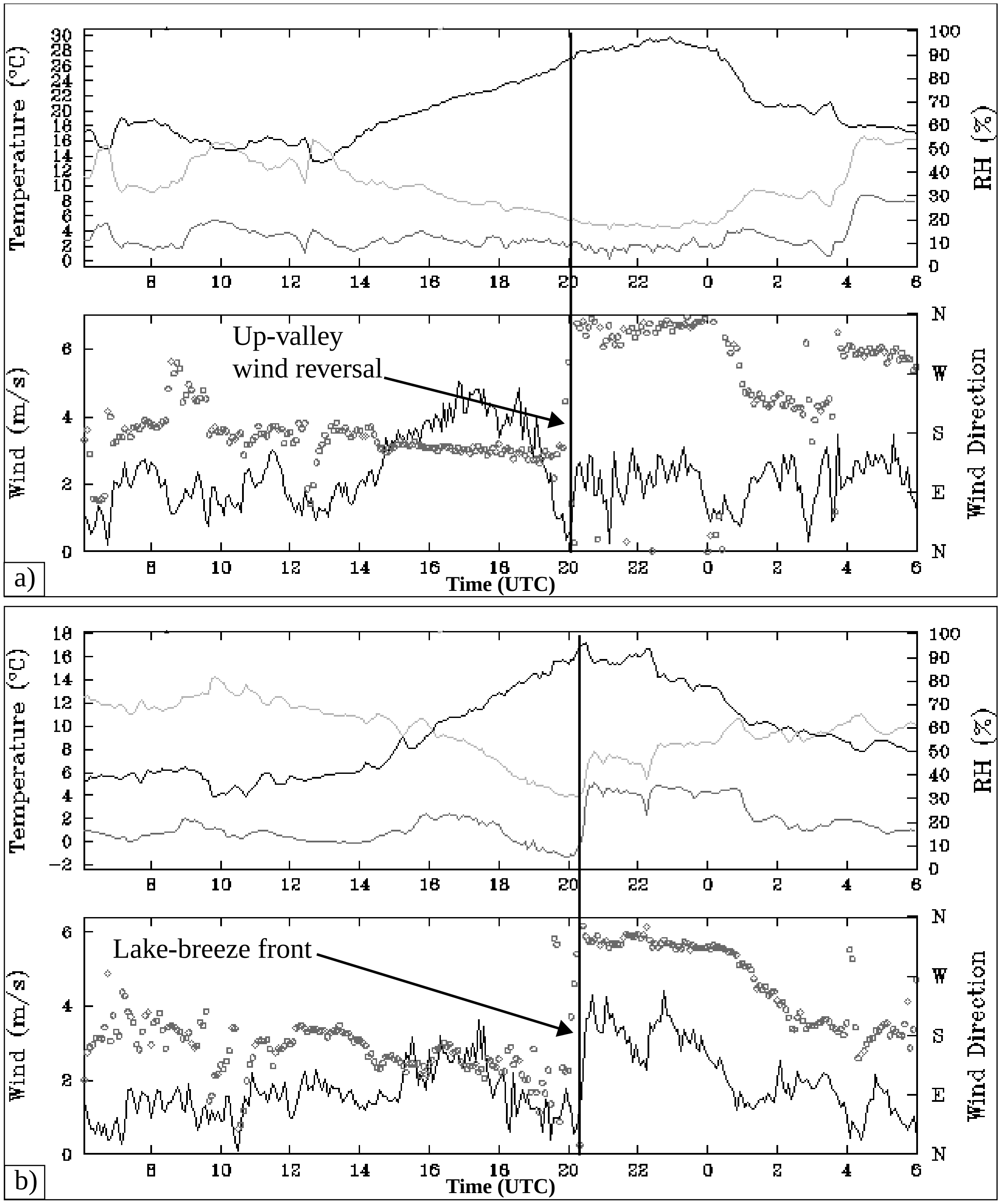


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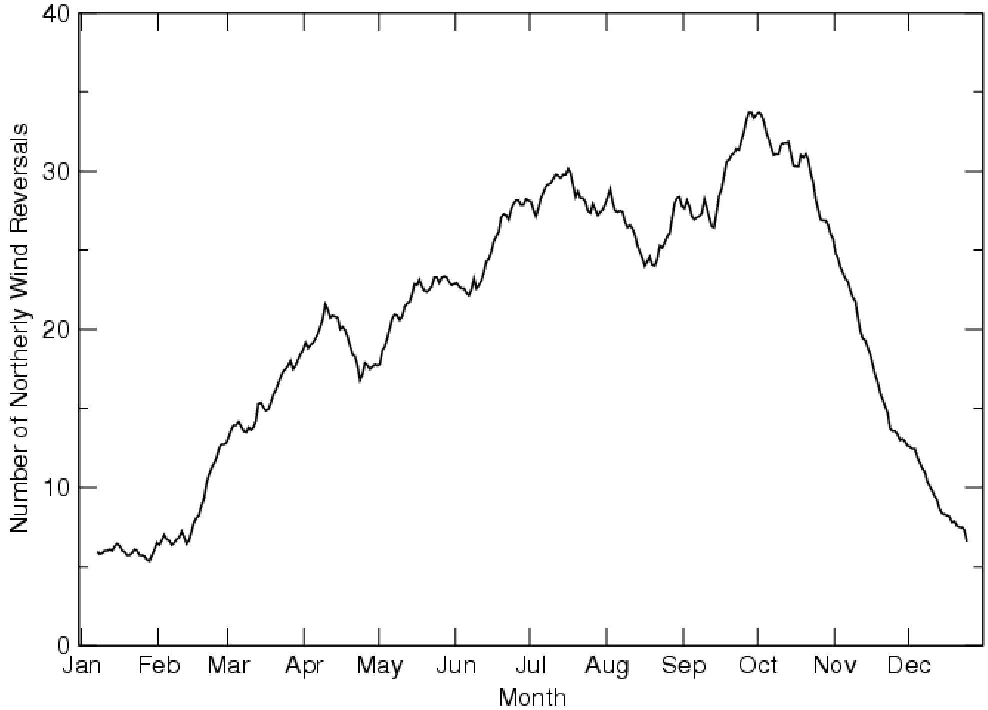


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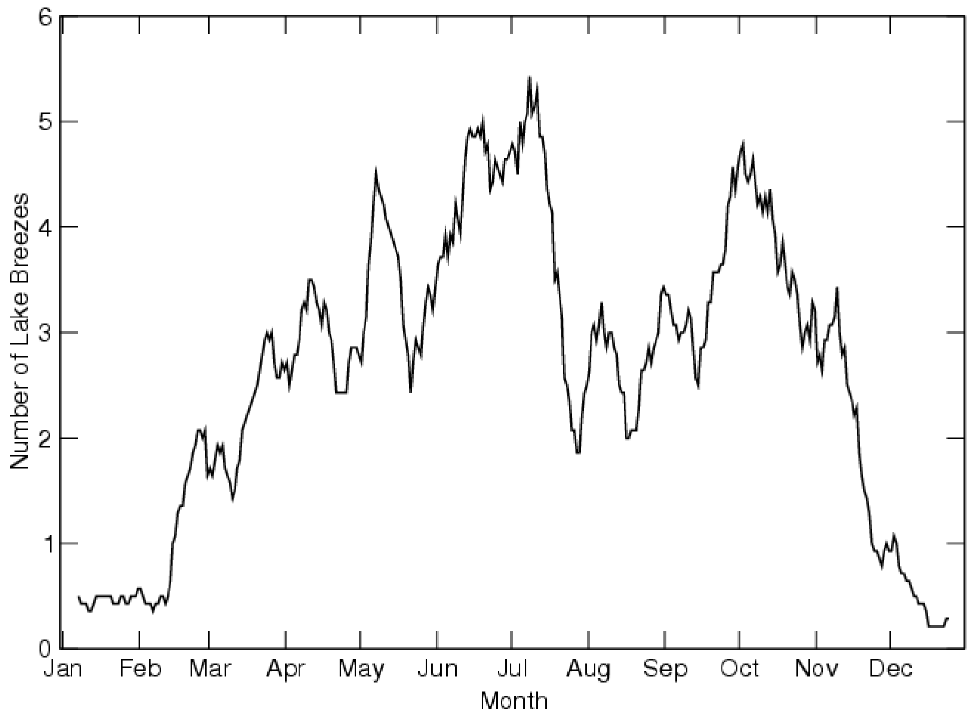


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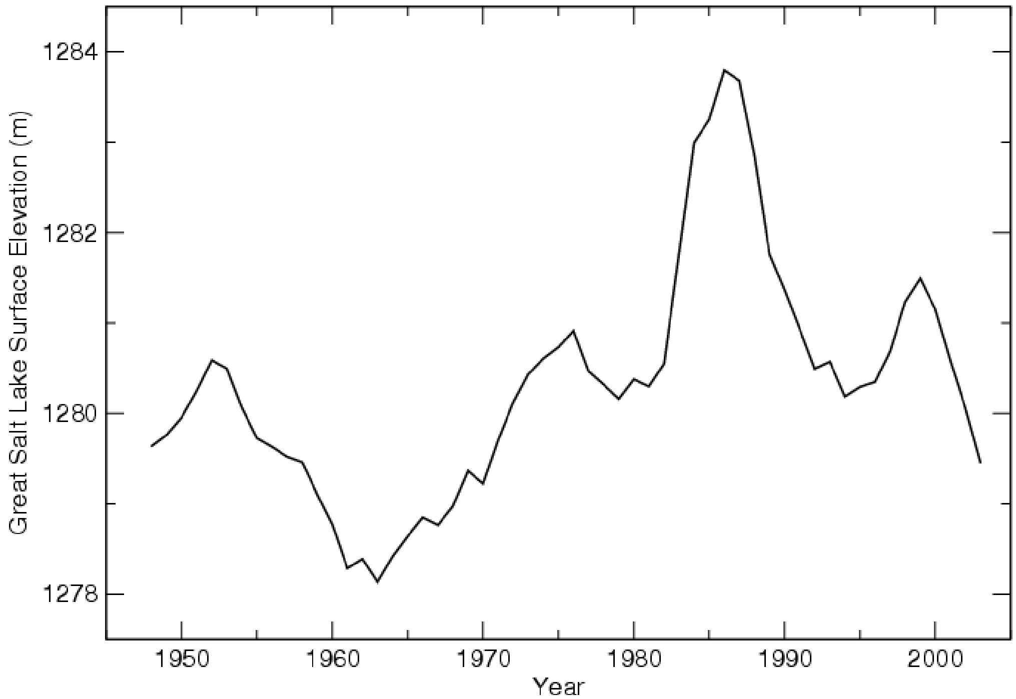


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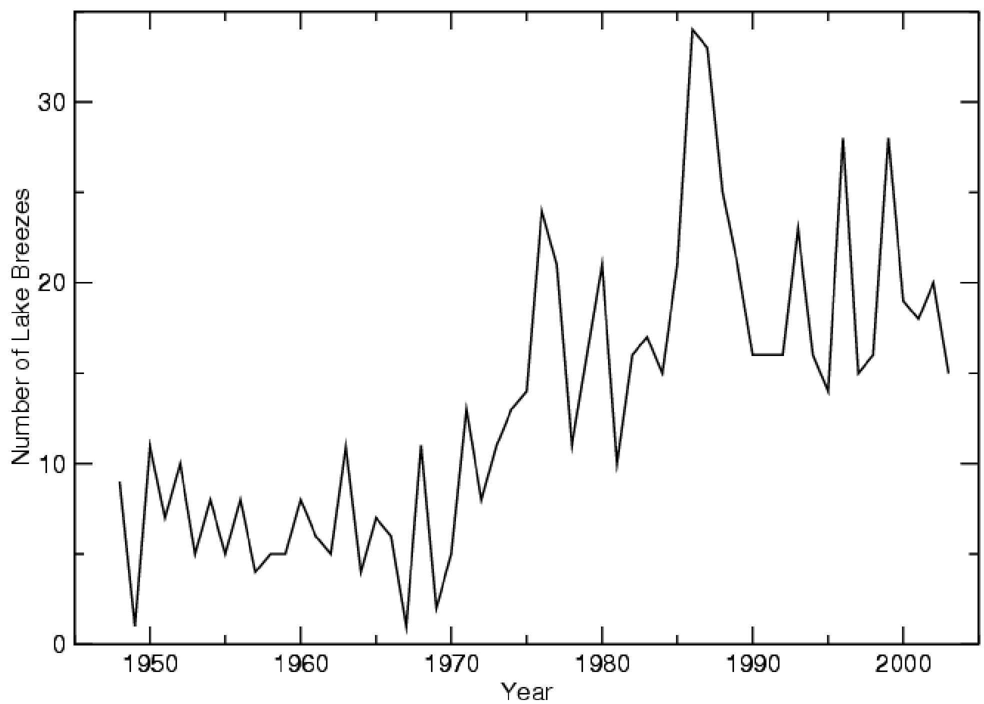


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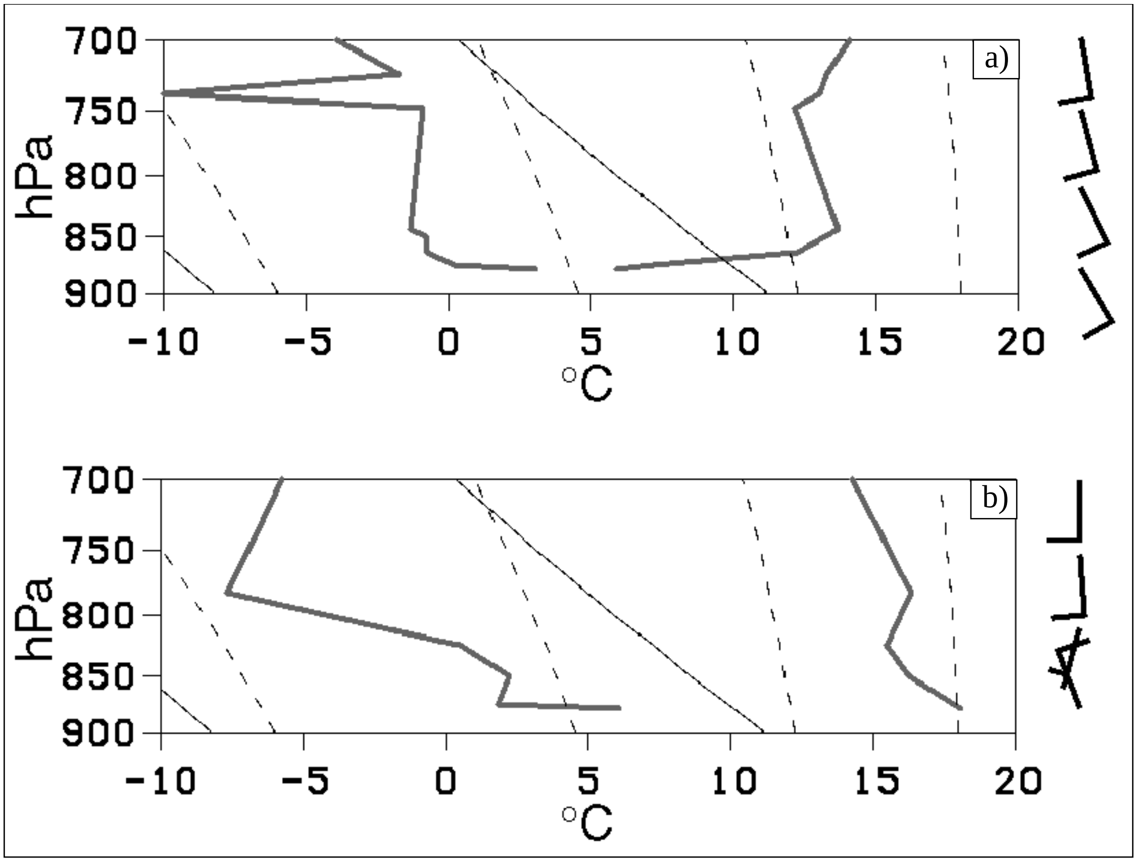


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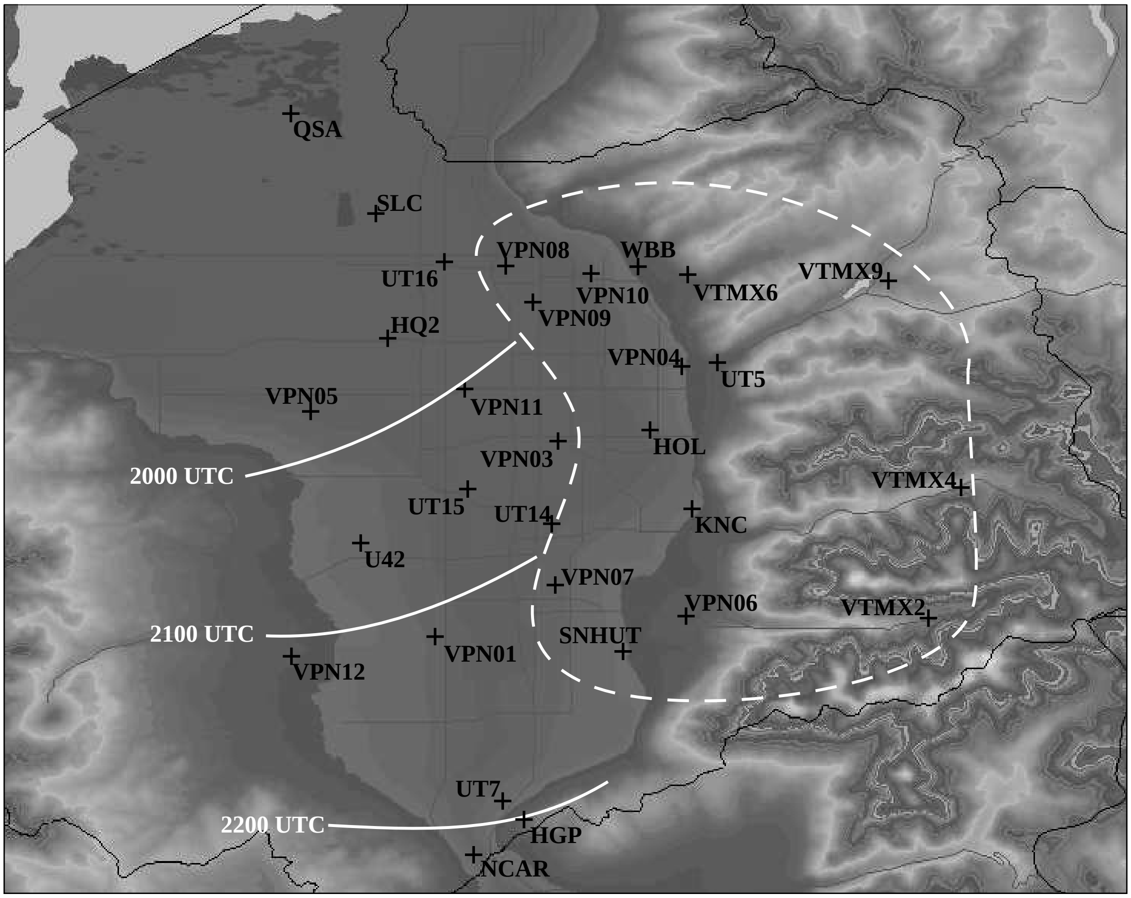


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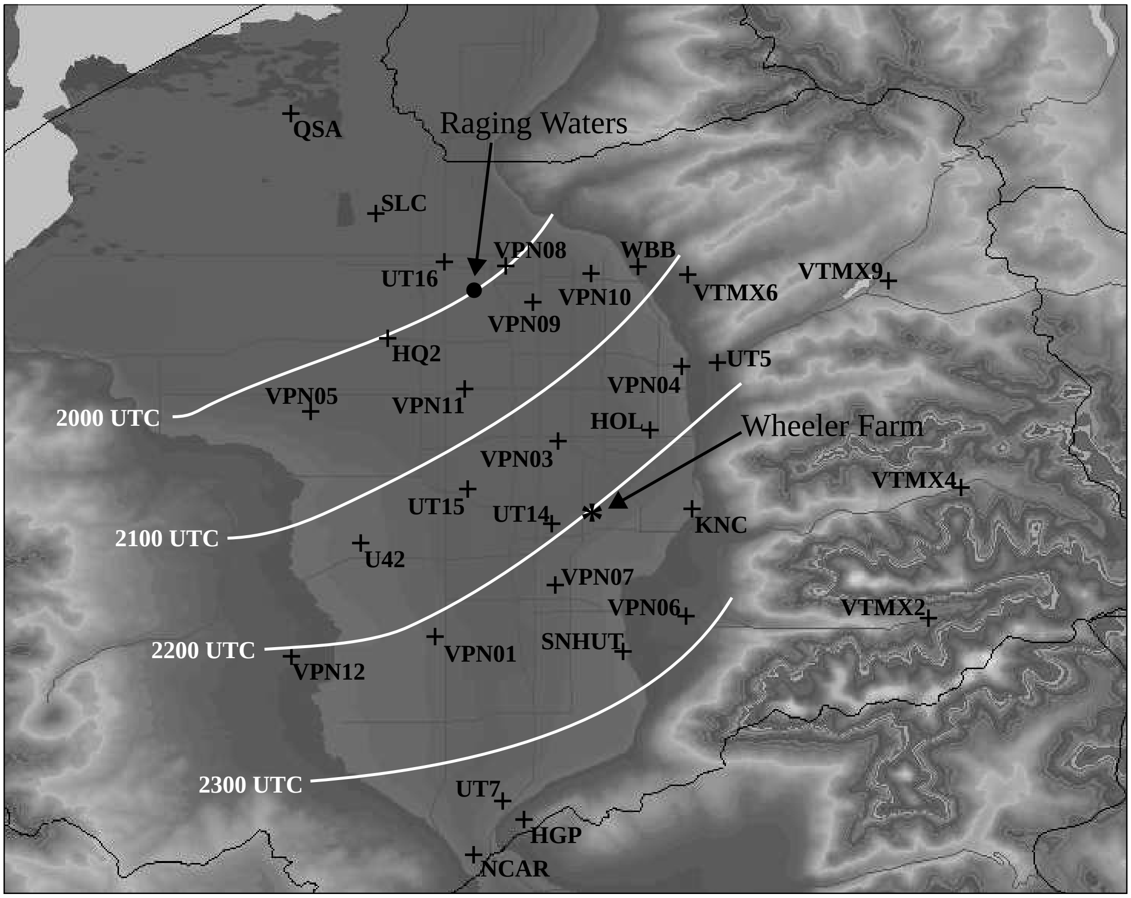


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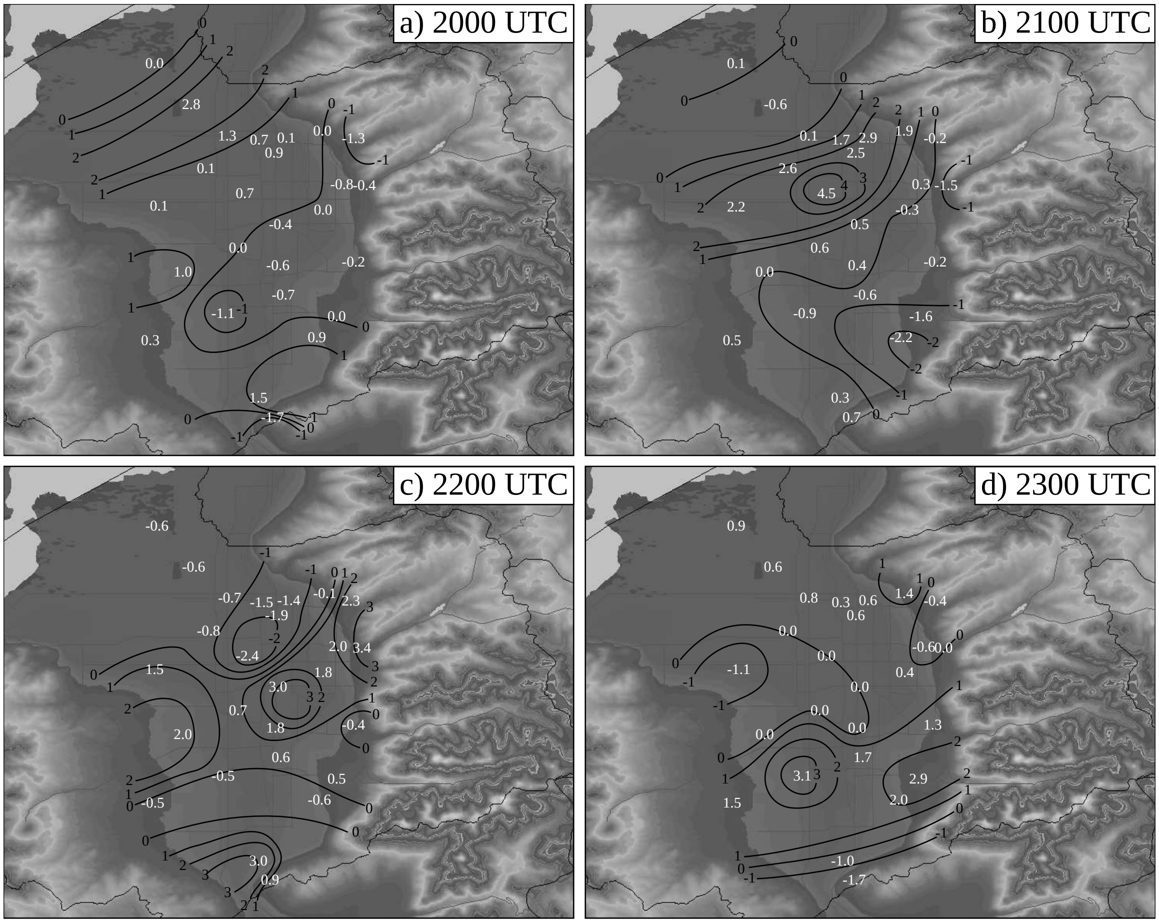


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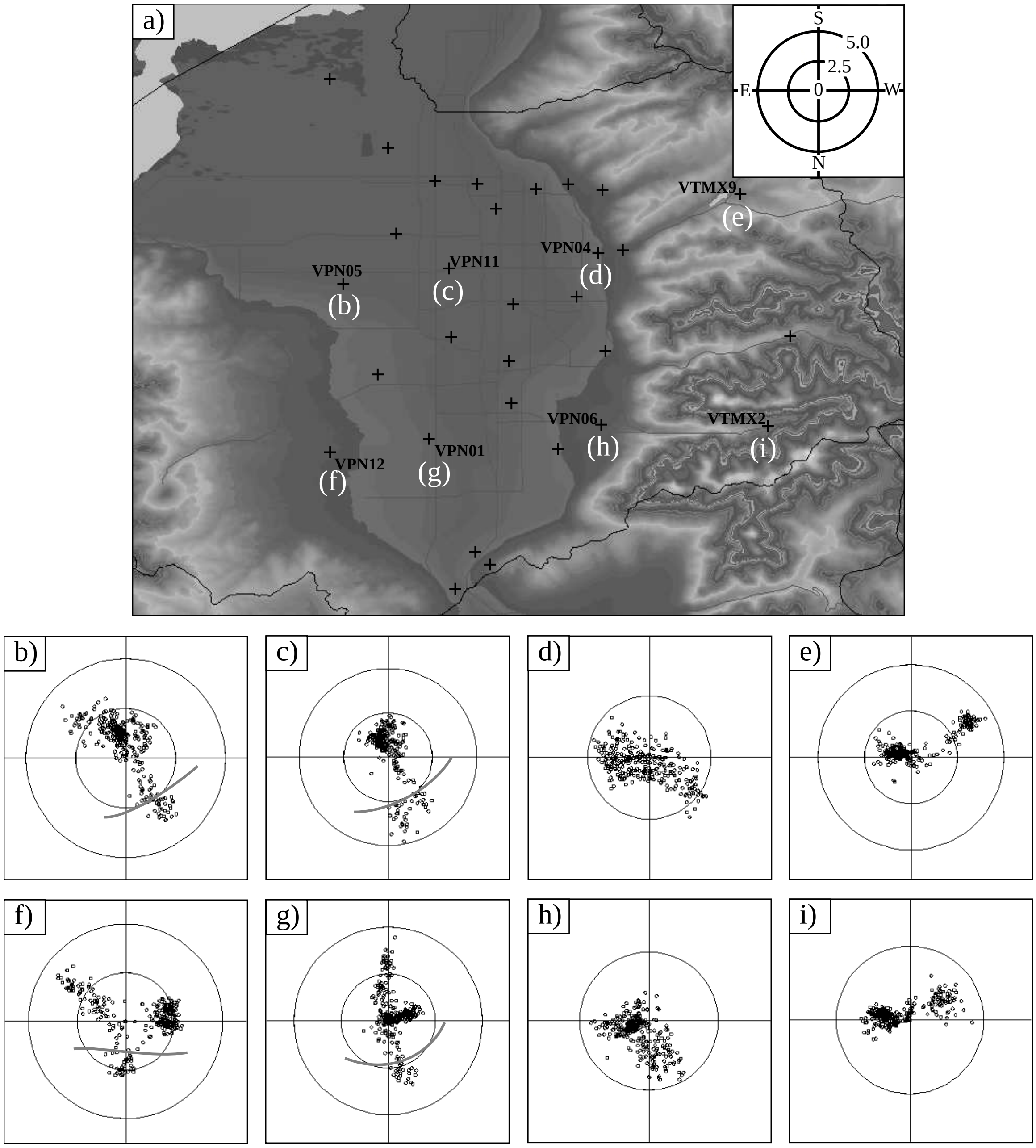


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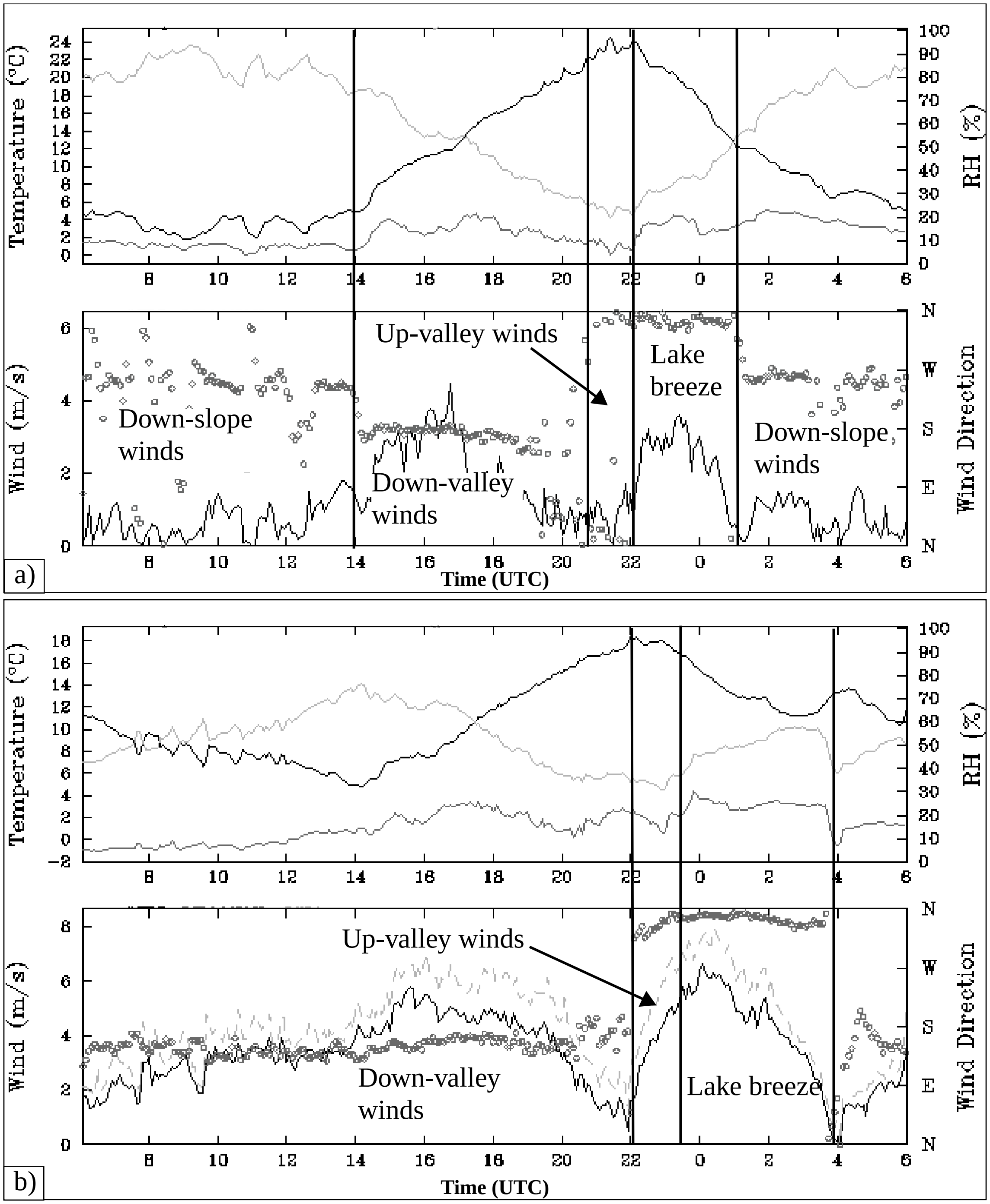


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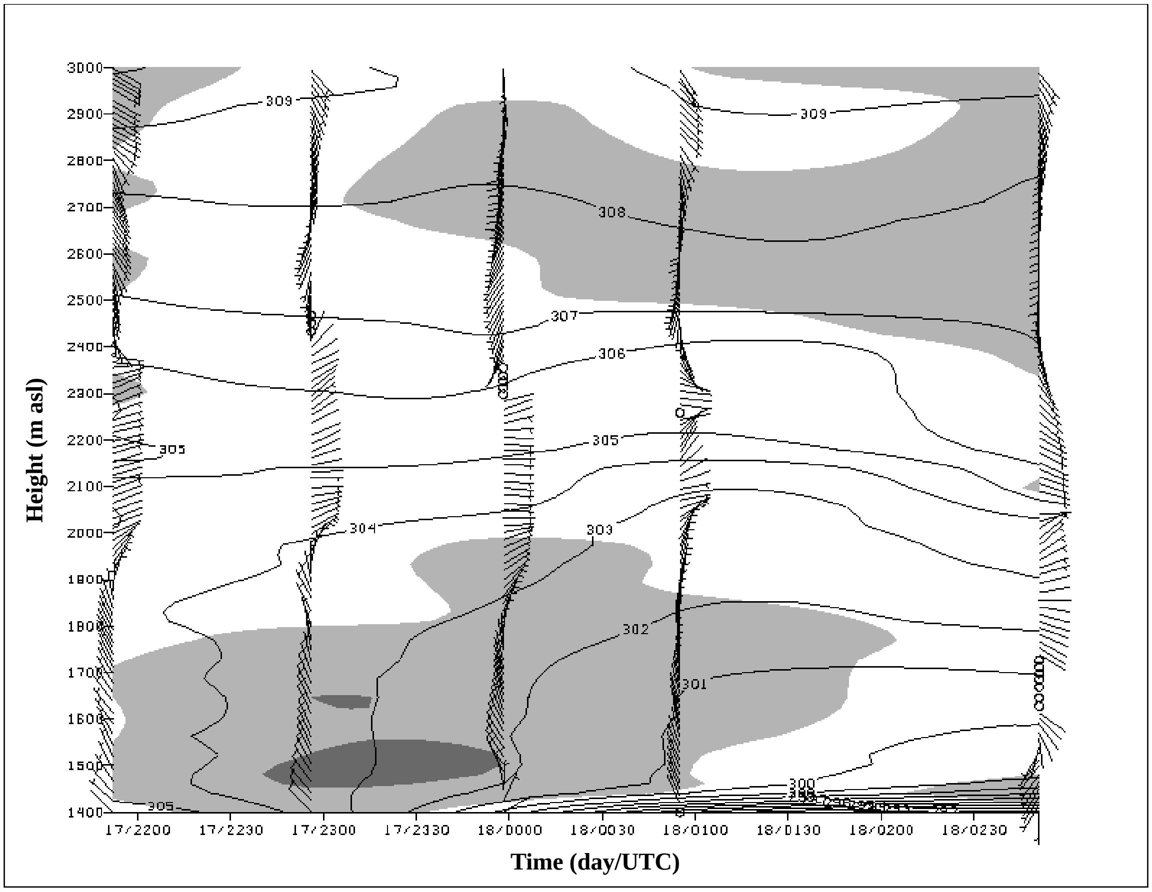


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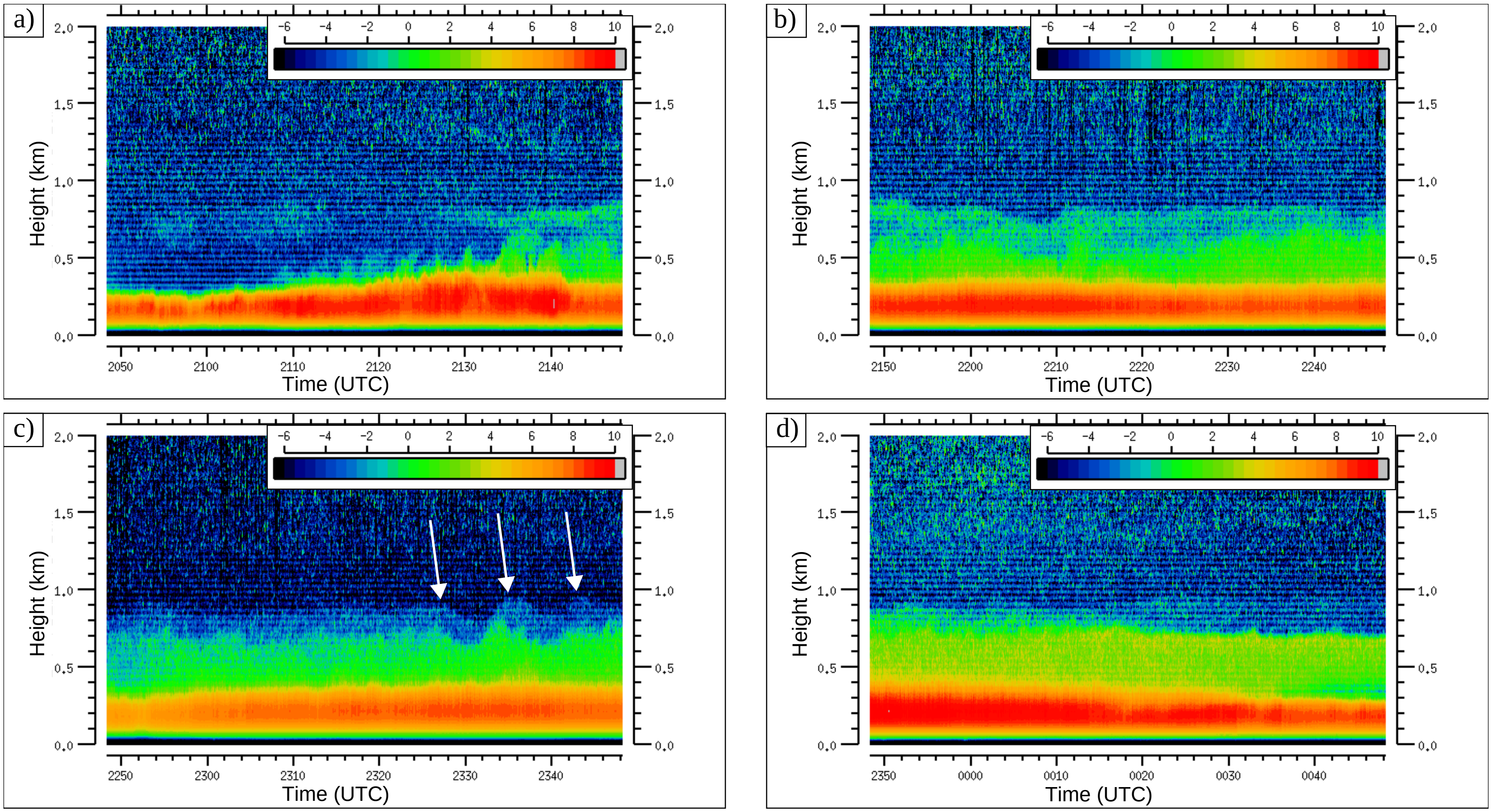


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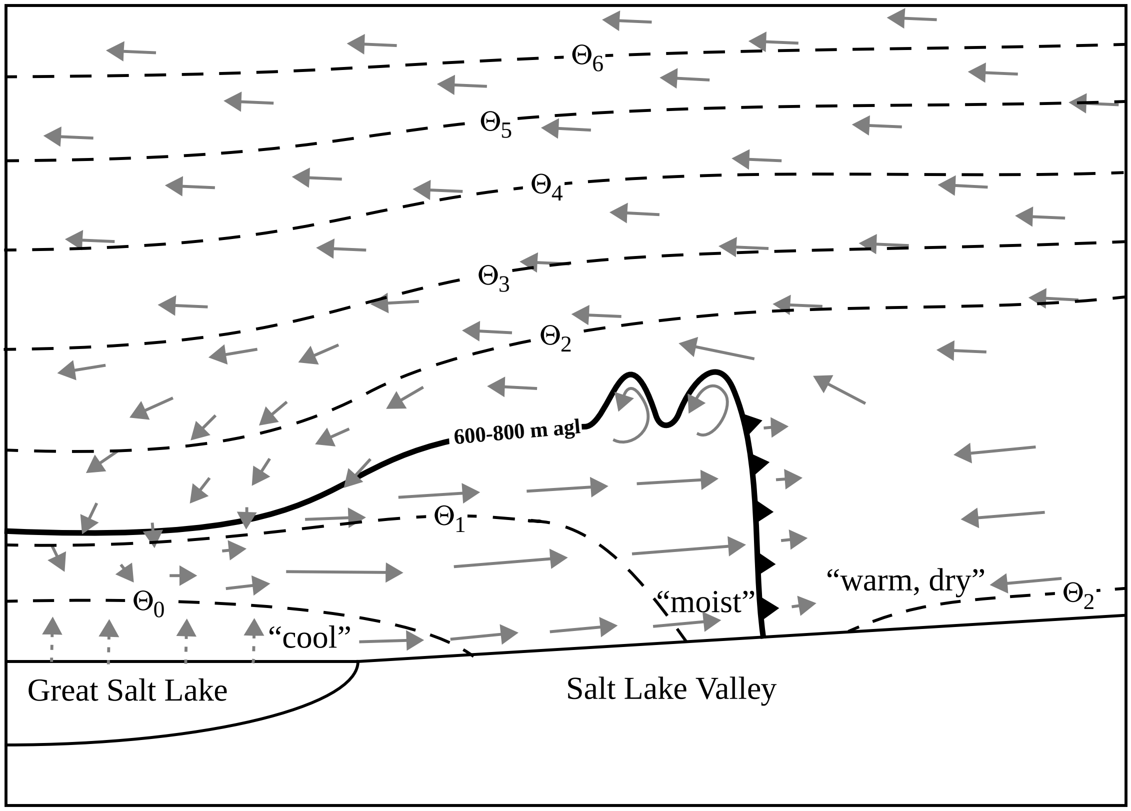


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