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Forcing mechanisms for Washoe Zephyr - a daytime downslope wind phenomenon in the Great Basin east of the Sierra Nevada

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NOTES AND CORRESPONDENCE

Forcing Mechanisms for Washoe Zephyr—A Daytime Downslope Wind System in the Lee of the Sierra Nevada

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ABSTRACT

This paper investigates the formation mechanisms for a local wind phenomenon known as Washoe Zephyr that occurs frequently in the lee of the Sierra Nevada. Unlike the typical thermally driven slope flows with upslope wind during daytime and downslope at night, the Washoe Zephyr winds blow down the lee slopes of the Sierra Nevada in the afternoon against the local pressure gradient. Long-term hourly surface wind data from several stations on the eastern slope of the Sierra Nevada and rawinsonde sounding data in the region are analyzed and numerical simulations are performed to test the suggested hypotheses on the formation mechanisms for this interesting phenomenon. The results from surface and upper-air climate data analyses and numerical modeling indicate that the Washoe Zephyr is primarily a result of a regional-scale pressure gradient that develops because of asymmetric heating of the atmosphere between the western side of the Sierra Nevada and the elevated, semiarid central Nevada and Great Basin on the eastern side of the Sierra Nevada. The frequent influence of the Pacific high on California in the summer season helps to enhance this pressure gradient and therefore strengthen the flow. Westerly synoptic-scale winds over the Sierra Nevada and the associated downward momentum transfer are not necessary for its development, but strong westerly winds aloft work in concert with the regional-scale pressure gradient to produce the strongest Washoe Zephyr events.

1. Introduction

Thermally driven circulations, such as slope flows and valley winds, are a common phenomenon found in mountainous regions in the western United States and

throughout the world (Whiteman 1990, 2000). These wind systems, along with the structure of the mountain boundary layer, affect local weather and climate and exert a major control over air pollution, visibility, forest fire, and energy usage in mountainous regions (Lu and Turco 1994; Smith et al. 1997; Brazel et al. 2005). Typically, over mountain slopes under quiescent synoptic conditions, winds blow upslope during the day and downslope at night in response to a horizontal temperature gradient between the air adjacent to the heated

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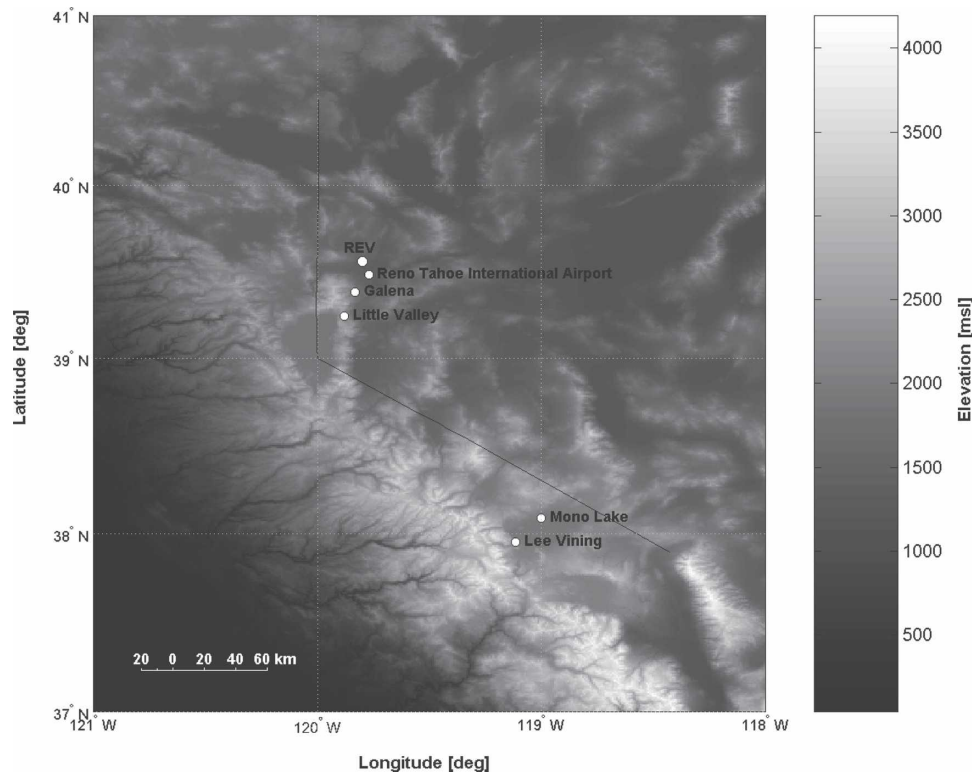


FIG. 1. The terrain relief of the Sierra Nevada and the locations of the five surface stations and the one upper-air sounding site used in the data analyses.

(daytime) or cooled (nighttime) slope surface and the ambient air at the same altitude (Atkinson 1981; Whiteman 1990). Over the eastern slope of the Sierra Nevada, however, a downslope flow occurs regularly in the afternoon in opposition to local thermal forcing. This daytime downslope flow is known historically as the Washoe Zephyr, as coined by author Samuel Clemens (Twain 1871). The flow usually originates at the mountain crest and is generally strong in magnitude with peak speed occurring in the afternoon or early evening. Strong winds associated with this downslope flow have been linked to dust storms in Carson City, Nevada (Twain 1871), and to convective activities occurring on the eastern side of the sierra crest (Hill 1980).

Despite its frequent occurrence and large impact on local weather in areas east of the Sierra Nevada, little is known about its cause. Mark Twain once described the Washoe Zephyr as a particular scriptural wind in that “no man knows whence it cometh.” There are only a few studies related to this phenomenon in the literature. Using vertical wind profiles obtained from numerous pilot balloon ascents in Lee Vining Canyon (Fig. 1), Clements (1999) showed that daytime down-canyon winds were a regular feature in the afternoon and that the reversal to down-canyon direction occurred after

the up-canyon valley wind developed. Kingsmill (2000) analyzed surface wind data from several stations in western Nevada and wind profiles from a Doppler sodar near the Reno–Tahoe International Airport over two summer months. He found that the onset time of several Washoe Zephyr events sampled over the 2-month period varied significantly, ranging from 1200 to 1800 LST, as did their duration, which varied from 3 to 9 h. The sodar data also revealed the kinematic evolution of the downslope wind, which usually consisted of a downward shift of stronger westerly momentum at onset and an upward shift at decay, and a strong downward motion immediately before onset and strong upward motion just after decay.

Two hypotheses are proposed to explain the Washoe Zephyr wind system that appears to behave differently from the typical mountain and slope circulations. The first hypothesis is that the flow is a result of the pressure difference between a mesoscale thermal low over the elevated desert topography in the interior of Nevada and higher pressure west of the Sierra Nevada (Hill 1980). The pressure difference, which usually peaks in the afternoon, draws air from west of the sierra crest down to the eastern slope, bringing more polluted air from the coastal region or from the Central Valley to

TABLE 1. Geographic information of the surface stations and the upper-air site and the period of data records used in the analyses.

Station name	Lat (°)	Lon (°)	Elev (m MSL)	Period of records	Variables measured
Galena	39.3794	−119.8319	1710	Nov 2002–Apr 2006	<i>T</i> , RH, <i>U</i> , <i>V</i> , precipitation
Little Valley	39.2444	−119.8808	1923	Jan 2002–Apr 2006	<i>T</i> , RH, <i>U</i> , <i>V</i> , precipitation
Lee Vining	37.954 17	−119.1144	2072	Dec 1985–Dec 2004	<i>T</i> , RH, <i>U</i> , <i>V</i> , precipitation
Mono Lake	38.091 45	−118.9979	1967	Jul 1982–Dec 2004	<i>T</i> , RH, <i>U</i> , <i>V</i> , precipitation
Reno Tahoe International Airport (surface)	39.483 89	−119.771 11	1345	Jan 2000–Jun 2006	<i>T</i> , <i>T_d</i> , <i>u</i> , <i>v</i> , gust, <i>P_{sta}</i> , total precipitation, visibility, weather, sky condition
Reno rawinsonde	39.56	−119.80	1516	Jan 1995–Mar 2006	<i>P</i> , <i>U</i> , <i>V</i> , <i>W</i> , <i>T</i> , RH

areas in the Great Basin. Similar flows driven by the regional-scale pressure gradient associated with thermal lows have been found in the coast range of California (Schroeder and Countryman 1960), in the Columbia basin of eastern Washington on the lee side of the Cascade Mountains (Doran and Zhong 1994), in the Mexico City basin (Bossert 1997), and at the Bolivian Altiplano (Egger et al. 2005; Zängl and Egger 2005).

The second hypothesis is that the strong surface downslope wind is caused by downward mixing of higher momentum aloft as the convective boundary layer over the eastern slopes of the Sierra Nevada grows above ridge-top levels where westerly winds usually prevail. Downward momentum transfer is considered a regular source for strong surface winds over areas of complex terrain. An example of strong surface winds as a result of downward momentum transfer is the afternoon wind system found in areas of the Rocky Mountains in Colorado (Banta 1984; King 1997). Since the westerly wind aloft would be sheltered from surface pollutant emissions by the subsidence inversion usually present over California, the daytime downslope flows would bring air with only low background ozone concentration to the surface. On the other hand, higher ozone concentration from west of the Sierra Nevada would be brought into the Great Basin by the flow if the first hypothesis is correct.

In this paper, we test these hypotheses using climatological data analyses and numerical modeling. Section 2 describes the dataset used in the climatological analysis followed by the results in sections 3 and 4. Section 5 presents numerical modeling results. Conclusions are drawn in section 6.

2. Data

Meteorological observations from five surface stations are used in the climatological data analysis. All five stations are located on the eastern slope of the Sierra Nevada (Fig. 1). Three of them (Reno, Galena,

and Little Valley) are in the northern sierra and western Nevada while two (Lee Vining and Mono Lake) are located in the central sierra of eastern California. Galena and Little Valley are Remote Automatic Weather Stations (RAWS) operated by the Bureau of Land Management. The Reno–Tahoe International Airport station is a National Weather Service station, while Lee Vining and Mono Lake are part of a network operated by the Great Basin Unified Air Pollution Control District (GBUAPCD).

Characteristics of these stations, including latitude, longitude, and elevation, are listed in Table 1, which also include the variables measured and the period of records for each site. At Reno, Galena, and Little Valley, the records are limited to the most recent five years. The records are much longer at the two other stations, dating back to the early 1980s. At all sites, winds are measured on 10-m towers. Data at each site underwent automated quality control procedures to remove erroneous values. Additional quality control procedures were applied to further remove suspected values from entering the climatological analyses. Despite occasional missing data due mostly to severe winter weather, the datasets are generally in good quality. From 1800 2-s samples, hourly vector averaged winds are computed and are identified by the end of the 1-h averaging period.

In addition to the surface observations, data from standard twice-daily rawinsonde soundings from Reno are used to relate winds at the surface to conditions aloft. The information for the sounding site and the period of records are also given in Table 1.

3. Behavior of surface winds

The general characteristics of the surface wind at each of the five stations are given by the wind roses for all seasons (Fig. 2a) and for the summer season (Fig. 2b). Clearly, there are some differences in the frequency distributions of wind direction between the three stations in the northern part of the sierra and the

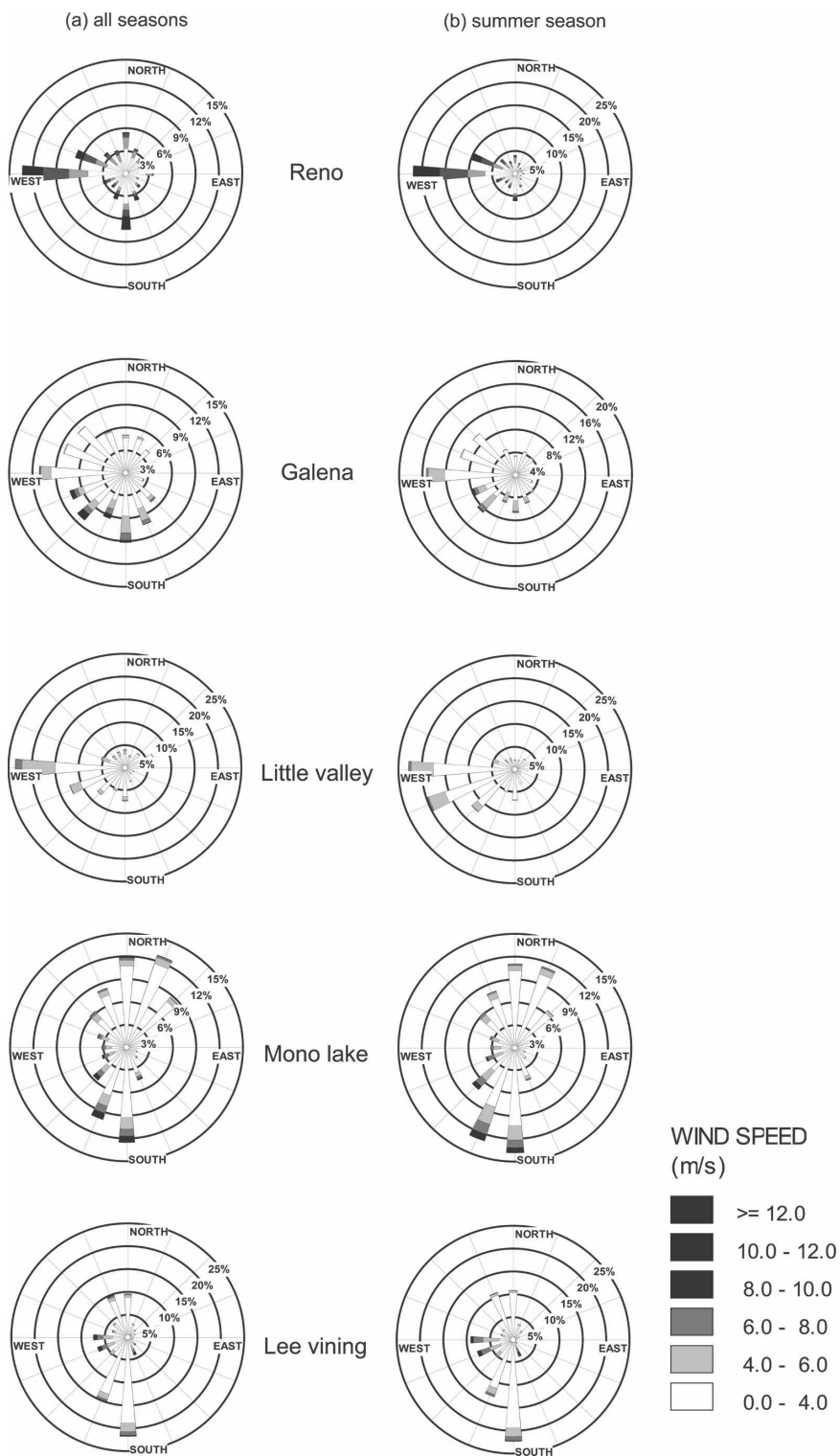


FIG. 2. Surface wind roses at the five stations for (a) all seasons and (b) the summer season.

two in the central part. Winds at the three northern stations in western Nevada are predominantly from westerly quadrants, with less than 20% of winds with an easterly component. Although westerly winds are also more common than easterly directions at the two stations in the central part of the sierra, there is an increase in the frequency of southerly winds at Lee Vining and both southerly and northerly winds at Mono Lake when compared with the three northern sites. Mono Lake is the only station where winds with an easterly component are not rare. Relative to the annual wind distribution, the summer season wind roses show an increased tendency for westerly winds. The summer season has less frequent occurrences of high wind events, which are normally associated with fronts passing through the area in the cold season.

A careful examination of each site and the surrounding topography suggests that these differences in surface winds can be largely explained by the specific site location and the local topography. The Mono Lake station is located on Paoha Island in the middle of Mono Lake. The north-northeasterly wind at this site, which has a frequency of about 20% and is usually weak, is most likely a nocturnal drainage flow from the higher terrain to the north and northeast of the station, while the southerly winds are more likely due to valley-scale circulations that occur within the eastern basins of the sierra. The Lee Vining site is located just slightly north of the mouth of Lee Vining Canyon. Westerly down-canyon flow, once it exits the canyon, would spread out and influence the station from the south or southwest. The increased frequency of the southerly wind at Lee Vining could also be attributed to local-scale flows from the higher terrain south of the stations. On the contrary, there are no other major terrain features except for the Sierra Nevada at the three northern stations. Since the Washoe Zephyr is known as westerly flow blowing down the eastern slope of the Sierra Nevada, it is useful to focus on westerly winds at these stations. Figures 3a,b show the frequencies of westerly winds defined as those from the southwest to northwest quadrant for each hour of the day for all seasons and for the summer season, respectively. There are some differences from one year to another, but the overall pattern is consistent. Although westerly winds may occur at any hour of the day, there is clearly a maximum in late afternoon and early evening when the local thermally driven flows are expected to be upslope from the east or northeast, and a minimum in late morning and early afternoon. This feature is more pronounced in the summer season when the synoptic forcing is generally weak for this region. The highest frequency of westerly downslope winds is found between 1500 and 2000 LST.

At Galena, in addition to the late afternoon–early evening peak, the westerly wind frequency remains high throughout the night. Further analysis of the data indicates that the nocturnal maximum of the westerly wind at Galena represents locally generated drainage winds that are usually much weaker compared to the downslope winds occurring in late afternoon. This can be seen in Fig. 4, which shows the diurnal variation of the westerly wind frequency at Galena for westerly wind speed greater than 5 m s^{-1} . The nocturnal maximum in the frequency distribution, as seen in Figs. 3a,b, disappeared, leaving only the late afternoon peak.

Although the Washoe Zephyr is a well-known phenomenon, no official definition in meteorological terms has been found in the literature. Based on the descriptions in the literature about the phenomenon and the experiences of local forecasters at the National Weather Service Office in Reno, Nevada (R. Milne 2006, personal communication), we define Washoe Zephyr as a westerly wind with sustained wind speed (hourly average) greater than 7 m s^{-1} starting after noon. Based on this definition, the basic characteristics of Washoe Zephyr, including the time of its onset, the duration, and the frequency of occurrence, are analyzed using the station data. It is found that during more than 85% of the time, a Washoe Zephyr event starts between 1300 and 2000 LST with a majority (>70%) occurring between 1500 and 1800 LST. There is a delay of about an hour in the onset time from Reno in the north where the averaged terrain height of the Sierra Nevada is lower to Lee Vining in the south where the terrain is higher. The duration of these events varies between 1 and 12 h, but over one-half of the events fall between 3 and 6 h. About 20%–25% of events are short-lived with a duration less than 3 h, while it is rare (<5%) to have an event that goes beyond 9 h. Although a Washoe Zephyr event based on our definition can occur all year, they are most frequent in the warm season with summer being the peak season. Less than 10% occur during the cold season from November to February.

4. Hypotheses testing

The two hypotheses on the origin of the Washoe Zephyr involve distinctly different mechanisms and testing the hypotheses requires looking at different variables and relationships. If the first hypothesis is true (i.e., the Washoe Zephyr is driven by a regional-scale pressure gradient resulting from a thermal low in the Great Basin and higher pressure west of the Sierra Nevada), there should be a close relationship between the characteristics of the Washoe Zephyr and the pressure difference across the Sierra Nevada. If the hypothesis

(a) All seasons

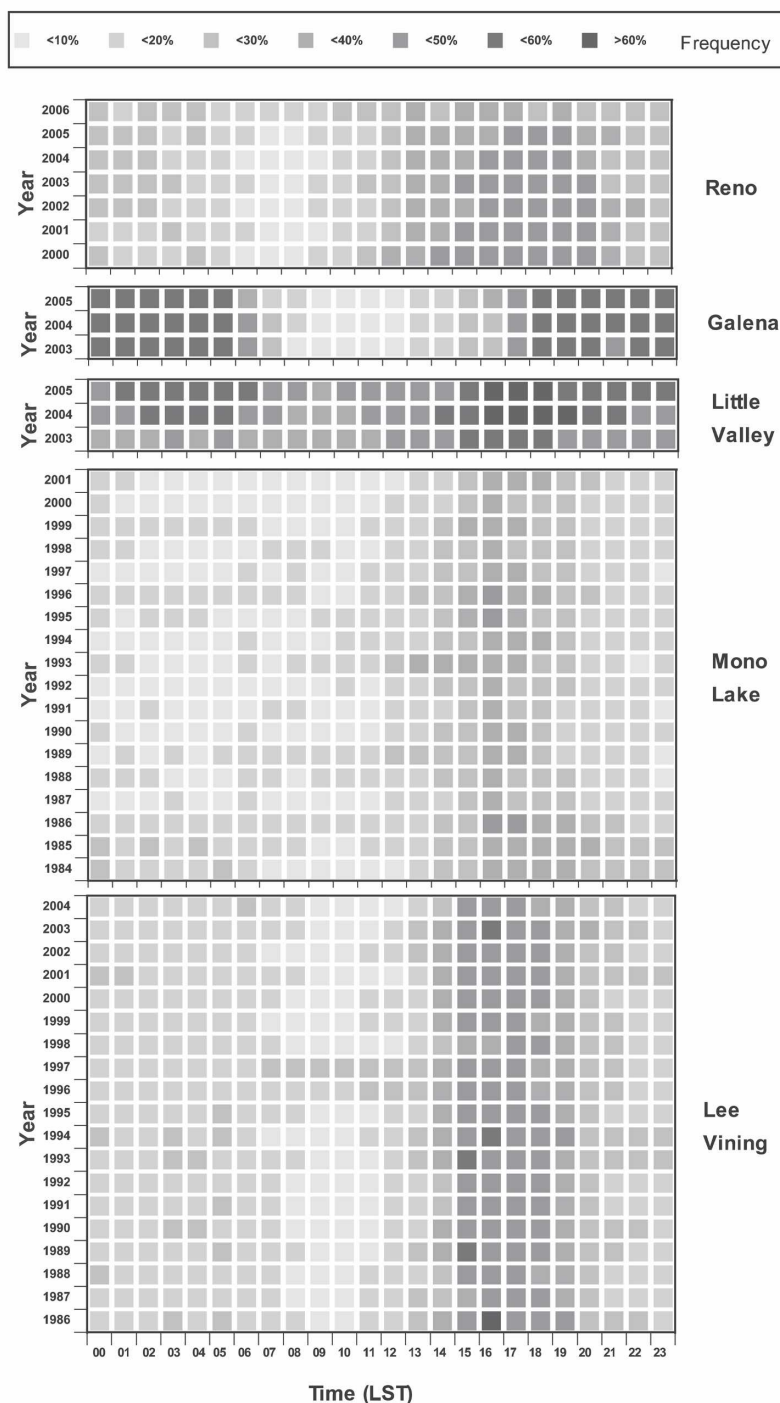


FIG. 3. Frequency distributions of winds from the southwest to northwest quadrant as a function of year and hour of day for (a) all seasons and (b) the summer season.

that the Washoe Zephyr is a result of downward momentum mixing by turbulence is true, then the surface wind speed and direction should be closely correlated to synoptic-scale winds above the mountain crest.

To test the two hypotheses, we approximate the syn-

optic wind speed and direction using the 700-mb (hPa) wind determined from the rawinsonde soundings from Reno. The pressure difference across the mountain is estimated using the mean sea level pressure at Reno in the Great Basin and at Sacramento in the Central Val-

(b) Summer season

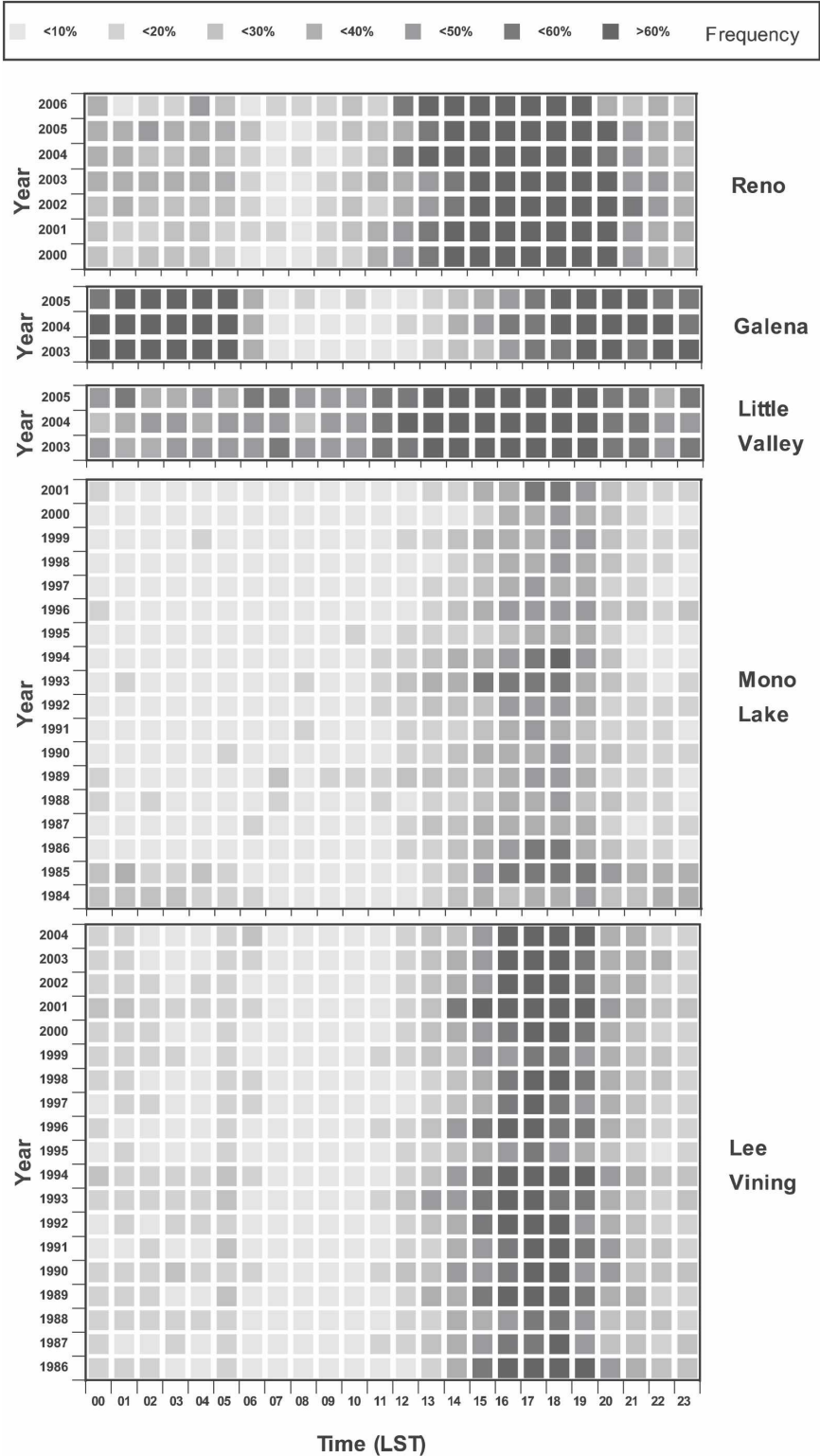


FIG. 3. (Continued)

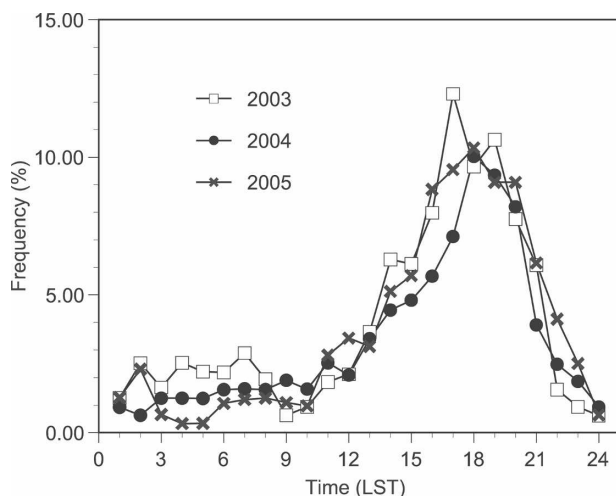


FIG. 4. Frequency distributions of westerly winds $>5 \text{ m s}^{-1}$ at Galena for each hour of the day for all seasons and for 2003–05.

ley of California. Figure 5 shows the time series of pressure difference, synoptic wind speed and direction, and the diurnal variation of the surface westerly wind at Reno and Lee Vining for the 2003 summer season. There is clearly a close relationship between the pressure difference and the development of afternoon westerly surface winds. The periods when a strong westerly

surface wind is absent in the afternoon hours correspond well to the periods when the pressure at Reno is much higher than pressure at Sacramento (negative value in the plot), and the days when strong and persistent westerly winds are seen in the surface observations are closely related to lower pressure at Reno and higher pressure at Sacramento. For example, the first and last week of June (corresponding to Julian days 152–157 and 175–181, respectively, in Fig. 5) was marked by the absence of strong westerly surface winds, while during most of the middle 2 weeks of the month (corresponding to Julian days 158–174, except for 166–168), strong westerly surface winds prevailed from noon to late evening on a daily basis. This pattern correlates very well to the pattern of pressure difference between Reno and Sacramento in that the pressure at Reno is much higher than pressure at Sacramento during the first and last week (negative difference in Fig. 5) while Reno pressure is generally lower in the middle two weeks.

An examination of the relationship between surface and 700-mb wind in Fig. 5 reveals a different story between surface winds and winds aloft. As expected for midlatitude regions, the synoptic winds are predominantly from the west. The synoptic wind speed, however, varies considerably from one day to another,

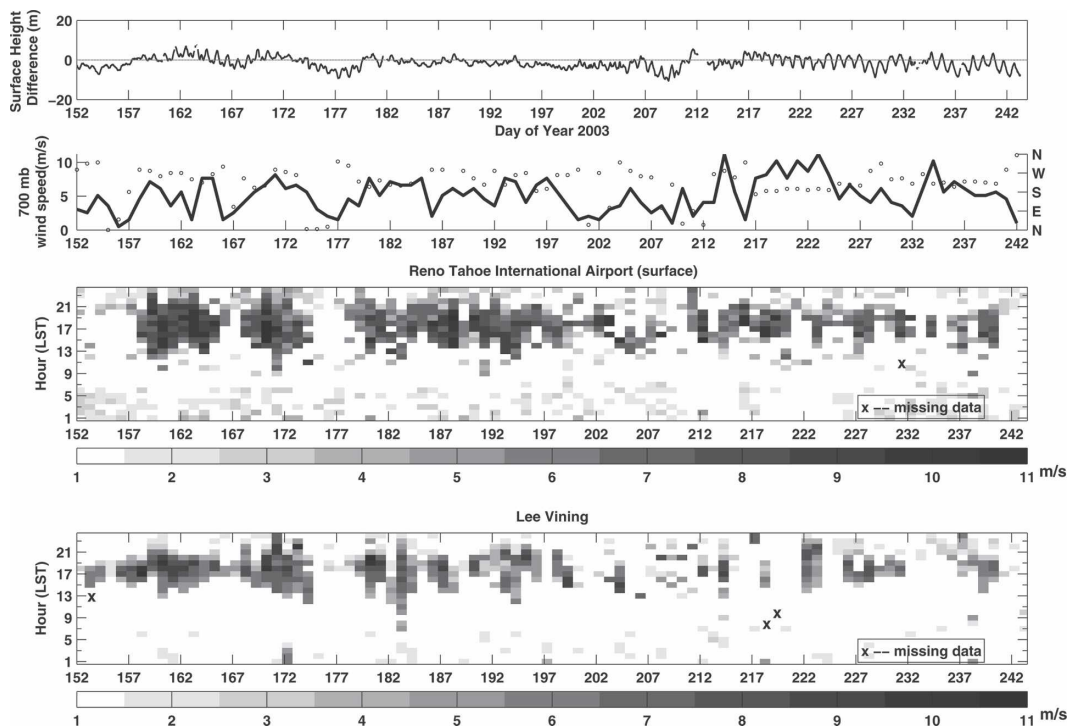


FIG. 5. (top) Difference of sea level pressure between Sacramento and Reno, (second from top) 700-mb wind speed and direction from Reno soundings at 0000 UTC on each day, and surface westerly downslope wind for each hour of the day for (third from top) Reno and (bottom) Lee Vining for summer of 2003.

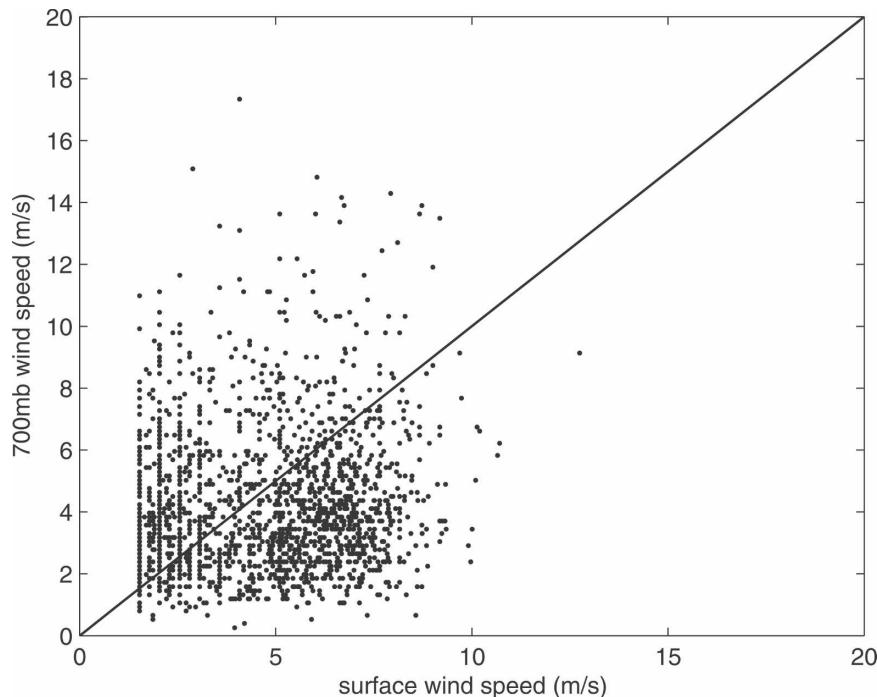


FIG. 6. The relationship between 700-mb wind speeds averaged from the 1200 and 0000 UTC soundings for the day and the mean afternoon surface wind speed at Reno for the summer of 2003.

ranging from less than 2 to over 15 m s^{-1} . There is no clear relationship between the synoptic wind speed and surface westerly wind speed and quite often the surface wind exceeds the wind speed aloft. For example, on 6–7 July (Julian days 187–188), the synoptic wind is less than 5 m s^{-1} , but the surface westerly winds are approaching 10 m s^{-1} . In addition, westerly winds also develop at the surface on days when the winds aloft are not from the west. For example, on Julian days 211 and 222 when the 700-mb winds are weak and from the east and northeast, westerly surface winds still developed in the afternoon. During the 10-day period of Julian days 217–227, the 700-mb winds are consistently from the south while westerly surface winds occurred on many of these days. These results suggest that a westerly flow aloft is not necessary for the westerly downslope wind found at the surface in the afternoon. The westerly surface winds on these days, however, tend to be weaker and do not last as long compared to the days when winds aloft are from the west.

The relationship between the strength of the surface wind and wind speed aloft can be seen more clearly in the scatterplot in Fig. 6. Each data point in the figure corresponds to a daily mean 700-mb wind speed determined by averaging the two soundings (1200 and 0000 UTC) for that day and the averaged afternoon surface wind speed for the same day. A typical plot of this type

would have most data points above the 1–1 line because 700-mb winds under normal circumstances are much stronger than surface winds. However, as can be seen in Fig. 6, more data points are cluttered under the 1–1 line, indicating that there are considerably more days when surface winds exceed 700-mb winds. This is especially true when 700-mb winds are relatively weak ($<6 \text{ m s}^{-1}$), which normally occurs when the region is under high pressure control. The correlation coefficient between the mean 700-mb wind and the mean surface wind is 0.1016 for all days and 0.085 for days when the mean 700-mb wind speed is greater than 7 m s^{-1} . The poor correlation suggests that the strong westerly wind at the surface appears to be decoupled from winds above the ridge-top.

Together the results from Figs. 5 and 6 indicate that the hypothesis that the Washoe Zephyr is caused primarily by downward mixing of strong westerly momentum aloft as the growing afternoon convective boundary layer entrains the westerly flow aloft is unlikely to be correct. Instead, the strong correlation between the pressure difference on the two sides of the Sierra Nevada and the development of the downslope surface winds in the afternoon supports the alternative hypothesis that the wind system is thermally driven by a regional-scale pressure gradient developed between the lower pressure over the heated, elevated terrain in the

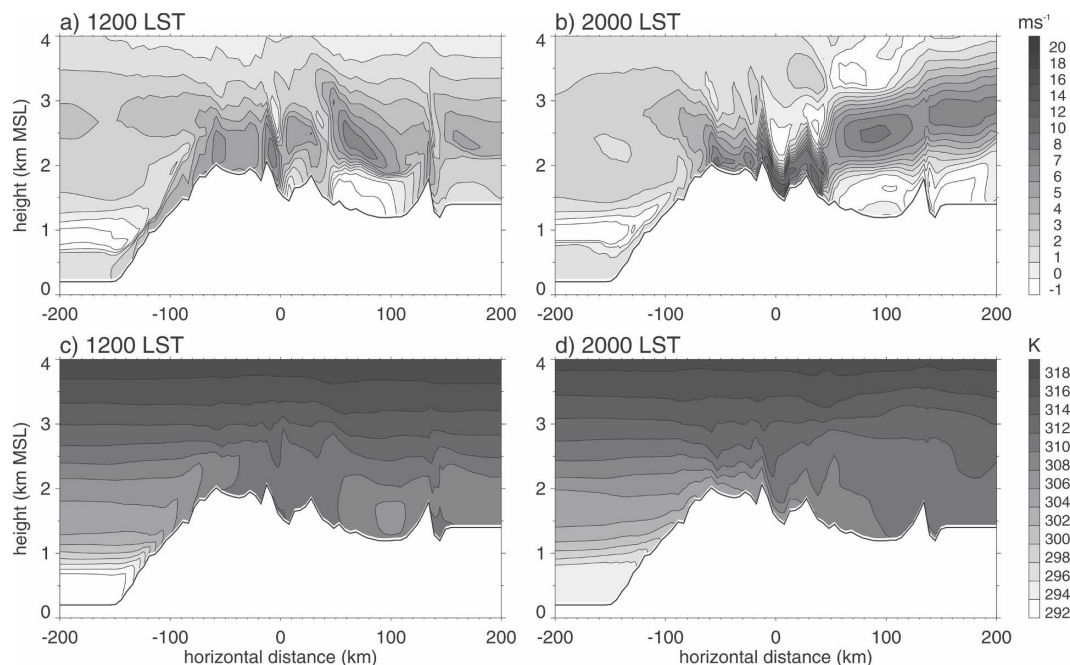


FIG. 7. (a),(b) RAMS simulated wind speed and (c),(d) potential temperature on an east-west cross section through the center of the domain at (left) 1200 and (right) 2000 LST.

Great Basin on the eastern side of the Sierra Nevada and the higher pressure on the western side.

5. Numerical simulations

To further test the hypotheses, numerical simulations are performed using the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992). The modeling domain consists of a single grid with horizontal grid spacing of 1 km. The grid has 40 vertical levels, with grid spacing from 30 m near the surface that gradually increases to 1000 m near the model top at about 12 km. The surface is assumed to have uniform vegetation cover with vegetation type taken as short grass. The domain is quasi-two dimensional with 450 grid points in the east-west direction and 6 grid points in the north-south direction. The topography for the domain was determined by averaging 50 east-west terrain cross sections at every kilometer centered at Reno (39.56°N, -119.80° W).

The simulation was initialized at 1200 UTC (0400 LST) on 5 July 2005, a day when Washoe Zephyr wind was observed in the afternoon at Reno, and the simulation lasted for 24 h. The initial temperature and humidity profiles were taken from the 1200 UTC (0400 LST) soundings at Vandenberg Air Force Base on the central California coast. The Vandenberg sounding was used instead of the Reno sounding because the

RAMS domain extends to the ocean while the Reno sounding does not provide atmospheric information below the station elevation of 1516 MSL. In addition, the Vandenberg sounding is representative of the ambient atmospheric conditions upwind of the sierra. Simulations are performed with four different initial wind profiles that are assumed to be uniform with height with $v = 0$ and $u = 0.1, 1, 3$, and 4 m s^{-1} , respectively.

Figure 7 shows the simulated u wind component and potential temperature over an east-west terrain cross section for the model run with an ambient wind speed of 3 m s^{-1} . The positive u values, representing the westerly component, are shaded to help visualize the eastward propagation of the westerly flow during the course of the day. At noon, 8 h after the model initialization, westerly winds from the lower terrain pass over the sierra crest down into the interior air basins. A weak, easterly return flow layer develops above the surface westerly wind layer in the Central Valley. The westerly flow continues to propagate eastward during the rest of the afternoon hours. An easterly upslope wind, which opposes the westerly wind penetration, collapses after sunset, allowing the westerly wind to prevail. The maximum speed of the westerly winds near the surface more than tripled the ambient wind speed of 3 m s^{-1} , which further supports the result from the data analysis that the strong surface wind is not a result of the downward transport of high momentum aloft by

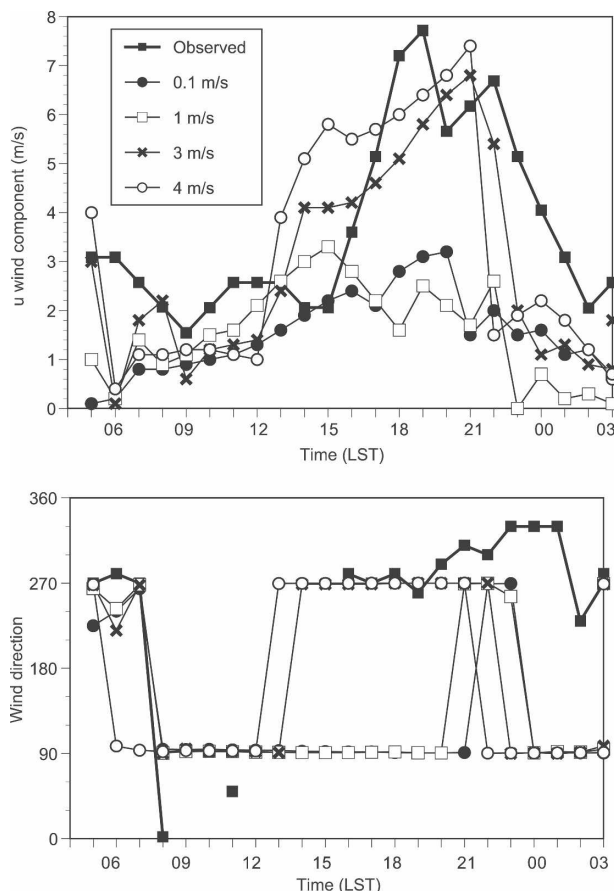


FIG. 8. Time series of wind (top) speed and (bottom) direction simulated using different ambient wind speeds at a grid point near Reno and the observed speed and direction at Reno for 5 Jul 2005.

turbulent mixing in a convective boundary layer. The potential temperature contours show that the westerly flow propagates like a density current bringing colder and denser air from the western slope of the Sierra Nevada into the eastern side, which is similar to the results of numerical studies by Bossert and Cotton (1994b), Bossert (1997), and De Wekker et al. (1998).

The influence of ambient westerly wind speed on the onset time and the strength of the surface westerly downslope flows can be clearly seen in Fig. 8, which shows time series of wind speed and direction simulated with different ambient wind speeds at the model grid point near Reno. The observed wind speed and direction at Reno are also shown in the figure for comparison. The observations show that the onset of Washoe Zephyr at Reno occurred at around 1700 LST, as indicated by a rapid increase in wind speed from 2–3 to 6–7 m s^{-1} along with a sudden shift in wind direction from east-northeast to west. The two simulations with an ambient wind speed of 3 and 4 m s^{-1} produce a near doubling of the wind speed when the westerly wind

arrived at the location of Reno, but the timing of the arrival is 2 h earlier than in the observation. It is interesting to note that even in simulations with an ambient initial wind speed of 0.1 or 1 m s^{-1} , a westerly downslope wind still arrives at the interior basin site, but at a later time and without a significant increase in wind speed.

6. Conclusions

Two hypotheses regarding the formation mechanisms for the Washoe Zephyr, an afternoon downslope wind frequently occurring on the eastern slope of the Sierra Nevada, were evaluated with a combination of data analyses and numerical simulations. Both the data and model results suggest that this wind system is generally not caused by downward momentum transfer as the deep afternoon convective boundary layer on the lee slope of the Sierra Nevada and in the Great Basin penetrates into the layer of westerlies aloft. Instead, the difference in elevation between the elevated, semiarid Great Basin on the eastern side and the lower region on the western side of the Sierra Nevada provides a source of asymmetric heating across the mountain range. The asymmetric heating evolves during daytime, generating a regional pressure gradient that allows air from the west to cross over the crest and to flow down the eastern slope in the afternoon. Although a westerly ambient wind is not necessary for the development of Washoe Zephyr, its presence leads to strong Washoe Zephyr events that start earlier in the afternoon and that last longer.

Thermally driven flow phenomena, analogous to Washoe Zephyr wind, have been reported in other locations. In an observational and numerical study of winds in the Rocky Mountains, Bossert (1990) and Bossert and Cotton (1994a) found evidence for the movement of air over a mountain barrier, driven by differential heating on the two sides of the crest with different elevations. Kimura and Kuwagata (1993) documented a similar afternoon downslope flow passing over a mountain barrier between a plain and a basin in Japan. Doran and Zhong (1994) attributed a regional flow found east of the Cascade Mountains in central Washington to the effect of the regional pressure gradient arising from the warmer air over the semidesert area on the lee side of the Cascades and the cooler marine air on the Pacific Ocean side. Recently, Egger et al. (2005) used in situ observations to study thermally driven flows from lower lands into elevated basins in the interiors of the Bolivian Altiplano during daytime as a result of temperature excess with respect to atmosphere at the same elevation above the surrounding

lower lands. These wind systems, although different in scale, are driven by a similar mechanism and have large potential impacts on weather and climate as well as on the transport and dispersion of pollutants.

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