Washoe Zephyr – A daytime downslope wind in the lee of Sierra Nevada

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1. Introduction

A daytime downslope flow, known as the Washoe Zephyr, that frequently occurs on the lee slopes of the Sierra Nevada, is investigated using long-term data from surface stations and rawinsonde soundings in combination with numerical simulations using the RAMS model. Typically, under undisturbed conditions, diurnal winds over mountain slopes blow up slope during the day and down slope at night as a result of differential heating and cooling of the sloping terrain and the air adjacent to the terrain. The Washoe Zephyr, however, blows downslope during daytime against the local pressure gradient force, and it is not entirely clear what causes this unusual behavior. Two hypotheses have been proposed. The first is that the flow is a result of the pressure difference between a thermal low developed in the interior of Nevada and the high pressure over the coast of California which draws the air from west of Sierra crest down to the eastern slope. The second hypothesis is that the surface downslope wind may be a result of downward transport of momentum from the westerly winds aloft as the convective boundary layer over the eastern slope of Sierra grows high in the afternoon into generally westerly flow layer aloft. Data analyses and numerical modeling are designed to test these hypotheses and identify the cause for this rather unique phenomenon.

2. Data

Meteorological observations from five surface stations in the lee of Sierra are used in the analyses. Figure 1 shows the locations of each of the stations. Two of the stations in the north, Galena and Little Valley, are part of the RAWS (Remote Automatic Weather Stations) network and the data were provided to us from MesoWest, a collection of independently operated mesonets across Western United States (Horel et al. 2002). Data for Reno Tahoe International Airport, a NWS Site, are purchased through the National Climate Data Center (NCDC). The two sites in the south, Lee Vining and Mono Lake, are 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 period of record for each site. Despite the different networks, at all sites, winds are measured on 10-m masts. Data at each site have gone through automated quality control procedures to remove erroneous values. Additional quality control procedures are applied to further remove suspected values from entering the climatological analyses. Despite occasional missing data due mostly to severe winter weather, the data quality is excellent. Hourly vector averaged winds are computed and are identified by the beginning of the 1-h averaging period.

In addition to surface observations, twice daily rawinsonde soundings released from Reno, are also used in the analyses in order to reveal the relationship between surface and upper air conditions. The information for the rawinsonde sounding site and the period of records are also listed in Table 1.

3. Surface wind analysis

The frequency distribution of westerly downslope flows over a diurnal cycle for summer months is shown in Figure 2. At all five stations, there is a pronounced maximum in late afternoon between 1500 and 1900 LST. A downslope flow occurred at more than 50% times during these hours when the local pressure gradient associated with the heating of the slope surface should result in an upslope flow. At Galena, there is also a nocturnal maximum, which, as will be shown later, is related to locally generated nocturnal drainage winds that are much weaker in strength compared to the downslope winds that occur in late afternoon.

The relationship between the surface winds and winds aloft can be clearly seen in Figure 3 that shows 700-mb wind speed and direction, 500-mb geopotential heights, both determined by the twice daily rawinsonde soundings at Reno, and the surface westerly wind speed for each hour of the day for July – Sept. 2005. As expected, the 700-mb winds were dominated by westerly flows. The wind speed, however, varied considerably from one day to another, ranging from less than 2 m s^{-1} to more than 15 m s^{-1}. Clearly, on numerous days the upper level westerly winds were much weaker that the westerly wind speed at the surface. There were also days when the upper level winds were not from the west, still a relatively strong westerly flow developed at the surface in late afternoon. These results suggest that it is unlikely that the late afternoon westerly downslope winds at these sites are caused by downward momentum transfer of strong westerly winds aloft when mixed layer grow high into the westerly wind layer in the afternoon.

4. Numerical simulations

To further test the hypothesis regarding the formation of the daytime westerly downslope winds on the lee of Sierra, numerical simulations were performed using the Regional Atmospheric Modeling System (RAMS) (Pielke et al. 1992). The model 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 was taken as short grass. Coriolis force and cloud effects were turned off. The domain is quasi two dimensional with 450 grid points in the east-west direction while only 6 in the north-south direction. The topography for the domain was determined by taking an average of 50 east-west cross sections at every kilometer 25 km north and 25 km of Reno (39.56 N, -119.80 W). Initialization of the simulation was at 1200 UTC on July 5, 2005, a day on which the Zephyr wind was observed. The initial temperature and humidity profiles were taken from the 1200 UTC soundings at Vandenberg Air Force Base on the Central California Coast and the initial wind was assumed to be near calm at 0.1 m s^{-1}. The simulation was made for 24 hours starting at 1200 UTC and the sensitivity of the simulated flows to external factors was investigated. In a way the simulation is similar to the elevated basin case in the De Wekker et al (1997) study in which the plain-to-basin flow was investigated. It was found in that study that under normal conditions thermally driven upslope wind on the plain side of the slope can eventually cross over ridge top to the basin side slope and overpower the upslope flow on that side to produce a late afternoon downslope flow against local pressure gradient force.

The spatial structure of the simulated winds at 12, 14, 16, and 18 hours of simulation are shown in Figure 4. Only the westerly u-component of the flow is shaded to emphasize the eastward propagation of the westerly flow in the course of the day, eventually leading to a break-in of the flow to the lee side slope in late afternoon and early evening. On the lee side, the shift from easterly to westerly directions is accompanied by an increase of the speed. The westerly flow propagates eastwards as a front, similar as the plain-to-basin flow which was investigated by De Wekker et al. (1997).

Two additional simulations with ambient wind speed of 1 and 4 m s^{-1} respectively were carried out to determine the influence of the ambient wind on the simulated flows. The results (not shown) for an ambient initial wind speed of 0.1 and 1 m s^{-1} are not so much different. For 4 m s^{-1}, a shift to predominantly westerly wind directions occurs earlier in the day with a gradual increase of wind speeds up to 8 m s^{-1}. In addition, there is an increase in the wind speed with the onset of the Zephyr flow for the 0.1 and 1 m s^{-1} case, which is not evident directly at the surface but above. In these low initial ambient wind conditions an easterly regional scale flow originating from the Great Basin develops late in the evening. A clear Zephyr flow can therefore be absent on these near calm ambient situations.

Simulations were also performed using a Lagranging Particle Model that is coupled to RAMS. Particles released from foothill on the west side of Sierra are transported to the lee side by the westerly wind (not shown).

5. Conclusions

The hypotheses regarding the formation mechanisms for the Washoe Zephyr winds, a daytime downslope wind frequently occur on the lee of Sierra Nevada Range, were tested through data analyses and numerical simulations. Results from both the data analyses and model simulations indicate that it is unlikely that the downward momentum transport of westerly winds aloft is a viable mechanism for this phenomenon. Rather, the afternoon downslope wind is a result of air being drawn from the west to the lee slope of the Sierra by a regional pressure gradient between the Great Basin and the California coast.

Acknowledgement

We thank Mr. Jim Parker at GBUAPCD and Dr. John Horel at the University of Utah for providing the surface data used in the analyses. The work is partially supported by NSF Grant ATM0521742.

References

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Table 1. Station information

Station Name	Latitude	Longitude	Elevation (ft MSL)	Period of records
Galena	39.3794	-119.8319	5610	Nov. 2002 – April 2006
Little Valley	39.2444	-119.8808	6310	Jan. 2002 – April 2006
Lee Vining	37.95417	-119.1144		Dec. 1985 – Dec. 2004
Mono Lake	38.09145	-118.9979		July 1982 – Dec. 2004
Reno Tahoe International Airport (Surface)	39.48389	-119.77111	4413	Jan. 2000 – June 2006
Reno Rawinsonde	39.56	-119.80	1516	Jan. 1995 – Mar. 2006

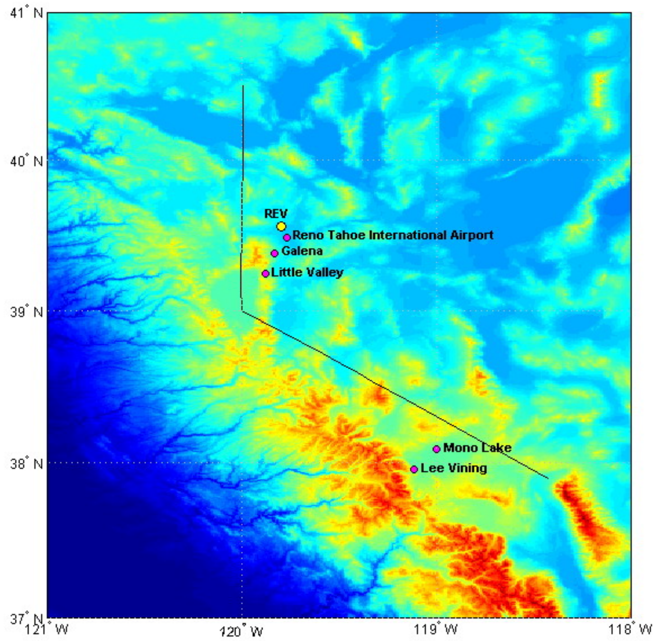

Figure 1. The topography and the locations of the five surface stations and one upper air station used in the data analyses

Summer (Jun - Aug)

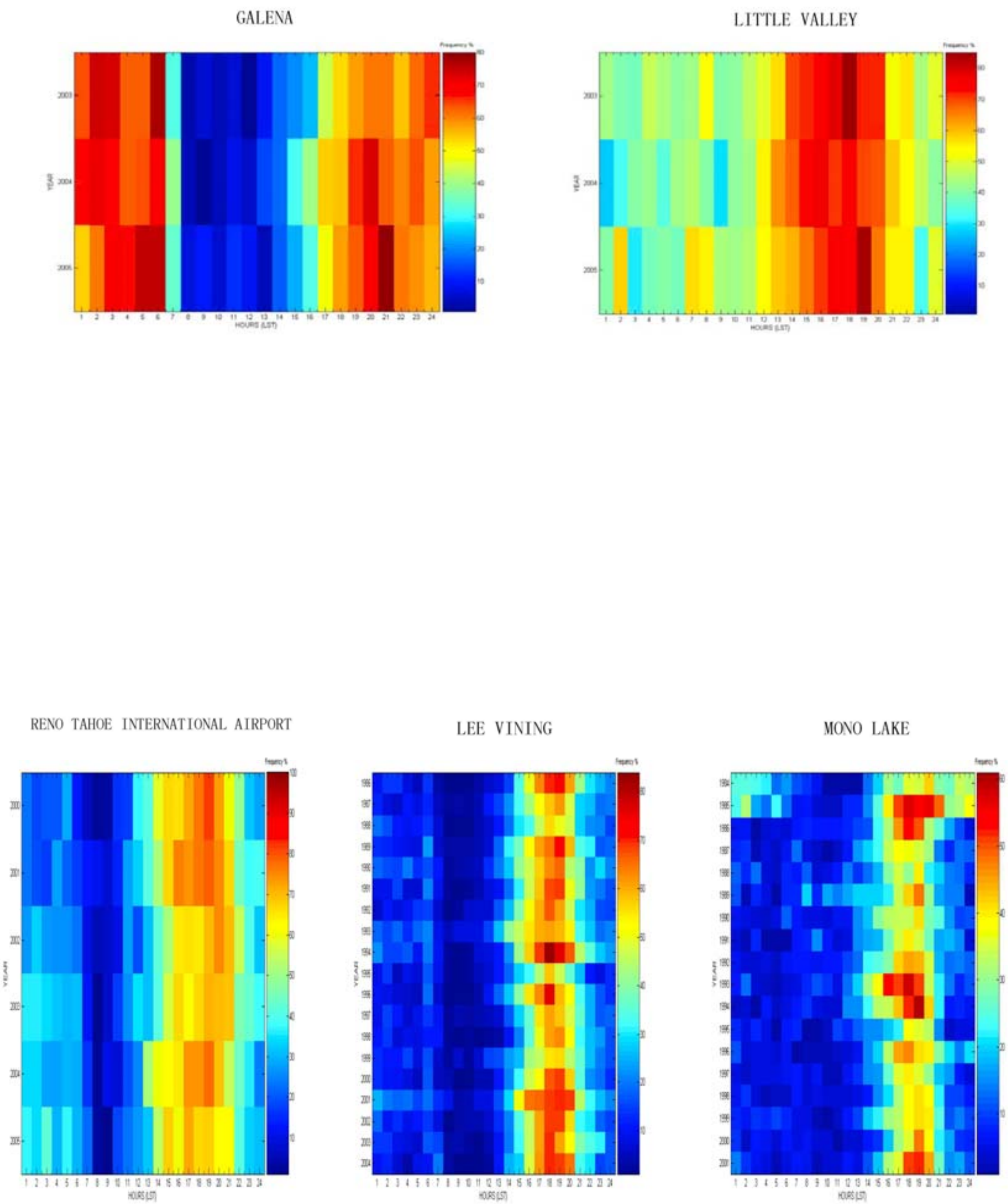

Figure 2. Frequency of occurrences of westerly wind at each hour of the day

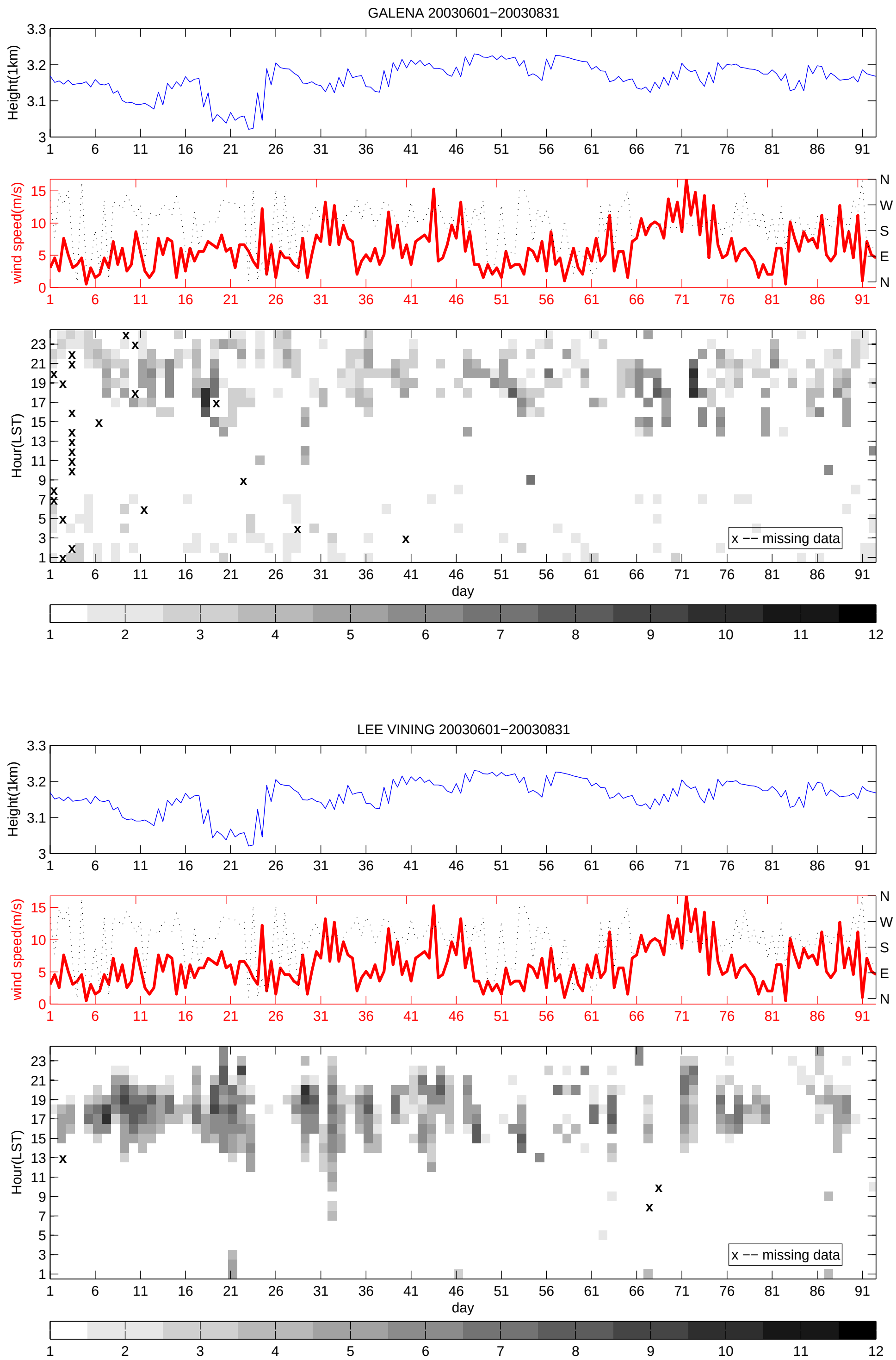

Figure 3. 500-mb geopotential height (top), 700-mb wind speed and direction (middle), and surface westerly wind speed at each hour of the day (bottom) for the summer months of 2003.

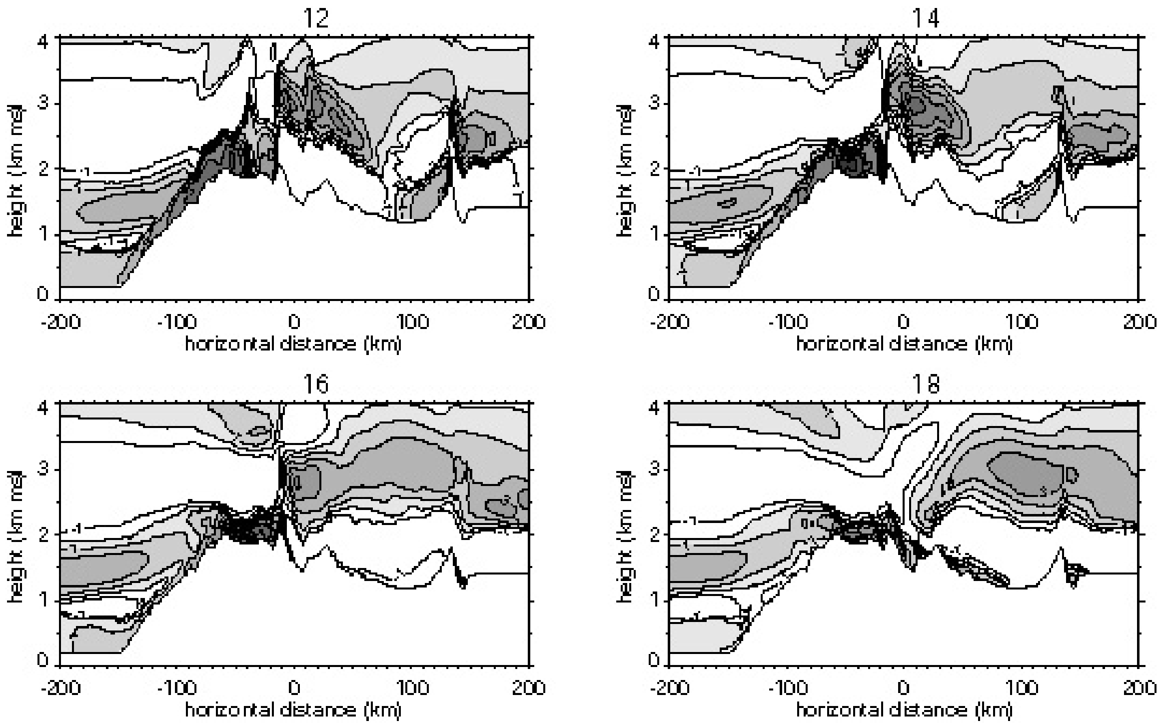

Figure 4. Simulated speed of the u component at 12, 14, 16, and 18 hours into the model simulation initialized at 1200UTC on July 5, 2006. Positive u component, representing westerly wind, is shaded.