THE RELATIONSHIP BETWEEN SYNOPTIC SCALE WINDS AND SURFACE FLOWS IN A DEEP VALLEY

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Abstract: The dynamic mechanisms that lead to high wind events in the deep, narrow Owens Valley in the lee of the Sierra Nevada in California, are studied using climate data form surface and upper-air observations. Four possible mechanisms are considered including downward momentum transfer, forced channeling, pressure-driven channeling, and frontal passage. The high wind events with winds blowing up-valley from south to north are primarily caused by forced channeling of strong synoptic winds ahead of a deep trough off the coast of California. The high wind events with northerly along-valley winds are associated with cold frontal passages, with post-frontal cold air under-running and displacing warmer air in the valley.

Keywords: *Valley wind systems, windstorms, terrain channelling, climate data analysis*

1. INTRODUCTION

High wind events with hour average speeds over 15 m s^{-1} and wind gusts exceeding 20 m s^{-1}occur several times a year in the lee of the Sierra Nevada. These high wind events not only can produce heavy damage to property, but also pose a health threat to local residents and tourists by producing severe dust storms that originate on the dry Owens Lake playa at the southern end of the Owens Valley in the lee of the southern Sierra Nevada. The combination of high winds and the dry, alkali soils of the Owens Lake bed produces some of the highest PM_{10} (particulate matter with diameter less than 10 microns) concentrations observed in the United States. Forecasting these high wind events has proven to be challenging because forecast models often perform poorly in this region due to the prominent mountain barrier and the steep orographic gradient. The lack of understanding of the complex interactions between the synoptic and mesoscale environments contributes to the difficulty of making accurate wind and pollution forecasts.

Several studies have provided detailed descriptions of individual wind storms in the lee of the Sierra Nevada and evaluated the ability of mesoscale models to simulate these windstorms (Cohn et al. 2000; Cain and Corey 2003). The recent T-REX field study in the Owens Valley (Grubišić et al. 2004) collected an extensive set of surface and upper air data for understanding the dynamical and physical mechanisms of high winds in the lee of the Sierra Nevada. These studies, however, were limited to several high wind cases in one season with little long-term climatic information. In this study, we combine long-term climate data from a line of weather stations along the axis of the Owens Valley with synoptic analyses to understand the characteristics of these high wind events and their driving mechanisms.

2. THE SITES AND DATA

The Owens Valley (Fig. 1) is a narrow valley located immediately to the lee of the southern Sierra Nevada of eastern California. It is bounded by the White and Inyo Mountains to the east and the Sierra Nevada to the west. The general Sierra Nevada crest rises approximately 3000 m above the valley floor and the highest peak, Mt. Whitney, rises over 4000 m above mean sea level. The valley is approximately 150 km long and 15 to 30 km wide, with the axis of the valley oriented north-northwest to south-southeast -- that is, nearly parallel to the crest of the southern Sierra Nevada.

Surface meteorological observations from six automatic weather stations situated along the Owens Valley axis (Fig. 1) are used in the climatological analyses. The northernmost station is at Bishop Airport while station Olancha is at the southern end of the valley. The other four sites (Big Pine, Independence, Lone Pine, and Keeler) are nearly equally spaced and provide information in the interior of the valley. The periods of record for the six sites ranged from 3 to 23 years, and at all sites winds were measured on 10-m masts at a sampling rate of one sample every 2 seconds.

3. RESULTS AND DISCUSSIONS

Several potential mechanisms for producing high winds in the valley are considered. The first is downward momentum transport, which occurs when winds within the valley are coupled to strong winds aloft through downward turbulent transport. Because this requires strong turbulence, downward momentum transport usually occurs during unstable or neutral stratification. Valley winds associated with downward momentum transport are expected to align with the wind direction aloft. The second mechanism, forced channeling, occurs when strong winds aloft are channeled through the valley. Forced channeling is the most commonly recognized form of wind channeling, in which the direction and the strength of the wind in the valley are governed by the direction and strength of the above-valley wind as projected in the along-valley direction. The third possible mechanism is pressure-driven channeling, which is produced by the superposition of the large-scale pressure gradient above the valley on the underlying terrain channel. In pressure-driven channeling, the observed direction of the winds in the valley depends not on the along-valley component of the winds aloft, but, rather, on the along-valley component of the horizontal pressure gradient above the mountain area, with the wind flowing from the high pressure end of the valley toward the low pressure end. Finally, strong winds in the Owens Valley may also be associated with the frontal passages that occur frequently in this region in the winter and spring. In this fourth mechanism, the cold air behind a cold front may undercut and displace the warmer air in its path. Strong surface winds can occur following the passage of the front until high pressure builds back over the area. In actuality, all four mechanisms may contribute in various degrees to the behavior of winds in a valley.

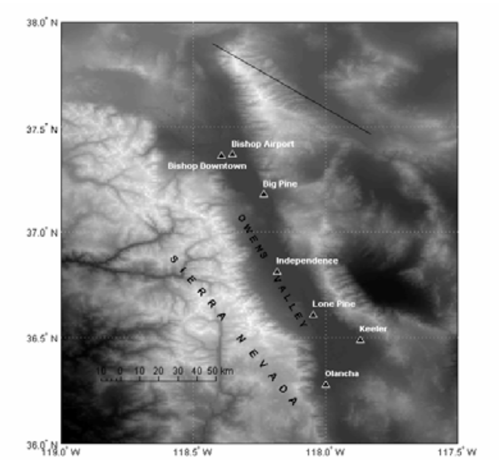

Figure 1. Owens Valley terrain and surface sites

Testing of these potential mechanisms requires knowledge of wind speed and direction above the valley at the time when high winds occur in the valley. Because the closest upper-air sounding site is more than 150 km away from the Owens Valley, the three-hourly 32-km resolution North American Regional Reanalysis (NARR) data are used to determine synoptic-scale winds above the Owens Valley.

Figure 2 shows composite wind roses for each of the six sites. At each station there is a strong tendency for the winds to blow parallel to the local valley axis. The alignment of the surface wind with the valley axis is even more pronounced in strong wind cases (not shown). Strong winds do not necessarily blow up valley during the daytime and down valley at night, as in the case of weak winds. The 625 mb wind roses determined from interpolating the NARR data over the Owens Valley (Fig. 3) indicate that winds aloft are predominantly from the western quadrants, as expected for mid-latitude locations. The fact that strong surface and upper-level winds do not necessarily align in the same direction and that strong winds in the Owen Valley occur not only in the convective boundary layer during daytime, but also in stable conditions at night suggest that it is unlikely that downward momentum transport by turbulent mixing plays a primary role in the development of high wind events in the Owens Valley.

The close alignment of the surface wind direction to the valley axis for high wind events suggests that winds in the valley are channeled by the topography. The question arises whether this channeling is forced channeling or pressure-driven channeling. This question can be answered by examining the relationship between the surface wind reversal and the wind direction change aloft. Although both channeling mechanisms result in winds inside the valley blowing along the valley axis, the valley wind reversal in these two cases occurs when winds aloft shift across axes that differ by 90°. In the case of forced channeling, the surface wind reverses direction when the geostrophic wind aloft shifts across a line normal to the valley axis. Pressure-driven channeling, on the other hand, causes the surface wind to reverse direction when the geostrophic wind aloft shifts across a line parallel to the valley axis. Given the nearly north-south orientation of the Owens Valley axis and the predominantly westerly geostrophic winds in the region, this means that the valley wind in the case of forced channeling will switch from up-valley (southerly) to down-valley (northerly) when the geostrophic wind direction shifts from southwesterly to northwesterly; whereas under the scenario of pressure-driven channeling, the reversal from up- to down-valley occurs when the geostrophic winds aloft switch across the valley axis from a westerly direction to an easterly direction.

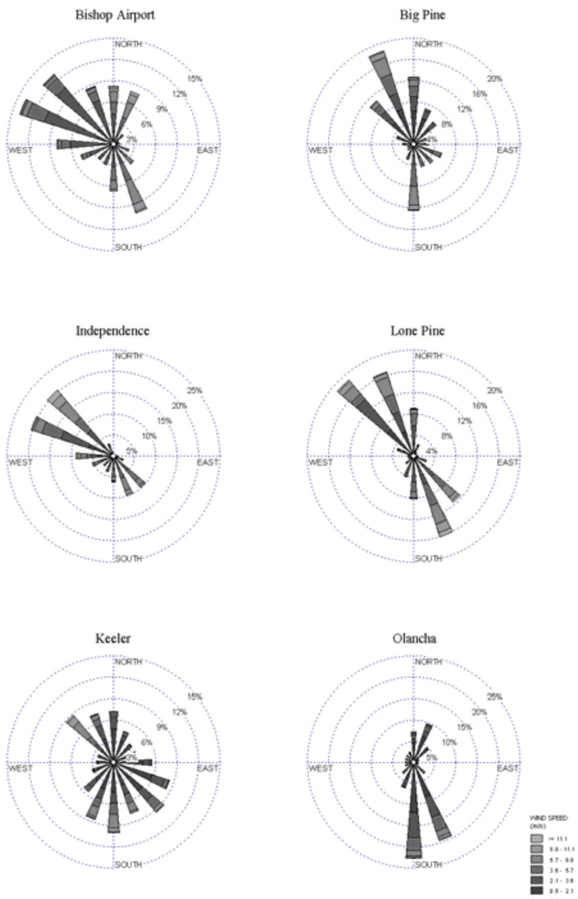

Figure 2. Composite wind roses for each of the six Surface stations using all available data

Figure 4 shows the joint frequency distribution of valley wind direction and geostrophic wind direction at 625 mb at Lone Pine when the surface wind exceeds 7 m s^{-1} at four different times of day. It is clear that the reversal of valley winds from down-valley to up-valley occurs when the geostrophic wind shifts from WNW to SSW across a line normal to the valley axis, in conformance with forced channeling theory. When the geostrophic wind changed from northwest to north-northeast, the valley wind stayed up-valley, rather than switching to down-valley as predicted by pressure-driven channeling theory. The same thing happens for both day (1000 and 1600 PST) and night (0400 and 2200 PST), further confirming that the high wind events are not driven by diurnally changing thermal forcing.

To test the fourth hypothesis that high wind events may be caused by frontal passages, surface and upper-air charts were examined for 48 selected high wind cases. The cases with strong northerly winds in the valley were usually accompanied by the passage of a cold front from the north. As the front passed through the area, the cold air behind the front under-ran the warmer air in the valley and allowed northerly winds to prevail. It is difficult to separate the effect of channeling of strong northwesterly upper-level winds behind the trough and the overrunning of the cold surface air behind the cold front. But, since every one of the 25 northerly strong valley flow cases was associated with a cold frontal passage from the north, we suspect that the surface cold front plays a more important role in the development of northerly wind cases in the valley. The event normally ends as high pressure builds back over the area.

The results here are limited by the location of surface stations that are all on the valley floor. The characteristics of winds on the sidewalls in the upper part of the valley might behave differently. Since winds above the valley axis are most frequently from the west, it is expected that westerly winds are more a feature of climatology of winds on the upper-valley sidewalls.

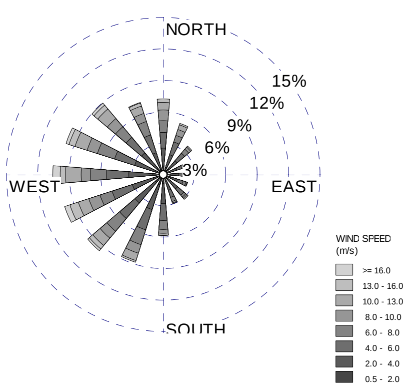

Figure 3. Composite 625 mb wind rose for Long Pine

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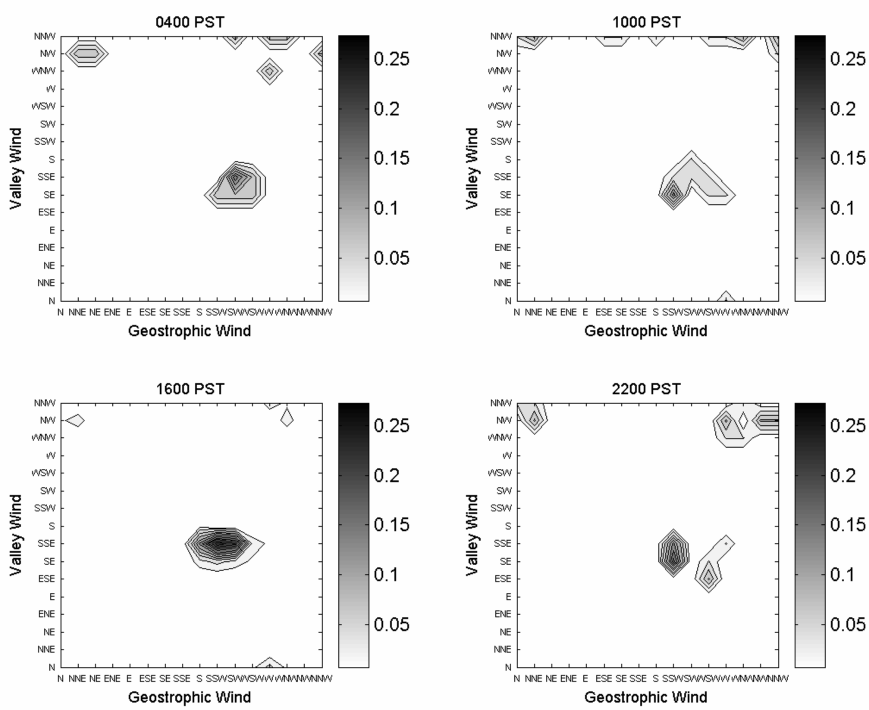

Figure 4: Joint frequency distribution of geostrophic wind direction (at 625-mb) and valley wind direction for surface wind speeds greater than 7 m s-1 at Lone Pine at 0400, 1000, 1600, and 2200 LST.