SPECIAL
Terrain-Induced Rotor Experiment (T-REX)
COLLECTION

Climatology of High Wind Events in the Owens Valley, California

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ABSTRACT

The climatology of high wind events in the Owens Valley, California, a deep valley located just east of the southern Sierra Nevada, is described using data from six automated weather stations distributed along the valley axis in combination with the North American Regional Reanalysis dataset. Potential mechanisms for the development of strong winds in the valley are examined.

Contrary to the common belief that strong winds in the Owens Valley are westerly downslope windstorms that develop on the eastern slope of the Sierra Nevada, strong westerly winds are rare in the valley. Instead, strong winds are highly bidirectional, blowing either up (northward) or down (southward) the valley axis. High wind events are most frequent in spring and early fall and they occur more often during daytime than during nighttime, with a peak frequency in the afternoon. Unlike thermally driven valley winds that blow up valley during daytime and down valley during nighttime, strong winds may blow in either direction regardless of the time of the day. The southerly up-valley winds appear most often in the afternoon, a time when there is a weak minimum of northerly down-valley winds, indicating that strong wind events are modulated by local along-valley thermal forcing.

Several mechanisms, including downward momentum transfer, forced channeling, and pressure-driven channeling all play a role in the development of southerly high wind events. These events are typically accompanied by strong south-southwesterly synoptic winds ahead of an upper-level trough off the California coast. The northerly high wind events, which typically occur when winds aloft are from the northwest ahead of an approaching upper-level ridge, are predominantly caused by the passage of a cold front when fast-moving cold air behind the surface front undercuts and displaces the warmer air in the valley. Forced channeling by the sidewalls of the relatively narrow valley aligns the wind direction with the valley axis and enhances the wind speeds.

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1. Introduction

High wind events are a frequent phenomenon in the lee of the Sierra Nevada. These events, which sometimes can have hourly average wind speeds exceeding 18 m s^{-1} (40 mph) and wind gusts in excess of 22 m s^{-1} (50 mph), 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 immediate 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 concentrations of particulate matter with diameter less than 10 μm (PM_{10}) observed in the United States (Reheis 1997). Forecasting these high wind events has proven to be challenging because forecast models often perform poorly in this region because of the prominent mountain barrier and the steepest orographic gradient in the contiguous United States. 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 documented high wind events and evaluated model predictions of these storms. Cohn et al. (2004) documented a dramatic windstorm that moved over the Sierra Nevada from the west using two radar wind-profiling systems operated by the National Center for Atmospheric Research (NCAR) in the Reno and Washoe basins east of the Sierra Nevada. The event was found to be caused by an upper-level disturbance that originated several days earlier over the mountainous regions of southwestern Alaska. With reported gusts of more than 20.6 m s^{-1} (46 mph), the high winds triggered a short-lived, intensive dust storm that affected visibility and air quality in the region. Cairns and Corey (2003) used the fifth-generation Pennsylvania State University (PSU)–NCAR Mesoscale Model (MM5) to simulate two severe windstorm events in western Nevada that resulted in extensive damage. For both cases, the model was able to capture the mountain waves believed to be responsible for the high winds. The operational Eta Model, in comparison, failed to forecast these high wind events, leading to the conclusion that a grid spacing of 5 km or less is necessary to predict high wind events in the complex terrain of the Sierra Nevada.

The severe windstorms in the lee of the Sierra Nevada are generally believed to be associated with mountain waves and rotors. Efforts to understand Sierra Nevada waves and associated rotors date back to the early 1950s when the Sierra Wave Project was conducted (Holmboe and Klieforth 1957; Grubišić and Lewis 2004). Most recently, another intensive field experiment titled the Terrain-Induced Rotor Experiment (T-REX; Grubišić et al. 2008) was conducted in March and April 2006 in the Owens Valley using ground-based and airborne remote sensing instrumentation. Numerical models also have been used to gain understanding of the wave dynamics and the structure and evolution of rotors for different large-scale and surface conditions (Clark et al. 2000; Hertenstein and Kuettner 2005; Doyle and Durran 2002; Vosper and Ross 2003).

The above-mentioned studies focused either on one or two severe windstorm events or short periods that were believed to have the highest frequency of wave activity. These studies shed light on the dynamical and physical mechanisms of individual wind storms, and provided substantial details on the spatial and temporal structure of waves/rotors. However, they were limited by their short duration and were therefore unable to provide enough information on the seasonal variation in windstorm frequency to gain a more complete understanding of high wind events.

In this study, we combine long-term climate data from a line of weather stations along the axis of the Owens Valley with data from the North American Regional Reanalysis (NARR) to understand the general characteristics of these high wind events and their driving mechanisms. We also identify synoptic patterns that are responsible for these events. A better understanding of the driving mechanisms and the synoptic settings should help improve the forecast skill for these events because weather forecast models are much more accurate at the synoptic scale than at the mesoscale, espeially for complex terrain regions like the Sierra Nevada.

2. Sites and data

The Owens Valley (Fig. 1) is a narrow valley located immediately to the east of the southern Sierra Nevada of eastern California. It is bounded by the Sierra Nevada to the west and the White and Inyo Mountains to the east. The Owens Valley floor has a mean elevation of 1200 m above mean sea level (MSL), while the Sierra Nevada have a largely uninterrupted mountain ridgeline of nearly 4000 m MSL and the White–Inyo Mountains have a mean elevation of approximately 3000 m MSL. The highest peak in the Sierra Nevada, Mount Whitney, is 4418 m MSL, while the highest peaks in the White and Inyo Mountains are 4342 and 3385 m MSL, respectively. The valley is approximately 150 km long with its axis oriented from the north-northwest to the south-southeast, nearly parallel to the crest of the

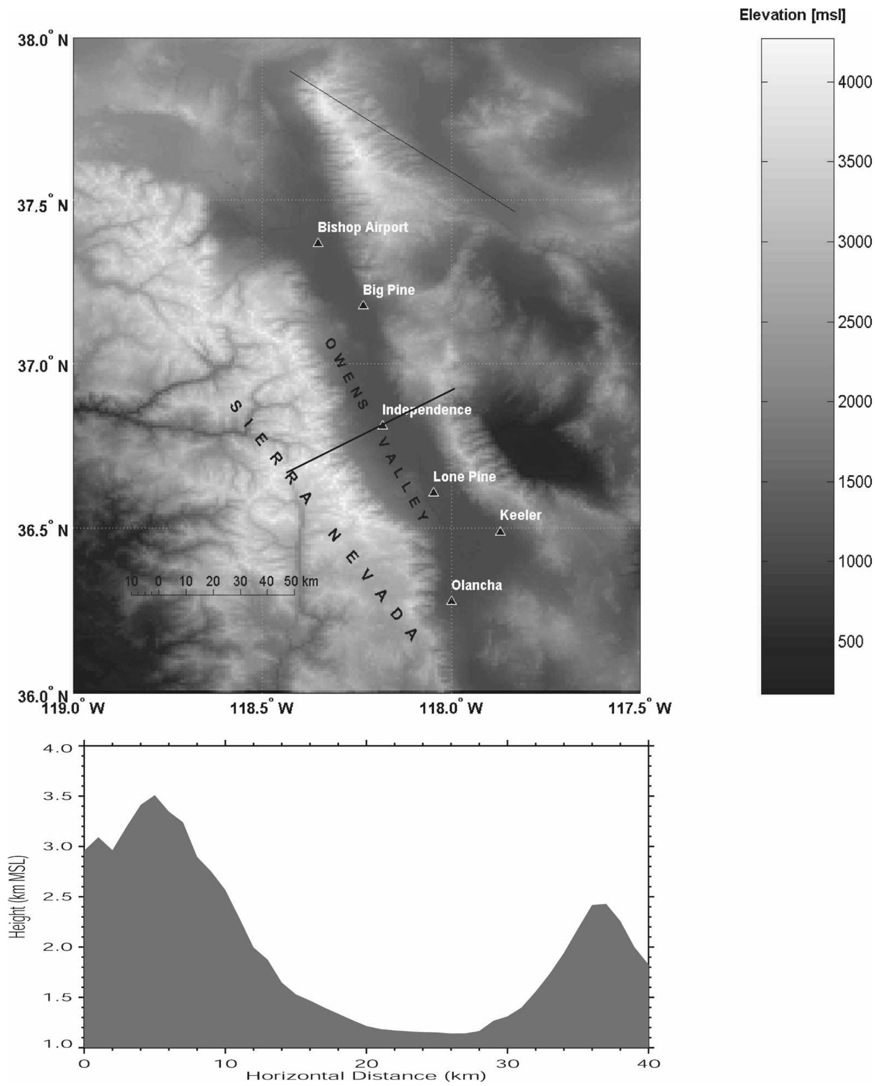

FIG. 1. (top) Owens Valley terrain and the locations of surface weather stations and (bottom) vertical cross section of the topography through Independence.

southern Sierra Nevada. The ridge-to-ridge width of the valley varies from 15 to 30 km. The valley is relatively narrow between Bishop in the northern part of the valley and Lone Pine in the southern part. Northward from Bishop the valley floor rises, and the valley widens considerably and splits into two valleys. At the southern end of the valley lies the dry Owens Lake bed, which was originally a 285 km^2 saline lake. The lake was reduced to a much smaller brine pool surrounded by a large area of dry, alkaline soils following the diversion of the Owens River water to Los Angeles in an aqueduct project completed in 1913. Situated in the rain shadow of the Sierra Nevada, the annual rainfall in the region averages about 10–15 cm yr^{-1}, with most precipitation falling from November through April. The valley floor is semiarid with widely dispersed shrubs and natural grasses, while the sidewalls are mostly rocky, but with widely scattered trees at elevations above 2000 m MSL

Surface meteorological observations from six automated weather stations are used in the climatological analysis. These stations are part of a network operated by the Great Basin Unified Air Pollution Control District (GBUAPCD) for monitoring air quality and the transport of fugitive dust from the dry Owens Lake bed. The locations of the stations and the topography are shown in Fig. 1. Station information, including latitude, longitude, and elevation, are given in Table 1, which also includes the period of record for each station.

The six stations are situated along the Owens Valley axis. The northernmost station is located at Bishop Airport and the southernmost station is at Olancha at the

TABLE 1. Station geographic information, period of observations, and hourly record in the analyses.

Station name	Lat (°N)	Lon (°W)	Elev (m MSL)	Period of record	Hourly records used in the analyses (total hourly records − missing or bad hourly records)
Bishop Airport	39.3672	118.3528	1254	1 Jan 1988–23 Aug 1991	29 705 (31 928 − 2223)
Big Pine	37.1764	118.2331	1234	23 Aug 1988–11 May 1990	14 973 (15 021 − 48)
Independence	36.8111	118.1819	1193	1 Jul 1988–1 Aug 1991	19 194 (19 479 − 285)
Lone Pine	36.6073	118.0479	1061	14 May 1986–16 Dec 2004	156 331 (162 978 − 6647)
Keeler	36.4916	117.8779	1102	14 Mar 1985–3 Feb 2005	162664 (174396 − 11732)
Olancha	36.2675	117.9930	1122	22 Nov 1985–1 Nov 2005	164749 (174440 − 9691)

southern end of the valley. The other four sites, which are nearly equally spaced, provide information inside the valley. The Big Pine site is about 50 km south of Bishop at a location near the center of the valley. The Independence site is located farther south at a point on the valley floor almost halfway through the valley in the town of Independence, California. The Lone Pine site is still farther south where the valley narrows as the Alabama Hills encroach from the west; this station is located at the foot of the hills. The valley widens to the south and the Keeler site is found on the northeast shore of Owens Lake. From there, the valley narrows again as it approaches its southern end at Olancha. The Olancha site is located closer to the Sierra Nevada on the west side of the valley than to the Inyo Mountains on the east side of the valley.

The six valley floor stations, selected for their even distribution along the valley's segment of interest and for their long periods of record, are suitable for the long-term historical data analysis used in the current study. It is worth noting, however, that a network of 16 automated surface weather stations were installed by Desert Research Institute in three parallel cross-valley transects in the midvalley near Independence (Grubišić et al. 2008) as part of the Sierra Rotor Project and the more recent T-REX project. These data add significantly to the automatic weather station coverage in the valley and should prove useful for additional future analyses as their periods of record increase.

The periods of record for the GBUAPCD meteorological stations varied from site to site, ranging from 3 to 20 yr (Table 1). At all sites, winds were measured on 10-m masts at a sampling rate of one sample every 2 s. Data at each site have gone through automated quality control procedures to remove erroneous values. Additional quality control procedures were applied to remove suspect values from the climatological analyses. Despite occasional missing data caused mostly by severe winter weather, the data quality was generally good. Hourly vector-averaged winds were computed from the 1800 two-second samples and are identified by the ending time of the 1-h averaging period.

3. Results and discussions

a. General behavior of surface winds

Before focusing on high wind events, we first examine the general behavior of the surface winds in the Owens Valley. Figure 2 shows composite wind roses for each of the six sites using all available data in their periods of record. At each station there is a strong tendency for the winds to blow parallel to the local valley axis. For example, at Independence and Lone Pine, the local valley axis is oriented from the north-northwest to the south-southeast, coinciding with the two predominant wind directions at these two sites. However, at Big Pine, the valley axis runs from the north-northwest to the south. As a result, winds at Big Pine are predominantly either from the north-northwest or from the south. The valley widens to the north of Bishop, leading to a much broader distribution of northerly wind directions at Bishop. The broadest wind distribution is seen at Keeler on the north shore of the dry Owens Lake bed. This broad distribution is due to the widening of the valley in the area of the lake. The skewed distribution at Olancha toward more frequent southerly winds is the result of the blocking of northerly winds by the high terrain to the north of the site.

In addition to their strong alignment with the local valley axis, surface winds in the Owens Valley also appear to be influenced by local thermal forcing. As expected from the theory of thermally driven circulations, daytime winds generally blow up valley and upslope while nighttime winds generally blow down valley and downslope. Figure 3 shows daytime and nighttime wind roses at Keeler and Lone Pine using all available data from their individual periods of record. The daytime winds at Keeler are mostly from the southerly quadrants indicating up-valley and upslope flows. At night, wind directions are generally down valley (from the north-northwest) or downslope (from the east). The same diurnal change appears at Lone Pine, with up-valley winds during the day and predominantly northwesterly down-valley flows at night. The nighttime winds have a stronger tendency to be thermally driven

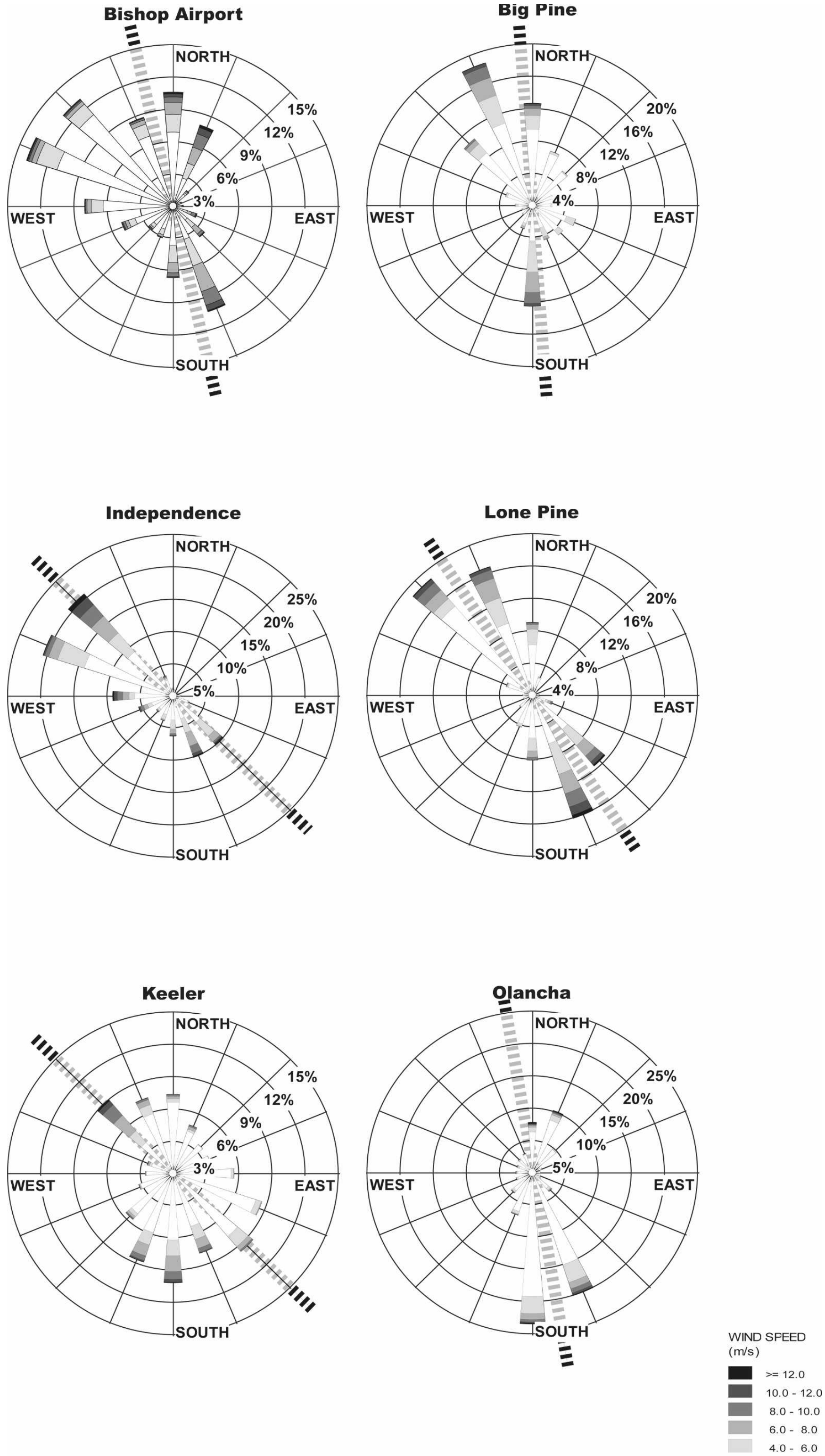

FIG. 2. Composite wind roses for each of the surface stations using all available data for the station. The local valley axis at each site is indicated by shading.

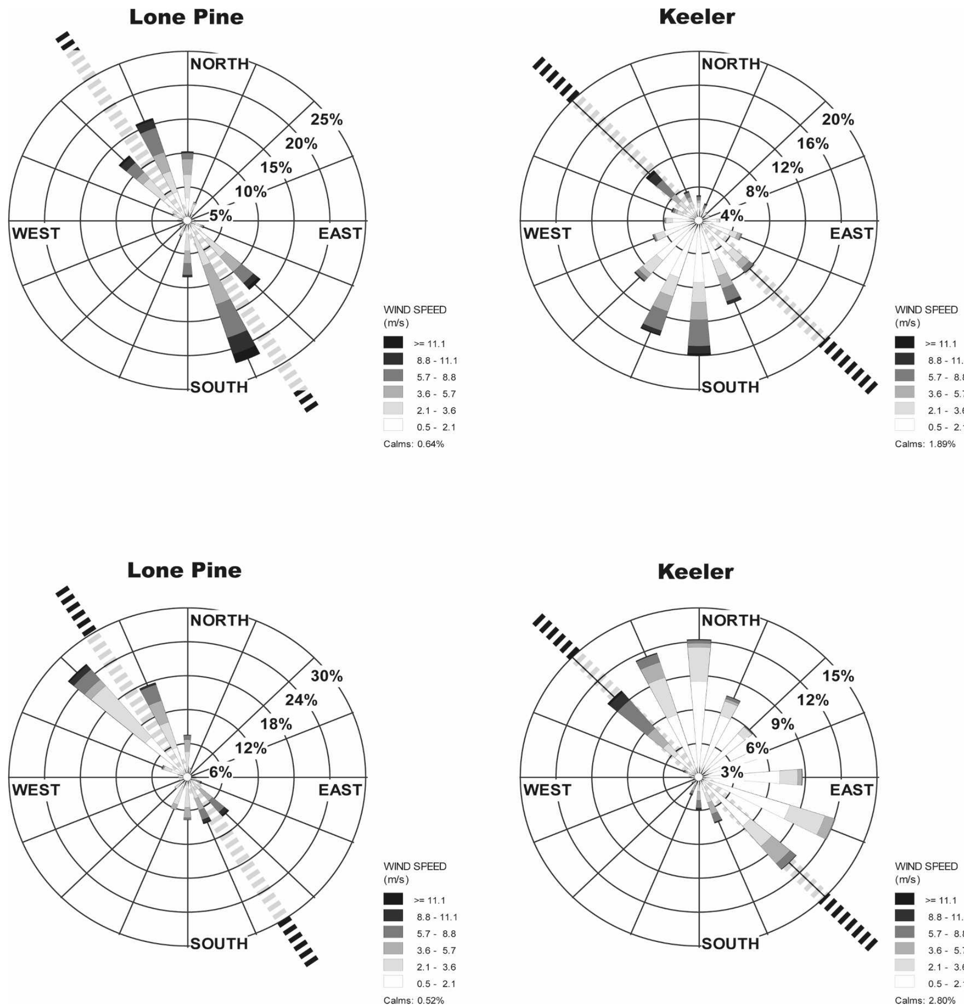

FIG. 3. Composite wind roses for Lone Pine and Keeler for (top) daytime and (bottom) nighttime using all available data for the station.

because of the formation of a surface-based inversion that decouples the surface layer from the atmosphere above, whereas the daytime winds are more often coupled to winds above the valley by turbulent mixing.

That nighttime winds tend to be more consistent than daytime winds is further illustrated in Fig. 4, which shows wind constancy as a function of time of the day. The wind constancy (Stewart et al. 2002) is defined as the ratio of the vector mean and the arithmetic mean wind speeds for each hour of the day, that is,

$$C = \frac{\overline{\mathbf{V}}}{\overline{\overline{V}}} = \frac{\left[\left(\frac{1}{N}\sum_{i=1}^{N} u_i\right)^2 + \left(\frac{1}{N}\sum_{i=1}^{N} v_i\right)^2\right]^{1/2}}{\frac{1}{N}\sum_{i=1}^{N}(u_i^2 + v_i^2)^{1/2}}, \quad (1)$$

where N is the total number of hourly wind records. If the wind is from the same direction at a given hour for all of the available days in the period of record, the constancy would be 1. If the wind is equally likely from all directions or it blows in one direction half the time and the opposite direction another half, the constancy would be 0. Figure 4 shows that, except for Keeler, located in the widest part of the valley, the constancy values are much higher at night than during the day. At most stations, the wind directions appear to be most consistent from day to day during the hours between midnight and early morning and least consistent during the morning and evening transition periods. The variable nature of the wind direction during the transition periods reflects the fact that the time of wind reversal from up to down valley or vice versa changes with season because of the seasonal variations of the sunrise/sunset times and the effects on local sunrise and sunset times of shadowing from the ridgeline and local topography. The lower constancy in daytime wind direction is

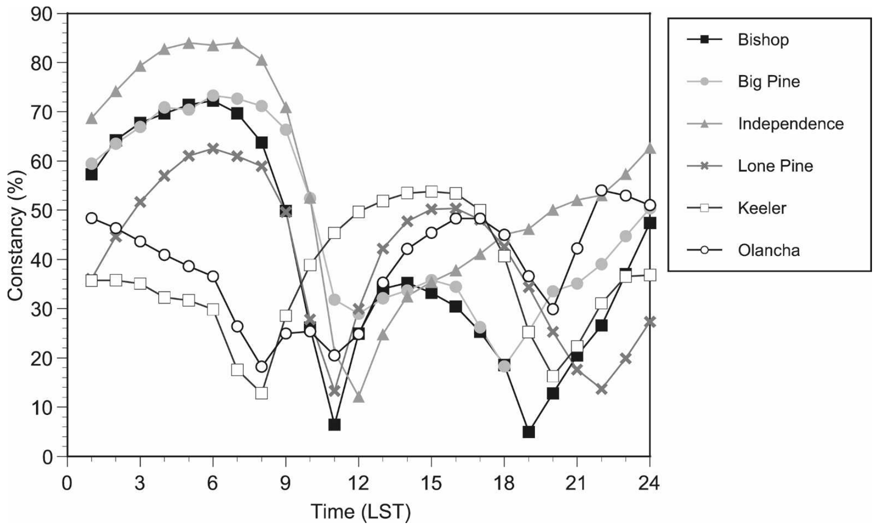

FIG. 4. Day-to-day wind constancy for each hour of the day for all six stations.

another indication of the role of daytime turbulent mixing in coupling the surface winds with winds aloft, allowing the wind direction aloft to modulate the surface winds.

b. *High wind events*

During extreme high wind events hourly average speeds at Owens Valley stations can exceed 18 m s^{-1} (40 mph) with wind gusts in excess of 22 m s^{-1} (50 mph). These windstorm events occur only a few times per year. In this study, we include these extreme events as well as somewhat weaker events that have the potential to produce dust storms and reduce visibility. Previous work (Schade et al. 2008; Reheis 1997) on windblown dust has found that sustained surface winds of 7 m s^{-1} or more would begin to pick up soil particles from the Owens Lake bed to produce dust storms. Wind roses for wind speeds equal to or exceeding 7 m s^{-1} are shown in Fig. 5. Although the general shapes of the wind roses are similar to those in Fig. 2, the wind direction distribution for high wind events is narrower and essentially bidirectional, with winds predominantly blowing either up or down the valley.

Also given in Fig. 5 is the frequency of occurrence of hourly averaged wind speeds greater than or equal to 7 or 10 m s^{-1} for each of the six stations. The probability of high winds differs among the six stations, with some sites more susceptible to high winds than others. Independence has the highest percentage (~16%) of wind speeds greater than or equal to 7 m s^{-1}, while Olancha has the lowest percentage (~5%). There is a significant drop in the frequency of occurrence of wind speeds greater than or equal to 10 m s^{-1}, but the pattern remains the same among the stations. The larger percentage of high winds at Independence may be related to its location in the southern Sierra Nevada below Kearsarge Pass, making the site more prone to the influence of strong downslope flows from the eastern slope of the Sierra Nevada. This is consistent with the wind roses for high winds shown in Fig. 5 where Independence is the only station that has westerly components.

To examine the seasonal variation of high wind events, we used the time period of 1988–91 when data are available at five of the six stations. We define a high wind event as one when three or more of the five stations have hourly average wind speeds that equal or exceed 7 m s^{-1}. Figure 6 shows the percentages of the high wind events during the period examined that occur in each of the four seasons. The results indicate a strong seasonal variation with approximately 40% of all high wind events examined occurring in the spring season from March through May, followed by the fall season with 24%. The high wind events are less frequent during the rest of the year, with summer being the least frequent season.

The lack of westerly directions in the wind roses raises a question about the previous belief that high winds in the Owens Valley are downslope windstorms on the lee side of the Sierra Nevada. Because the downslope windstorms would be coming down the eastern slopes of the Sierra Nevada that form the western sidewalls of the Owens Valley and sweep through the valley from west to east, there should be a pronounced peak of westerly wind frequencies in the surface wind roses for high winds. The rare occurrence of westerly winds in Fig. 5 suggests that other mechanisms may modify the

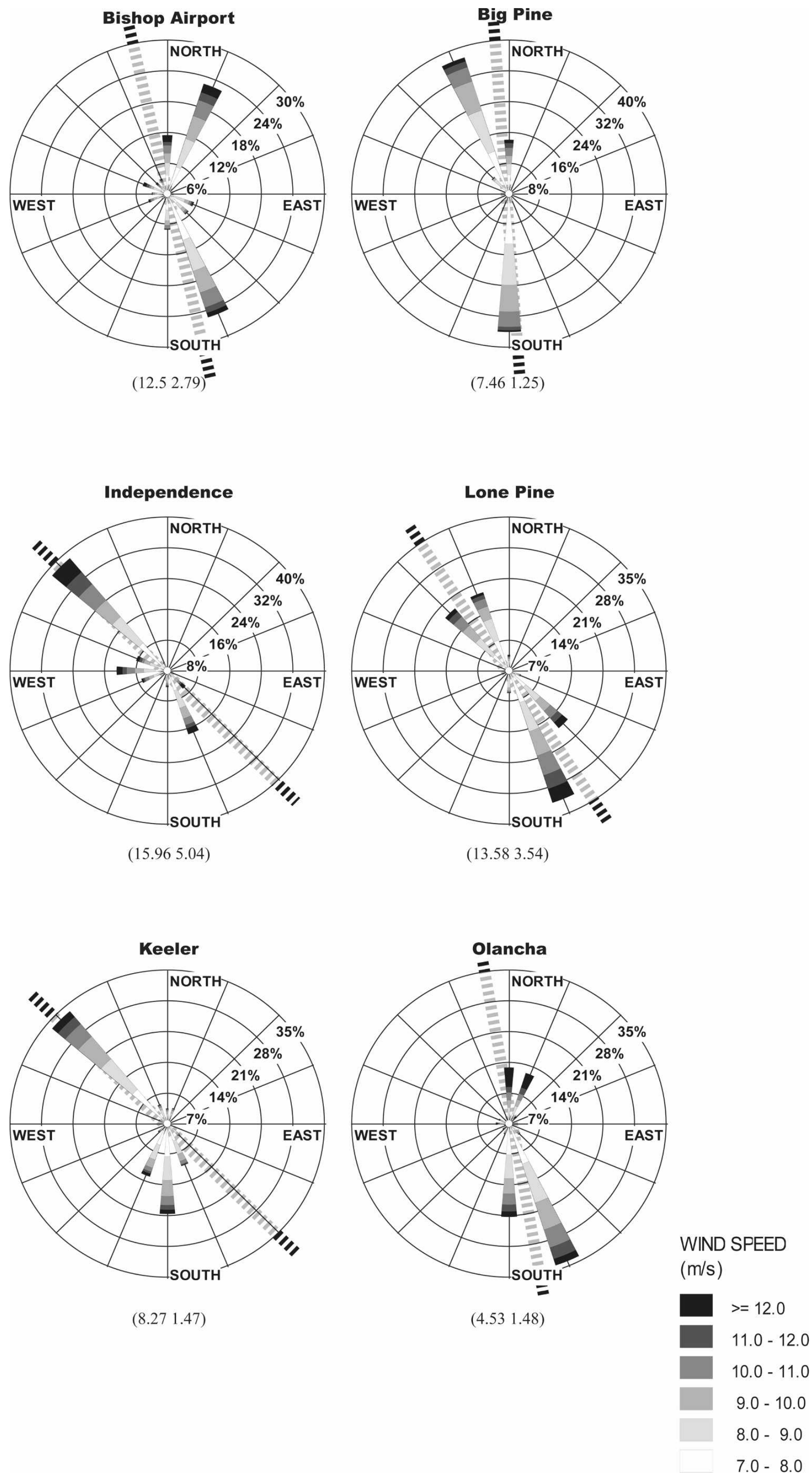

FIG. 5. Composite wind roses for wind speeds greater than 7 m s^{-1} for each of the six stations. The two numbers below each station plot indicate the total frequency of wind speeds exceeding 7 and 10 m s^{-1}, respectively, determined from all available data at each station.

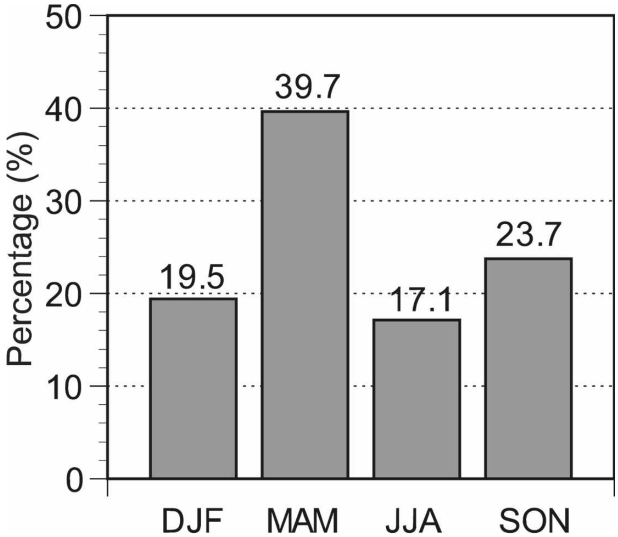

FIG. 6. The seasonal frequency of high wind events, based on period of record from 1988 to 1991, when observations at five of the six stations were available. A high speed event was defined as an event when three or more of the five stations experienced hourly average winds equal to or exceeding 7 m s^{-1}. December–February: DJF; March–May: MAM; June–August: JJA; September–November: SON.

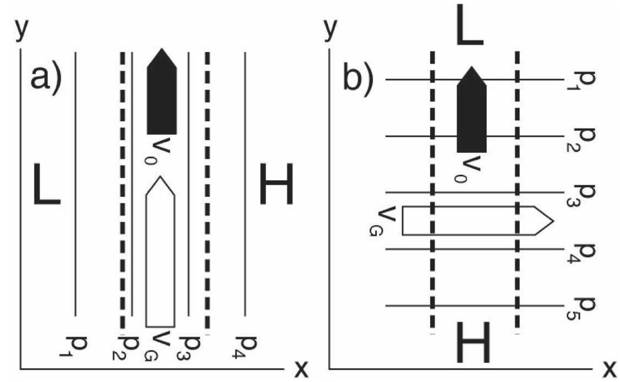

FIG. 7. Illustration of flow channeling in a north–south valley (indicated by the two parallel dashed lines) where the isobars above the valley are labeled. The geostrophic wind (V_G) flows parallel to the isobars with low pressure on the left, and the wind inside the valley is indicated by V_0. (a) *Forced channeling* causes winds inside the valley to be driven along the valley axis in the direction of the along-valley component of the above-valley wind (i.e., in this special case where the upper wind is along the valley axis, this is *perpendicular to the pressure gradient*). (b) *Pressure-driven channeling* causes the wind to flow along the valley axis from the high pressure end toward the low pressure end (i.e., *along the pressure gradient*). This illustrates the differing results inside the valley of the forced and pressure-driven channeling mechanisms.

downslope windstorms or play a more important role than downslope windstorms in causing high wind events on the floor of the Owens Valley.

c. *Mechanisms for high wind events*

Different mechanisms have been put forward to explain the high winds found in mountain valleys (Whiteman 2000). They include 1) downward momentum transport, 2) terrain channeling, including forced channeling and pressure-driven channeling, and 3) frontal passages.

Downward momentum transport 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. Downward momentum transport may also be produced by gravity waves, which are not limited to unstable conditions. Winds in the valley driven by downward momentum transport are expected to align with the wind direction aloft.

High winds in a valley may also be a result of terrain channeling. There are two types of channeling—forced and pressure driven. Forced channeling occurs when strong winds aloft are channeled by the valley sidewalls; this 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 (Fig. 7a).

Pressure-driven channeling (Fig. 7b) is produced by the large-scale pressure gradient above the valley that is superimposed on the underlying terrain. 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. In contrast to forced channeling, winds in the valley caused by pressure-driven channeling always blow along the valley axis from the high pressure end toward the low pressure end (Fig. 7b). Pressure-driven channeling was first recognized in the shallow Rhine Valley of southern Germany (Wippermann and Gross 1981; Fiedler 1983; Wippermann 1984; Gross and Wippermann 1987; Kalthoff and Vogel 1992). Later, Whiteman and Doran (1993) found that winds in the Tennessee Valley are also often produced by pressure-driven channeling. Because the Owens Valley is narrower and deeper than the Tennessee Valley, it is not obvious that pressure-driven channeling would also be found in the Owens Valley. For example, local pressure gradients that form within this very deep valley might significantly alter the effects of the superimposed pressure gradient.

Strong winds in the Owens Valley may also be associated with frontal passages that occur frequently in this region in winter and spring. Cold, dense air behind a cold front may underrun and displace 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 of the above-mentioned mechanisms may contribute in various degrees to the behavior of winds in a valley.

Both downward momentum transfer and terrain-channeling mechanisms require the knowledge of wind speed and direction above the valley at the time when high winds occur in the valley. For climatological analyses, upper-level wind data are typically provided by the standard twice-daily rawinsonde soundings. The Owens Valley, unfortunately, lies in a large gap of the U.S. rawinsonde network. The surrounding upper-air stations at Desert Rock Airport in Mercury, Nevada; in Reno, Nevada; and in Oakland, California, are more than 200 km away from the Owens Valley. Considering the topographic complexity of the region, a simple interpolation of upper-level winds from the surrounding rawinsonde stations to the Owens Valley is likely to be inaccurate. As an alternative to a simple interpolation of upper-air sounding data, we used the NARR dataset to determine synoptic-scale winds above the Owens Valley. The NARR is a set of meteorological analyses over North America available for the period from October 1978 to the present. The analyses are available with 32-km horizontal resolution, 3-h temporal resolution, and 50-hPa vertical resolution, and they are produced through reprocessing the historical meteorological observations using the National Centers for Environmental Prediction's (NCEP's) regional forecast model (Eta Model) and the associated three-dimensional variational data assimilation (3DVAR) system [the Eta Data Assimilation System (EDAS)]. Relatively large errors have been found when comparing NARR to in situ point observations in the complex topography of the western United States, which mainly result from NARR's relatively coarse topography resolution. The use of NARR data in this study, however, is limited to winds at 625 hPa (about 3900 m MSL), a level where the winds are expected to be more accurate than at lower altitudes within the topography. Further details on NARR are given by Mesinger et al. (2006).

1) Downward momentum transfer

Downward momentum transfer requires intense turbulent mixing. The intensity of turbulent mixing varies significantly over a diurnal cycle with high intensity during the day, especially in the afternoon when the atmosphere is very unstable, becoming weak and intermittent at night under stable conditions. If downward momentum mixing is responsible for the high surface winds in the valley, then the hourly distribution of strong surface winds would also exhibit a strong diurnal signature with a higher frequency during the day, especially in the afternoon.

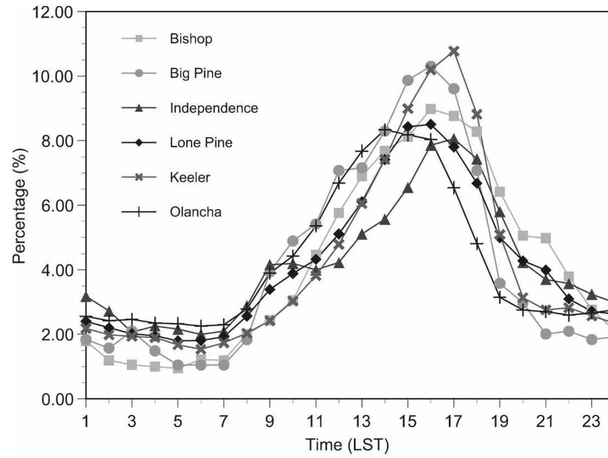

FIG. 8. The percentage of hourly mean winds equaling or exceeding 7 m s^{-1} for each hour of the day determined using all available hourly data.

Figure 8 shows the percentage of occurrence when hourly mean winds equaled or exceeded 7 m s^{-1} for each hour of the day and for all six stations. Despite the substantial differences in the total number of cases among the six stations resulting from the different lengths of observational records at each station, the same diurnal pattern emerged from all of the stations. The diurnal distributions of the high wind percentage show a single afternoon peak. High winds appear to occur much more frequently during daytime than at night. The percentage of high wind events is relatively uniform throughout the night, but increases during the day to reach a peak value between 1400 and 1700 LST at each of the six stations. This behavior, which is consistent with the diurnal variation of boundary layer turbulence and momentum transfer, suggests that downward momentum transfer by turbulent mixing plays an important role in the development of high valley winds during the daytime when the atmosphere is unstable. The same mechanism, however, is unlikely to play a major role in the development of high wind events at nighttime because turbulence is weak in the nocturnal inversion and the surface is decoupled from layers aloft.

The diurnal variation of high winds is further examined in Fig. 9, which shows the percentage of high wind events as a function of the wind direction and hour of the day. The plots further illustrate the bidirectional nature of strong winds in the Owens Valley, with wind

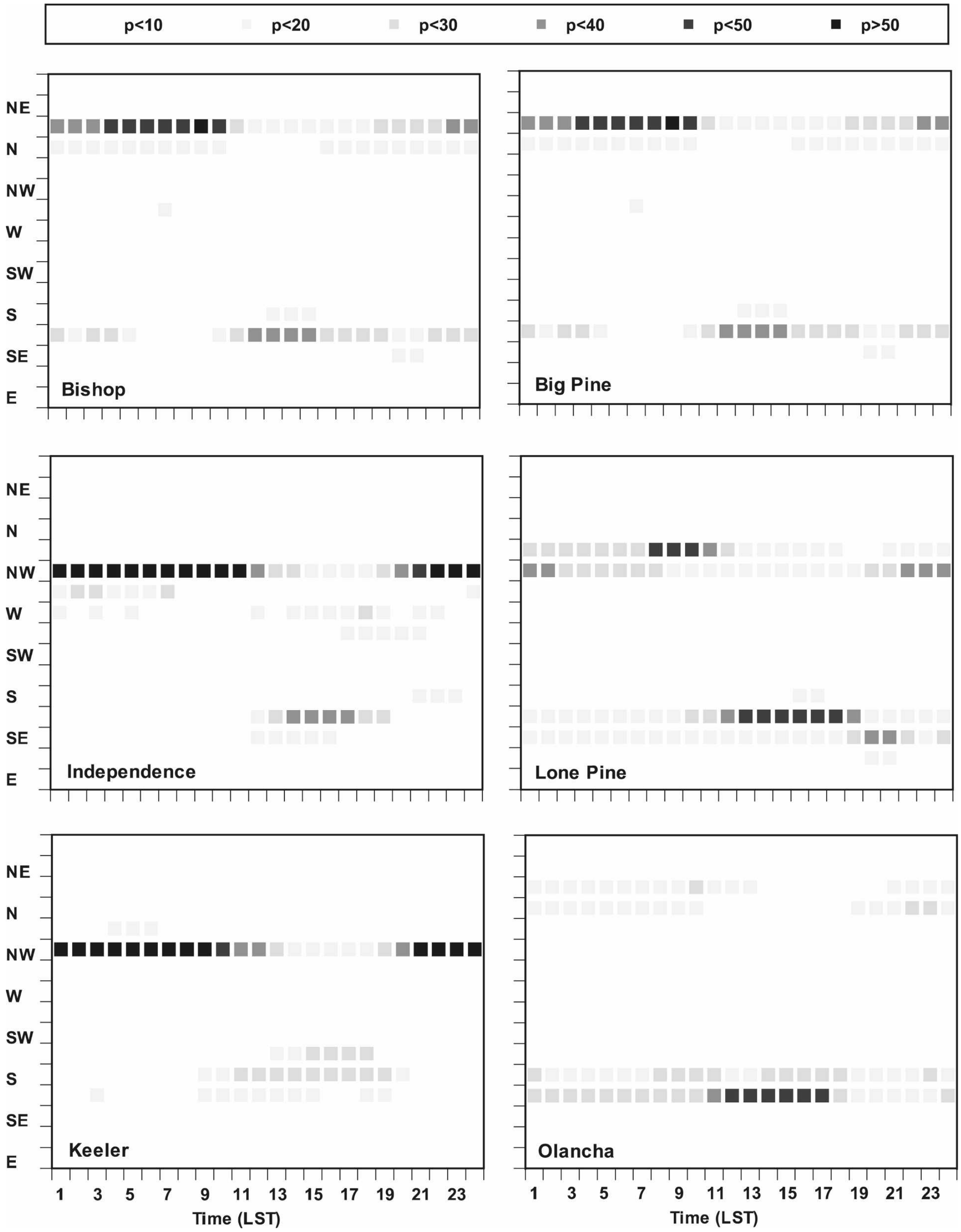

FIG. 9. The percentage of high winds with speeds equal to or exceeding 7 m s^{-1} as a function of hour of the day and wind direction based on all available hourly data.

direction being either up or down valley. The plots also reveal a clear difference in the diurnal distribution of the frequency of occurrence of northerly and southerly winds. Both types of high wind events may happen at any time of the day, indicating that the diurnally varying local along-valley thermal forcing is not the primary driving force for these high wind events as it is for the thermally driven up- and down-valley winds. However, the local thermal forcing appears to contribute to the formation of these high wind events because there is a clear afternoon maximum of southerly high winds that is up valley, which coincides with a weak minimum of northerly winds that is down valley. While the southerly winds are less common at night, the northerly wind frequency is relatively uniformly distributed over time, except for a somewhat reduced frequency during a few afternoon hours when the local thermally driven up-valley flow opposes the northerly winds. This suggests that downward momentum transfer resulting from turbulent mixing in a convective boundary layer is less important for the development of northerly wind cases than for the southerly wind cases that occur much more frequently in the afternoon.

It is worth pointing out the difference between the downward momentum transfer, referred to here, and that traditionally used in explaining typically stronger daytime winds in a wide valley or over a plain. In the latter, the surface winds are usually in the same direction as the winds aloft. However, winds above the Owens Valley, as represented by the 625-hPa winds from NARR grid points near the valley (Fig. 10), are most often from westerly directions, as would be expected for midlatitude locations, whereas the surface winds in the valley, especially strong surface winds, tend to parallel the valley axis as shown in Figs. 2 and 5. Both the mismatch between the surface wind directions and the wind directions above the valley and the close alignment of the surface winds with the valley axis suggest that the flow is channeled by the topography.

2) FLOW CHANNELING

Although the data clearly point to terrain channeling as a mechanism for high wind events in the Owens Valley, it is not clear which type of channeling dominates. In other words, are high surface wind events primarily caused by forced channeling or pressure-driven channeling? The answer may be found by examining the relationship between the surface wind reversals and wind direction changes aloft. Although both channeling mechanisms result in winds inside the valley that blow along the valley axis, a 180° shift in wind direction in the valley occurs when the winds aloft shift across different geostrophic wind directions for the two mechanisms. In the case of forced channeling, the surface wind would reverse direction when the geostrophic wind aloft shifts across a line normal to the valley axis so that the projected geostrophic wind in the along-valley direction changes sign. Pressure-driven channeling, on the other hand, produces a 180° change in wind direction inside the valley when the geostrophic wind direction aloft shifts across the valley axis. Given the near north–south orientation of the Owens Valley and the predominantly westerly geostrophic winds in the region (Fig. 10), the valley wind in the case of forced channeling will switch from up valley (southerly) to

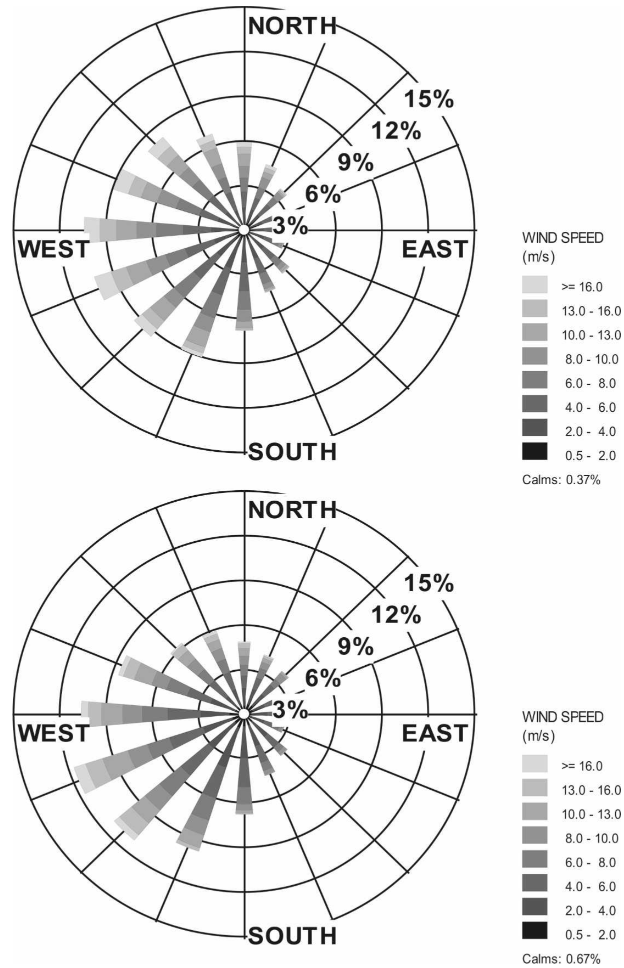

FIG. 10. Wind roses for the 625-hPa pressure level from a NARR grid point near (top) Independence and (bottom) Big Pine using data records from the same time periods as those for the corresponding surface stations.

down valley (northerly) when the geostrophic wind direction shifts from southwesterly to northwesterly or from southeasterly to northeasterly; however, for pressure-driven channeling, the reversal from up valley to down valley occurs when the geostrophic winds aloft switch across the valley axis from southwesterly to southeasterly or from northwesterly to northeasterly.

Based on a methodology developed by Whiteman and Doran (1993), the type of channeling (either pressure driven or forced) may be determined from a joint frequency distribution of surface and above-valley geostrophic wind directions. The geostrophic winds above each site are approximated from the NARR 625-hPa winds. Figure 11 shows the joint frequency distribution of surface and geostrophic wind directions at four stations when surface wind speeds equal or exceed 7 m s^{-1}. The calculation used all the available data points

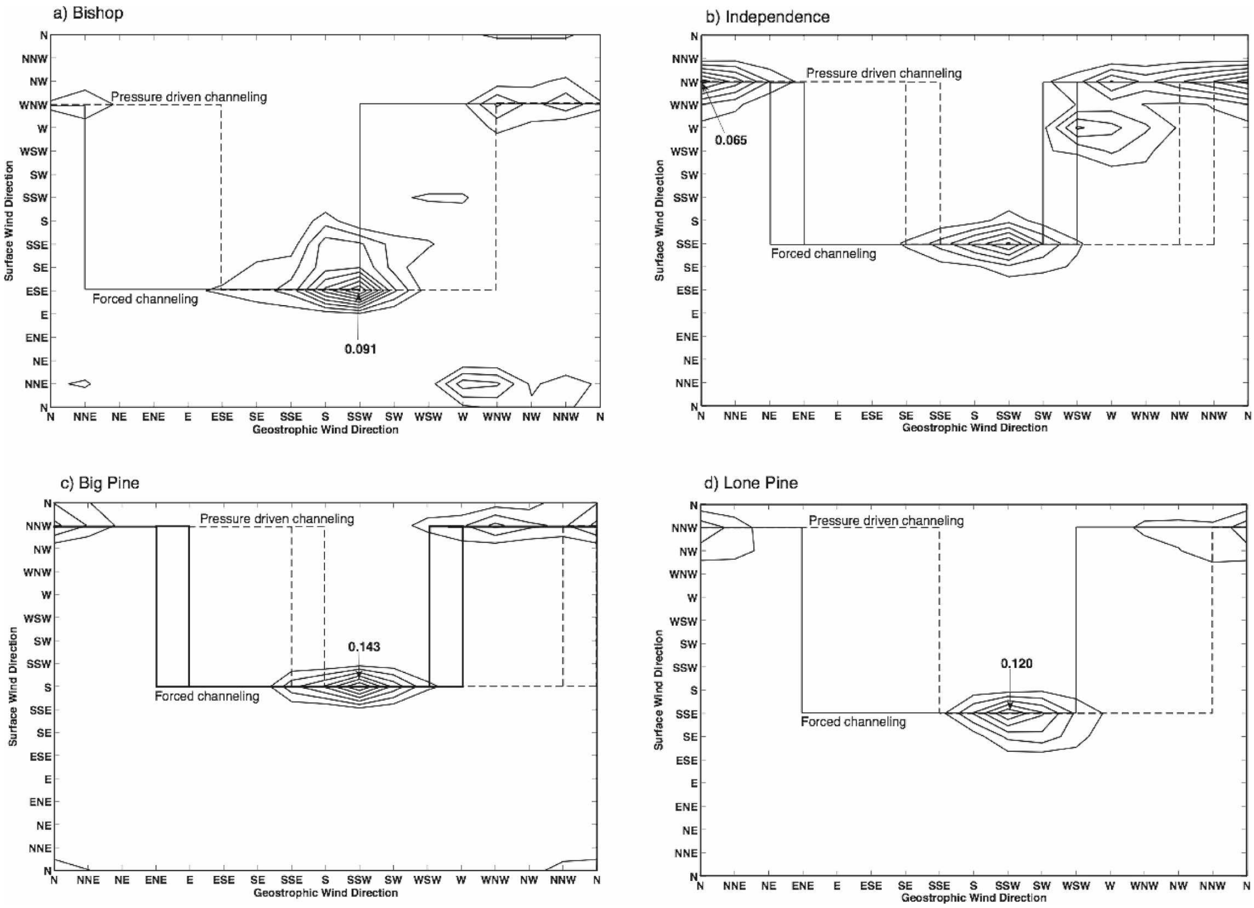

FIG. 11. Joint frequency distribution of the geostrophic and valley wind directions for valley wind speeds greater than 7 m s^{-1} at (a) Bishop, (b) Independence, (c) Big Pine, and (d) Lone Pine. The geostrophic wind direction is determined using the 625-hPa wind at the nearest NARR grid point. The contours are the joint wind direction frequencies (%). The lines illustrate the relationship between the surface and geostrophic wind directions as expected from the forced (solid line) and pressure-driven channeling (dashed line) theories. A range of geostrophic wind directions is indicated for the wind reversal directions at Big Pine and Independence because the up- and down-valley wind directions are not 180° apart.

when the surface data, which are hourly, and the 625-hPa wind from NARR, which is 3 hourly, coexist for each site. Also outlined in the plots are the idealized curves expected from forced and pressure-driven channeling. At Independence and Big Pine, the reversal of valley winds from down to up valley appears to occur when the geostrophic wind shifts from the west-northwest to the south-southwest across the line normal to the valley axis, which seems to fit to the forced channeling pattern better. When the geostrophic wind switches from the northwest to the north-northeast across the valley axis, the surface winds remain up valley, rather than switching to down valley as predicted by pressure-driven channeling theory. However, application of the method is inconclusive for Bishop and Lone Pine because the data could fit either the pressure-driven channeling or forced channeling curves. The difficulty in the interpretation of the joint frequency distribution is due to the paucity of geostrophic winds from the easterly quadrants resulting from the relatively short period of record and the prevailing westerly winds at the Owens Valley latitude.

Another potential problem when applying the joint frequency distribution method to differentiate between forced and pressure-driven channeling arises because of the unusually deep valley atmosphere. The 2.5-km-deep air column between the valley floor and the crest in the Owens Valley accounts for nearly 30% of the air column above the valley floor. Either local or mesoscale pressure gradients within the valley atmosphere might significantly modify the synoptic-scale pressure gradient above the valley. Consequently, the method developed for the shallow Tennessee Valley and the Rhine Valley may not work well for such deep valleys.

The near-zero joint frequencies for westerly surface winds and westerly geostrophic winds in the subfigures of Fig. 11 suggest that westerly downslope windstorms do not often penetrate to the floor of the Owens Valley. Independence, however, is an exception. There, the nonzero joint frequencies may be caused by Kearsarge Pass, a major pass in the southern Sierra Nevada located immediately west of Independence.

3) SYNOPTIC CONDITIONS AND FRONTAL PASSAGES

To investigate the synoptic flow patterns associated with the high wind events in the valley and to test a hypothesis regarding the role of frontal passages, we examined surface winds at all six stations for each day of a 3-yr period (1988–90) when data were available for all stations. A total of 48 high wind days were selected, including 23 southerly up-valley cases and 25 northerly down-valley cases. The criteria for selection were that winds at three or more of the six stations had to equal or exceed 7 m s^{-1} and blow more or less consistently either up or down valley for more than 12 h. A composite of 500-mb geopotential height and wind fields were produced using the 3-hourly gridded NARR dataset for all of the southerly and northerly cases. Results are shown in Figs. 12a,b, respectively. The northerly and southerly high wind cases are characterized by two distinctly different synoptic patterns. In the case of strong northerly surface winds, the Owens Valley is behind an upper-level trough and ahead of the arrival of a ridge located offshore of California. The position of the Owens Valley relative to the synoptic pattern results in strong synoptic winds from the north and northwest. The strong southerly surface wind cases occur prior to the arrival of a deep 500-mb trough just offshore of California, with winds over California and Nevada from the southwest ahead of the approaching trough axis. The geopotential height gradient in the synoptic pattern is stronger for the northerly cases than for the southerly cases.

It is interesting to note that in both the northerly and southerly high wind cases, the synoptic-scale pressure is lower to the north of the Owens Valley and higher to the south. According to the theory of pressure-driven channeling, this would always produce southerly channeled flow in the Owens Valley if the atmosphere is barotropic. However, in the observations, the northerly channeling cases are as frequent as the southerly cases, which obviously could not be caused by pressure-driven channeling. According to Fig. 9, northerly high surface winds are also not a likely result of downward momentum transfer because it happens somewhat less frequently in the afternoon when turbulent mixing is most intense.

To understand what drives the northerly high wind events, we examined surface and upper-level synoptic charts individually for each of the 25 selected northerly strong valley wind cases. We found, with only a few exceptions, that northerly high wind cases were accompanied by the passage of a cold front from the north. Sometimes the cold front is a segment of a large extratropical cyclone centered in southern Canada or the Midwest, and at other times the cold front is associated with a weaker and more regional low pressure system centered just east or northeast of the region. As the front passes through the area of western California, the cold air behind the front underran the warmer air in the valley and allowed northerly winds to prevail. The event normally ends as high pressure builds back over the area.

A careful examination of surface weather charts for the 23 selected southerly wind cases revealed that the strong southerly winds were usually accompanied by a 500-mb cutoff low (which is absent in the composite map because of averaging) located off the coast of California and a surface low pressure system ahead of the upper-level low that is present in Nevada, southern Oregon, or southern Utah. The position of the surface low relative to the valley and the strong southwesterly upper-level winds ahead of the trough works in concert to produce the strong southerly up-valley flows in the Owens Valley. The events usually end when the upper-level low moves east of the Owens Valley. In the case of strong southerly winds, the synoptic pressure gradient is superimposed on the surface pressure gradient; the pressure channeling also plays a role.

4. Conclusions

The Owens Valley of California is the largest natural source for particulate matter in the United States because of the dry Owens Lake bed at the southern end of the valley, the lack of precipitation on the east side of the Sierra Nevada, and the frequent occurrence of high winds. Accurate forecasting of the high wind events is critical for air quality management in the region. In this study, climate data from six surface stations in the valley are combined with analyses from the North American Regional Reanalysis to characterize high wind events and identify dynamic mechanisms leading to these events in the Owens Valley. The results may be useful for understanding high wind events in similar deep mountain valleys in other parts of the country and the world.

Surface winds at each station are bi-directional, in general, with wind direction closely aligned with the local valley axis. Low-speed surface winds are thermally driven, blowing up valley during daytime and down valley during nighttime. The local along-valley

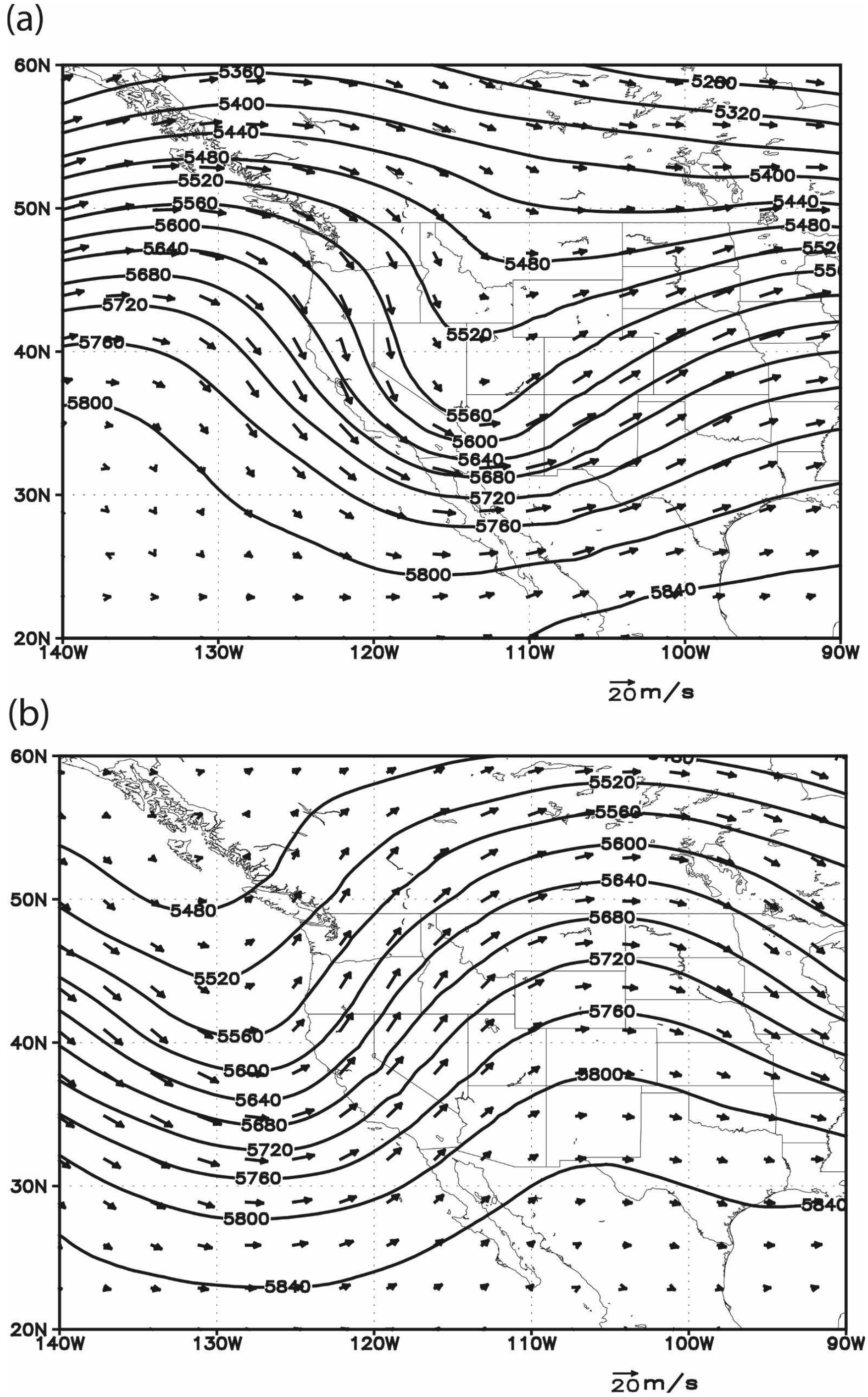

FIG. 12. Composite charts of 500-mb geopotential heights and wind vectors for (a) the selected northerly high wind events and (b) the selected southerly high wind events in the Owens Valley.

thermal forcing becomes much less important for high wind events with sustained wind speeds equal to or greater than 7 m s^{-1}. These may occur at any time of the day and are driven primarily by regional- or synoptic-scale forcing.

Several mechanisms potentially responsible for high valley winds are examined, including downward momentum transfer by turbulent mixing in the convective boundary layer, terrain channeling, and frontal passage. The terrain channeling is further divided into two categories—forced channeling, when strong winds are channeled by the valley sidewalls, and pressure-driven channeling, when the overlying synoptic-scale pressure gradient is superimposed on local forcing to produce a valley wind blowing from the high pressure end of the valley to the low pressure end.

Various analyses designed to examine each individual mechanism suggest that different mechanisms are responsible for the formation of northerly and southerly high wind events in the Owens Valley. In the case of strong southerly winds that are more frequent in the afternoon and less common at night, downward momentum transfer, forced channeling, and pressure-driven channeling appear to all play a role. The synoptic weather patterns accompanying these southerly high wind events are typically characterized by either a deep 500-mb trough or oftentimes a cutoff low just offshore of California with strong upper-level winds from the south-southwest ahead of the trough over the Owens Valley. The synoptic-scale pressure gradient is superimposed on a surface pressure gradient associated with a surface low pressure center that often forms in the divergence area ahead of the trough axis to the north of the Owens Valley, leading to strong southerly valley winds.

Northerly high wind events typically occur when the Owens Valley is behind or to the west of an upper-level trough axis with strong north-northwesterly synoptic winds aloft. These northerly surface wind cases are almost always accompanied by a surface cold front that passes the area of the Owens Valley from the northwest to the southeast. The cold, northerly flows behind the cold front prevail at the surface by undercutting and displacing the warmer air in the valley. The valley sidewalls help channel the generally northerly wind behind the cold fronts into a direction parallel to the valley axis. The forced channeling helps to enhance the speed of the northerly wind through the valley. Downward momentum transfer and pressure-driven channeling appear to be less important in northerly wind events.

The results presented in this study are limited by the lack of wind information above the valley floor because all of the stations are located along the valley axis at the bottom of the valley. The fact that high winds at the surface are predominantly blowing from either the south-southeast or the north-northwest parallel to the valley axis regardless of the wind direction aloft (most often westerly) suggests that a transition layer must exist in the upper part of the valley. In this transition layer, the synoptic-scale wind direction above the valley must transition to the north-northwest or south-southeast valley-parallel direction at the valley floor. An important question is where and how deep this transition layer is in this very deep valley. Unfortunately, the current dataset cannot answer this question. The dataset from the recent T-REX intensive field campaign (Grubišić et al. 2008) in the Owens Valley, which included numerous rawinsonde soundings and radar wind profiler observations within the valley, holds the key to this and other questions regarding the vertical distribution of the winds in this deep valley.

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