Mountain and Valley Winds of Lee Vining Canyon, Sierra Nevada, California, U.S.A.

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Abstract

Observations have been made in a major, eastern canyon of the Sierra Nevada, and are the first documentation of the mountain and valley wind system in this range. The topography of the “Eastside” of the Sierra Nevada is unique, producing some interesting flow patterns. Surface and upper-air data have been collected during summer and winter from 1994 through 1997. The mountain wind and similarly the valley wind have been observed as regular features of Lee Vining Canyon. However, results have shown a complex wind regime where the normal up-canyon valley wind is often replaced with a down-canyon flow by mid-afternoon. This wind, which depends on a number of mechanisms, is more common during summer than winter which suggests that it may be thermally driven. During winter, katabatic flows have been observed in the upper reaches of the canyon proper, while a distinct valley wind dominated the lower regions of the canyon.

Introduction

Local mountain and valley wind systems have been studied for many years, leading to a basic understanding of the dynamics involved. The parameters of these thermally driven wind regimes are documented for many mountainous regions throughout the world, but for the Sierra Nevada, these winds and their quantitative and qualitative aspects are unknown. This paper examines the wind system of a single, eastern Sierra Nevada canyon in order to develop a more complete image of Sierra Nevada wind flow. The additional familiarity of this wind regime will not only create a more detailed description of mountain and valley wind systems, but is the first study of its kind in the Sierra Nevada. This study will be useful in the understanding of Mono Basin’s winter pogonip phenomenon (a super-cooled fog that plagues the region many times throughout the winter season) and will be important to air pollution studies of the Sierra Nevada and the Great Basin. The purpose of this paper is to discuss observations made in Lee Vining Canyon of the mountain-valley wind regime during the winter 1995–1996 and June 1996.

There are two basic components of the valley wind system as summarized by Whiteman (1990): the slope winds and the valley winds, which are both thermally driven. The slope winds blow parallel to the incline of the valley sidewalls, while the valley winds blow along the axis of the valley. Slope winds are driven by buoyancy forces produced by temperature differences between the air in the slope and the ambient air at the same altitude. The valley winds are a result of horizontal pressure gradients that are driven by temperature differences that form along the valley axis as well as between the valley proper and the adjacent plain. Typically, slope winds blow up-slope during the day and down-slope at night; the valley winds blow up-valley during the day and down-valley during the night. Their onset can vary depending on valley geometry and influence from external or regional wind systems (Whiteman, 1990). In this paper the nomenclature valley wind is often used to describe the up-canyon flow, while mountain or drainage wind is used to describe the nocturnal down-canyon flow.

The first reported observation of the mountain wind in the Sierra Nevada was most likely made by John Muir when he described the mountain night wind during his ascent of Mount Ritter in 1872 (Muir, 1894). Some simple observations were also made in Yosemite Valley by E.E. Matthes during an expedition for the U.S. Geological Survey (Matthes, 1911). He found the valley wind to be a regular feature of Yosemite Valley, and on one occasion this wind brought smoke from a nearby wild fire up into the valley proper, hindering his surveying. A pilot study was conducted during the summer of 1977 that examined upslope winds in the southern High Sierra. Results were limited, but Morgan and Slusser (1978) noted that a complex wind system exists for that region of the Sierra Nevada.

The wind system of Lee Vining Canyon is quite unique. This is due in part to the canyon having a “nontypical” valley geography, which is found throughout the eastern Sierra. Topographically, the canyons of the eastern Sierra Nevada differ from the idealized valleys studied elsewhere. Eastern Sierra canyons have two components: the upper canyon and the lower canyon. The upper part of the canyon is characterized as that within the “mountain front proper,” which is where the vertical relief of the side walls is greater than the valley floor area. The lower canyon is distinguished from the latter by its symmetric lateral moraine walls, which have low vertical relief and extend into the Mono Basin. As a consequence of these differing topographies, the wind characteristics of the upper and lower canyon may differ dramatically leading to a unique wind regime.

Experiment Site

Lee Vining Canyon (37°55’N, 119°09’W) is located east of the Sierra Nevada crest, east of Yosemite National Park and southwest of Mono Lake (Fig. 1). It is one of the main canyons or valleys that lead from the Sierra crest and drain to the Mono Basin. This canyon was chosen because of its location and size, and represents a fine example of eastern Sierra canyons that are characterized by their U-shaped geometry and their symmetric lateral moraines extending into the basins to the east.
The valley length is 13.9 km and is aligned west to east. The canyon opens from the mountain front proper (Mono Dome) and the canyon moraines extend into the Mono Basin (Fig. 2). The horizontal area of the canyon at ridge height is approximately 18.7 km². The opening width at the mountain front boundary is 2.8 km. The valley floor slope at the Aspen campground (ACG) is 2.3° and 1.2° at the meteorological station (MET) (Fig. 2). Slope of the valley side-walls are as follows: at ACG the north slope measures 35° and the south slope at 28.7°. At the MET site both the north-facing slope and the south-facing slope have a measurement of 21.8°.

The canyon crest height on the north side of the canyon is 2987 m, which gives a relief of 700 m from the canyon floor, and at Mono Dome (3238 m) the relief is 945 m above ground level (AGL). On the south side of canyon the crest height measured 3535 m at the Dana Plateau. This gives a relief of 1250 m from the canyon floor. For the canyon proper, I will use 700 m AGL for average crest height. At the MET site, the crest...
heights of both the north and south moraines are 150 m above the canyon floor.

**Data Collection and Methods**

Wind and temperature data were collected from 17 January to 1 March 1995 using a 6-m tower located just west of the Lee Vining Ranger Station, which is located approximately 5 m above the main canyon floor on a small, recessional moraine. This tower was equipped with a datalogger, a thermometer, a three-cup anemometer, and a wind vane, each at 3 m and 6 m. Data consist of hourly averaged wind speed, wind direction, and temperature. During the winter of 1995–1996, the same system was used with instruments located at 3 m and 10 m. This tower was situated farther up the canyon at the MET site (Figs. 1, 3). Data have also been examined from a tower belonging to the Great Basin Unified Air Pollution Control District (GBAPD), located at the opening of Lee Vining Canyon near the town of Lee Vining (Fig. 2). Data collected here include hourly averages of temperature, barometric pressure, wind speed, and wind direction at 10 m.

Pilot balloon observations were made using 10-g and 30-g balloons and a single theodolite with readings taken at 30-s intervals. The inherent errors associated with single theodolite technique as stated in the papers by Colson (1952) and Ayer (1958) have been taken into account. I made the balloon observations alone with the use of two microcassette tape recorders, one for the timing tones and the other for the recording of the readings. Balloons were filled with helium using appropriate mass for correct total-lift force of the balloon. Analysis assumes a constant ascent rate of 150 m min⁻¹ and wind speed values are given for interpolated heights. No-lift balloons were used to examine slope winds. These were released at various locations throughout the canyon at various times of the day and will be discussed in the next section.

**Observations and Results**

**SURFACE TOWER OBSERVATIONS**

The MET tower recorded daily surface-wind reversals occurring between 1000 and 1100 PST for the up-canyon flow and 1500 and 1700 PST for the down-canyon component, with an average maximum velocity of 3 m s⁻¹ for the up-canyon component. Wind reversals in Lee Vining Canyon were found during the winter season. Reversals were observed to be more distinct and regular during periods of low synoptic influence.

A typical winter day is depicted in Figure 4, which shows surface data from both sites (MET and GBAPD) for 24 December 1995. The maximum wind speed is in the up-canyon direction and the times of the first reversal are between 0900 and 1100 PST. This wind lasts 4 to 6 h on average before the drainage flow dominates and the wind direction reverses back to down-canyon flow between 1400 and 1600 PST. The down-canyon component is very light, rarely exceeding 3 m s⁻¹ and is a drainage wind that flows down canyon along the axis of the lateral moraines. The air temperature stayed near or below 0°C, which is not uncommon for the eastern Sierra Nevada. The reversal at the MET site (Fig. 4) is very distinct with the maximum wind speed occurring at 1300 PST in the up-canyon direction. However, the drainage is very weak, never exceeding 0.2 m s⁻¹, which is within the error of the instrumentation. These very light winds are fumigated down between the lateral moraines and can be referred to as shallow, katabatic slope winds. At the GBAPD tower, the wind speed magnitude does not build as it does at the MET site. Here the wind maximum is 2.7 m s⁻¹ in a down-slope direction. This direction is out of the canyon at the opening or mouth of the canyon proper.

Figure 5 shows surface data for 2 March 1996. This data shows the reversal to up-canyon flow occurring first at the GBAPD site and then an hour or so later occurring in the canyon at the MET site. This is also shown in Figure 4, and is due to the topography, where the MET tower is located within the lower canyon and the GBAPD tower is out in the basin. Since the MET tower is more sheltered than the GBAPD tower, the reversals there tend to develop later due to heating beginning in the basin first. However, Banta (1984) and other investigators found the wind reversal occurring simultaneously within valleys studied elsewhere.

At times of synoptic influence, such as in post-frontal environments, outflow was the dominant component and reversals in the wind direction never fully developed. By this meaning a
FIGURE 4. Surface data for 24 December 1995 showing wind reversal occurring at both sites.

FIGURE 5. Surface data for 2 March 1996 showing wind reversal occurring at both sites.
distinct reversal over at least 4 h in hourly averaged direction. However, on clear days the up-canyon flow dominates much of the time between 1000 and 1500 PST, and this is considered the valley wind. One criteria for a valley-wind day is the twice daily wind reversal for the surface wind discussed by Vergeiner and Dreiseitl (1987). The tower data show that Lee Vining Canyon valley-wind days are common during winter as well as in the summer months. The frequency of reversal days seems high for the winter season with an average of 59%; December averaged 68%, January 55%, February 59%, and March 55% (Fig. 6).

Summer surface data was unavailable for the MET tower. However, data from the GBAPD tower indicated that surface wind structure was similar to that found in the winter with the exception of stronger up-canyon flows occurring later in the afternoon. This would appear typical due to the increased seasonal solar heating. In addition, there were many days showing a mid-afternoon reversal from the usual up-canyon valley winds to down-canyon flow. This interesting feature will be discussed in more detail in the following section.

**PILOT BALLOON OBSERVATIONS**

Pilot balloon observations have shown wind maximum and minimum at specific heights within the canyon proper. The mountain wind is shown to exist between the heights of 160 m and 463 m AGL for summer. The vertical extent of the mountain and valley wind is finite, and its speed reaches a maximum at a certain height (Ekhart, 1948; Buettner and Thyer, 1966). Its upper boundary is near or below ridge height, and the maximum speed is reached within the lower half of the layer. A minimum in velocity is an indicator of the maximum height of both the drainage flow and the valley wind (Vergeiner and Dreiseitl, 1987). The base height of the transition layer is identified by Barr and Ogill (1989) as that height where the wind speed decreases to a minimum and, simultaneously, the wind direction changes by more than 50% of the difference between the down-valley direction and ridge-top wind direction. In general, for Lee Vining Canyon, the upper-level (above ridge height) or ambient flow is westerly and near perpendicular to the Sierra Nevada and is in the same direction as the canyon axis.

Summer observations were made when the synoptic conditions allowed for a general westerly upper-level flow over California and Nevada. Figure 7 shows the vertical wind profile for consecutive pilful (pilot balloon) ascents on the morning of 4 June 1996. At 0956 PDT the down-canyon drainage flow is evident while above crest height the westerly upper-level flow dominates. At 1040 PDT the wind direction is now up-canyon and the onset of the valley-wind regime has started. The top of the valley-wind layer is above the crest height and above this the westerly ambient flow is evident. This identifies the up-canyon flow or valley wind. At this time the maximum wind speed in this direction was 2.8 m s⁻¹ at 50 m AGL. At 1321 PDT, a daytime down-canyon flow has developed and continues throughout the day. This wind, known locally in northern Nevada as the Washoe Zephyr, might be more appropriately termed

![Image of diagrams showing wind patterns for December, January, February, and March]
or referred to as the Tioga in the eastern Sierra Nevada since it appears to originate from Tioga Pass (Fig. 1). The Tioga continues into the late evening when it diminishes and the nocturnal mountain wind with a much lesser magnitude continues into the morning. The Tioga, however locally known, has not received much attention in the current literature. Hill (1980) suggested that daytime down-canyon winds are caused by a number of factors ranging from synoptic scale terrain-induced circulations to mesoscale differential heating, and at times the production of these winds can be attributed to surface pressure gradients (Hill, 1980). Banta (1984) and King (1996) suggested that daytime down-canyon winds are a result of downward mixing of momentum from aloft. Once the convective boundary layer entrains the westerly momentum air from aloft, the stronger upper-level westerly winds replace the up-canyon valley winds. When conditions permit, the Tioga wind regime can occur on many days.

Data from the GBAFD tower for the summer 1995 were examined using a criteria that the down-canyon flow must occur between the hours of 1100 and 1600 PDT in which the maximum in wind speed must not exceed 7 m s$^{-1}$. However, there are cases when the wind speed does exceed this criterion, as in Figure 7. Daytime down-canyon wind days occurred with a frequency of 40% for the month of June, 48% for July, 45% for August, 19% for September, and 16% for October (Fig. 8). The decline in frequency in the autumn months suggests that these winds are thermally driven or are related to a thermally developed regime and may not be subject to just the mixing of momentum from aloft.

In the Truckee Meadows (Reno, Nevada), the Washoe Zephyr term is often used to describe the strong south wind from the Washoe Valley that is associated with an approaching cold front. This often makes the nomenclature confusing. The National Weather Service Forecast Office in Reno, Nevada is aware of a wind similar to the Tioga and has been able to forecast it using data from Truckee, California (NWS, pers. comm., 1997). This wind regime is most likely a result of a large-scale pressure gradient which tends to develop from the stronger heating of the interior of Nevada. Possibly the first description of this phenomenon may have been by Samuel Clemens, who under the pen name Mark Twain described this wind as originating at the mountain crest level. "It probably is manufactured on the moutaintop for the occasion, and starts from there. It is a pretty regular wind, in the summer-time. Its office hours are from two in the afternoon, till two the next morning" (Twain, 1871). Twain also describes the magnitude of this wind to be very strong resulting in dust storms. The phenomenon he described is most likely a foehn wind which is a downslope wind event that does not occur with such regularity as the Tioga, and therefore is not the same diurnal down-canyon wind as found in Lee Vining Canyon. Typically, these wind events are associated with severe and often damaging wind speeds with an abrupt change in temperature and relative humidity (Barry, 1992). Therefore, it may

![Figure 7: Vertical wind profiles for 4 June 1996 at the ACG site showing afternoon transition from up-canyon flow to the diurnal down-canyon wind. $h_c =$ canyon crest height.](image)

![Figure 8: Frequency of summer diurnal down-canyon wind days for 1995.](image)
be more appropriate to use the term, Washoe Zephyr, when describing severe downslope winds in the eastern Sierra Nevada.

Figure 9 shows a sequence of vertical wind profiles for 5 June 1996, which indicate an interesting flow above the early morning drainage winds. At 0515 PDT, the mountain wind was found to have a maximum speed of 4 m s$^{-1}$ at a height of 265 m above valley floor. This is 0.4 $\times$ the valley depth. At 0525 PDT this wind had a maximum velocity of 5.2 m s$^{-1}$ at a depth of 0.2 $\times$ valley depth. This is 160 m above the valley floor. Similarly at 0743 PDT the maximum was 3.2 m s$^{-1}$ at 160 m AGL. These observations are about one quarter to one third of the assumed valley crest height. Notice (Fig. 9) that above the drainage flows there is a light return circulation or the so called antiwind. This flow was found at and near the crest height, except at 0743 PDT where the drainage flow depth decreased, the anti-flow decreased to a height below the crest height at 560 m AGL. This is the first known observation of a return flow in the Sierra Nevada and because of limited observations, this wind system deserves future study. However, caution must be used when describing antiwind systems as difficulties arise in identifying their characteristics. These compensation currents are rarely observed because they are not confined to the valley and are typically much weaker than the prevailing synoptic winds. There have been few reports of antiwind systems since Buettner and Thyer (1966) found return relaxations in the valleys of Mount Rainier, Washington (Whiteeman, 1990). These winds occupied the upper portions of the valleys below the ridgetop heights. It is usually found that antiwinds are not constrained to flow between valley walls, and thus are not exactly opposite in direction to the surface winds. Sometimes the antiwinds may even be perpendicular to the main valley flow, especially when the canyon or valley has bends (Buettner and Thyer, 1966).

The valley wind has been observed (Fig. 10) at the lower balloon release site, which is in the lower canyon where the lateral moraines meet with the mountain front proper, west of the MET site (Fig. 2). At 1021 PDT the wind maximum is near the surface and tapers off towards crest height. Also, at 1037 PDT the transition height is shown to have occurred at roughly crest level and the wind speed is uniform or constant from 300 m to 1000 m AGL. Above this point, the wind speed increases to 7,4 m s$^{-1}$ and its direction is westerly. The direction changes from approximately 80$^\circ$ at 50 m to 240$^\circ$ at 950 m AGL. This shows the transition from the up-canyon component to the gradient flow where the maximum valley wind of 4 m s$^{-1}$ occurs at 160 m AGL. No-lift balloons were used at this site where it was observed that a low level flow, approximately 20 m AGL, continued up canyon at a constant height. This indicates a shallow up-canyon wind which may be the lower limit of the of the valley wind. Wagner (1938) states that winds in shallow valleys can be referred to as slope winds along the sloping valley floor. This may be the case in lower Lee Vining Canyon because of the low relief of the lower moraine walls (Fig. 2). However, this wind continues in height well above the moraines to the main mountain front crest height (700 m AGL) before the upper-level wind dominates.

Winter observations were made during a very cold period during March 1996. A cold front had moved through the region two days before observations began. On the morning of 2 March 1996 the temperature at ACG was $-13^\circ$C during the first pilot balloon release. This day was a typical, winter morning where light drainage winds were observed at the surface and temperatures rose to 10$^\circ$C at 1230 PST. In Figure 11, the sequence of vertical wind profiles shows the development of the valley wind at the ACG site. At 0700 PST there is a down-canyon drainage flow of 1.2 m s$^{-1}$ at 100 m AGL. Near and above the crest height the flow continues in a westerly direction increasing in speed, which is associated with the upper-level synoptic flow. At 1209 PST, up-canyon flow is shown to dominate throughout the depth of canyon, this is the valley wind. Observations at 1237 PST revealed a distinct up-canyon flow near the surface as well as throughout the lower levels of the canyon. From these findings, it can be stated that the valley wind system does exist during winter and usually after morning heating of the Mono Basin and lower canyon. The magnitude of the winter valley wind when compared with the summer valley wind is less, but the magni-
Attitudes are not as much as those described by Vergeiner and Dreissell (1987), because of the local valley and basin topography.

One interesting feature of Lee Vining Canyon is what is termed by locals as the "Ellery Bend." This is a constriction in the head of the canyon located at Lake Ellery and just above Poole Plume (Figs. 1, 2). The wind here has been known to blow skiers off their feet as they turn the bend on Highway 120. Even in summer a strong down-canyon wind occurs at this location. On most winter days, katabatic winds were observed flowing down out of the Ellery Lake bowl into Lee Vining Canyon. On these days, the MET site, which is located farther down the canyon, recorded daily surface wind reversals where up-canyon flow dominated during the midday hours. This indicates that the down-canyon wind slides under the developed valley wind, but soon diminishes because of slowing due to friction with the canyon floor and an opposing force with the valley wind (Oke, 1978). Buettner and Thyer (1966) found similar wind regimes during their studies on Mount Rainier, where the valley wind was dominant in the lower sections of the valley and higher up the valley there was a down-valley flow.

OBSERVATIONS WITH NO-LIFT BALLOONS

A few observations were made with no-lift balloons. Party balloons were used with small lead weights for mass. These were released at various times and locations along the canyon. It was not possible to track the balloons with double theodolite technique because of the lack of more than one person. Two releases deserve mention. The first was taken at the lower canyon site west of the MET station on 6 June 1996 at 1100 PDT. The balloon was released at ground level with no initial push and followed by eye. As the balloon gained lift it traversed the canyon floor towards the center and began to rise vertically to a height which appeared to stay constant at approximately 10 to 20 m AGL. At this so-called constant height the balloon went up-canyon appearing to follow the canyon axis. The height remained constant as far as the eye could see. This balloon was only followed for a few minutes until it was lost due to its distance up-canyon.

The second release was taken at 1148 PDT 6 June 1996 on Highway 120 just below Ellery Bend (Fig. 2); it was tracked for a period of more than 10 min using a compass only. After release, the balloon took off up-slope following the contour of the terrain indicating that a slope-wind layer was present. After reaching the top of the ridge, the balloon lifted from the slope and headed eastward. The balloon appeared to circle clockwise (as viewed from below) above the head of the canyon for the duration of the tracking. This flow can be described as an up-slope wind feeding into the main circulation of the canyon. Since

FIGURE 10. Vertical wind profiles for 5 June 1996 at the "lower" canyon site.


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the balloons were watched from a single point, their ranges were unknown, and their appearances may have been deceptive.

Conclusions and Summary

Observations of the mountain and valley wind regime of Lee Vining Canyon have been made during the summer and winter seasons from 1994 through 1997. The findings discussed in this paper present the first observations of this wind system for the eastern Sierra Nevada.

Results show a distinct wind reversal and an up-canyon wind regime in the canyon proper and at the outflow region for both the summer and winter seasons. The reversal onset and finish tends to start earlier in the outflow region than in the canyon proper indicating that the winds propagate up from the Mono Basin into the canyon.

Upper-air observations show three distinct wind-flow regimes existing in Lee Vining Canyon. The first is the mountain wind, which is a nocturnal down-canyon flow resulting from the drainage of colder air from the higher elevated terrain of the Tioga Pass area. These winds were found to be regular features during the summer and winter months with jet maximums of 5 m s\(^{-1}\) occurring at heights approximately 0.2 to 0.4 × the valley depth. The mountain winds were observed to have a return flow or antwind occurring near and slightly above the canyon crest height. Typically, the antwind had smaller wind speeds than the mountain wind, and was found only in a few cases. Further observations are required to explain the possibility that the antwind is a regular feature of this wind regime and that it may exist for other regions of the Sierra Nevada. On average, the maximum height of the mountain wind occurred at or below the canyon crest height. The cessation of the mountain wind occurred by mid-morning as the up-canyon flow developed.

The second wind regime is the valley wind. The valley winds blow up the canyon during the daytime. These winds tend to develop by mid-morning and were found during the summer and winter months with more frequency during winter due to the development of the third wind regime. Wind speeds for the valley wind were between 3 and 4 m s\(^{-1}\) which is typically less than that of the nocturnal mountain winds. Usually, valley winds have greater wind speeds than the mountain winds because daytime heating can produce stronger pressure gradients. In addition, it was found that the magnitude of the winter valley wind was less than that for the summer and is due to the seasonal differences in heating of the local topography. There were times when synoptic conditions, such as frontal passage, caused canyon outflow to dominate for a period of more than one day. In addition, katabatic (drainage) flows were observed in the upper canyon while a wind reversal and valley wind regime were present in the lower region of the canyon. This pattern was found more frequently during winter.

The third wind regime found in Lee Vining Canyon is more complex than the latter two. This wind occurs mostly during the summer months and tends to develop by mid-afternoon. The nomenclature associated with this wind has often been confusing and contradicting. Therefore, I have suggested that the term Tioga be used when referring to this wind in the eastern Sierra Nevada. The Tioga is a daytime down-canyon flow that replaces the normal up-canyon valley wind. It has a frequency of almost 50% for all summer days with average velocities on the order of 5 to 6 m s\(^{-1}\). This flow is probably caused by a number of mechanisms including a large-scale pressure gradient which develops in response to heating contrasts between the mountains and the interior of Nevada. In addition, downward mixing of momentum from aloft may cause the upper level westerly winds to mix down into the canyon proper. The Tioga is not the same as the locally known Washoe Zephyr which is a severe down-slope wind phenomenon. Further, because of the dominance of the Tioga during summer, it is fair to state that valley-wind days occur more frequently during the winter months where the mechanisms which cause the Tioga tend to be found less frequently.

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