Asymmetric Removal of Temperature Inversions in a High Mountain Valley

ROBERT D. KELLY

Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming

(Manuscript received 12 April 1986, in final form 17 November 1987)

ABSTRACT

During July 1985 the transition from nighttime to daytime wind regimes was studied in a steep-sided, broad mountain valley at about 2200 m MSL, in southeastern Wyoming. An array of surface weather stations and pilot balloon releases from several sites were used to measure the boundary layer (BL) and surface winds, starting before sunrise and ending about midday. On nights with clear skies and strong radiational cooling, downslope drainage winds occurred at the surface and through the depth of the BL; by midday, after complete removal of the BL inversion, regional winds dominated. The horizontal and vertical patterns of wind change, as regional winds replaced drainage winds, were determined by the pattern of inversion removal within the valley.

In this wide mountain valley, erosion of the BL inversion starts on the west side and progresses eastward, lagging 1–2 h after the onset of surface heating and resulting in an asymmetric pattern of inversion removal that is apparently independent of regional wind direction but may depend on valley orientation. The general process of inversion removal along the east-facing, west flank of the valley is similar to that observed in the South Park Basin and along the front range of Colorado. The asymmetry observed in the Laramie case was noted only in limited cases in South Park, perhaps since South Park is not entirely flanked by mountains to the east. Other observations, also in Colorado, show that inversion removal in steep-sided but narrow mountain valleys may be a symmetric process that is independent of both valley orientation and above-valley wind direction.

1. Introduction

In recent years some of the interest in boundary layer (BL) meteorology has turned to events, structures and processes over complex terrain. Several field projects have concentrated on BL processes over the mountainous terrain of the western states. The ASCOT experiment in north-central California has emphasized patterns of drainage and diffusion in mountain-valley systems, using gaseous tracers, and surface, tower, and balloon measurements (Fosberg 1984). Another experiment in north-central Colorado has focused on the patterns and mechanisms of inversion breakdown in narrow, steep-sided mountain valleys (Whiteman 1982). As part of the same project, thermodynamic and dynamic numerical model results have been studied and compared with the field measurements (Whiteman and McKee 1982; Bader and McKee 1983 and 1985).

In these modeling experiments and field observations for narrow, steep-sided valleys, the process of inversion removal includes two basic mechanisms: 1) growth of a surface-based convective BL due to surface heating; and 2) descent of the inversion top due to upsheal currents along the valley sidewalls. One of the interesting results of Bader’s two-dimensional (2-d) numerical studies is that inversion removal tends to be symmetric across the valley. In other words, the inversion is eroded at the same rate on both sides of the valley, and the inversion top descends uniformly across the valley. Bader and McKee (1985) explored this idea in some detail, and found the cross-valley symmetry to persist with a range of valley width-to-depth ratios (from 2 to 16), with east–west and north–south valley orientations, and with differing degrees of vertical shear in the horizontal winds above the valley. The lack of dependence on valley orientation seems especially interesting since, for example, the east-facing wall of a north–south valley should warm much more rapidly in the morning hours than the west-facing wall.

Field observations more similar to the present study are presented by Banta and Cotton (1981) and by Banta (1984), from the South Park Area Cumulus Experiment (SPACE) of 1977. In the South Park mountain basin of central Colorado, diurnal winds often evolve in three regimes: 1) downslope and down-valley flows induced by radiational surface cooling; 2) shallow upsheal winds on the west side of the basin, due to surface heating; and 3) afternoon winds consistent with the ridgetop winds, due to mixing as the convective boundary layer grows to ridgetop level or higher.

Using aircraft cross sections of wind and potential temperature, Banta (1984) examined the transitions from regimes 1 to 2 and from 2 to 3 in more detail. In
some cases, along the east-facing slope of the west side of the South Park Basin, the transition from downslope to upslope winds occurred first on the basin floor, then at sites along the west side of the basin. In other cases the transition was nearly simultaneous. In all cases, the shift from upslope flow to ridgetop westerlies started on or along the west side of the basin and propagated eastward across the basin floor. Subsequent modeling studies (Banta 1986) support these observations, and show that the eastward propagation speed of the upslope-to-westerly transition depends on the strength of the ridgetop winds. The model results also indicate the importance of the early morning inversion layer. Without this inversion, upslope winds do not develop. Apparently, the inversion layer acts to “shield” the lee slope from mixing induced by the ridgetop westerly winds.

Using a month-long climatology of surface winds along the front range of northern Colorado, Toth and Johnson (1985) describe a series of wind transitions very similar to those observed in SPACE. In this locale, both types of transition, i.e., from downslope to upslope and from upslope to westerly winds, start in the foothills area and propagate eastward.

In this paper we describe the process of inversion breakdown in a steep-sided but wide mountain basin in southeastern Wyoming. The observations suggest mechanisms different from those proposed for steep-sided, narrow valleys, but similar to those described for South Park and the northern Colorado front range. An important topographical difference for the present study is that the basin opens and drains northward, and has mountain walls on both the east and west sides. Our observations suggest an asymmetric process of in-
ing pilot balloons with theodoilites. For this experiment we used 30-g balloons, inflated with helium to give a rise rate of about 188 m min⁻¹ (3.14 m s⁻¹), assuming average temperature lapse rates approaching dry adiabatic conditions (Boatman 1974).

On 25 July (see section 4) pilot balloons were released from each of the three sites shown in Fig. 1. Balloon releases began at sunrise (0600 MDT) and continued every half hour until 1100 MDT. Each balloon was tracked for 10 min after release, with azimuth and elevation values recorded every 30 s. Using the assumed rise rate of 188 m min⁻¹, this allows calculation of horizontal wind speed and direction at intervals of 94 m, up to 1881 m above the surface.

In the sections to follow, data from two days (4 and 25 July 1985) are presented as case studies. For the 4 July case, only valley surface wind measurements are available; for 25 July both surface wind and pilot balloon measurements are presented.

3. Case study: 4 July 1985

The synoptic weather pattern on 4 July included a large area of high pressure at the surface, centered over southern Alberta and western Montana, giving northerly regional winds over southeastern Wyoming. Thus the regional surface wind direction was parallel to the axis of the Laramie Valley (Fig. 1).

Figure 2 is a plot of surface wind speeds and directions at stations 5, 7 and 8 for 0000 to 1300 MDT on 4 July 1985. As shown in Fig. 2, drainage winds persisted at station 5 until at least 0800 MDT. Between 0800 and 0900 MDT the winds changed to an easterly, upslope direction. By 1100 MDT the winds at station 5 had entered the northerly regional flow pattern. At station 7 winds consistent with drainage persisted until after 1100, and were replaced with northerly regional winds by 1200 MDT. Winds at station 8 were downslope (drainage) until after 0700, and had gained some upslope component by 0800 MDT. By 1000 MDT the winds at station 8 were distinctly upslope. Between 1100 and 1200 MDT, the station 8 winds shifted markedly to the northerly regional wind direction.

These shifts in wind direction suggest an asymmetric pattern in the morning transition to regional winds, with stations on the west side of the valley (those receiving the strongest surface heating just after sunrise) changing from drainage to regional winds before those on the east side.


a. Synoptic weather pattern

At 0600 MDT 25 July, a short-wave trough was present over the northern Rocky Mountain states. The trough centerline at 700, 500, and 300 mb was above the eastern borders of North and South Dakota, while
the trough itself was moving eastward. At 500 mb (about 5820 m MSL), the winds over southeastern Wyoming were from the northwest at about 10 m s⁻¹. At 700 mb (about 3120 m MSL) the winds over southeastern Wyoming and northern Colorado were generally from the north at less than 10 m s⁻¹.

The synoptic-scale surface weather pattern in Montana, Wyoming, and Colorado at 0000 MDT was dominated by a large area of high pressure, with weak horizontal pressure gradients and light and variable surface winds. At 0000 MDT the center of the surface high was in central Colorado. By 1200 MDT the center of the surface high had migrated northeastward from central Colorado to the Nebraska panhandle.

b. Regional winds

Figure 3 shows the surface winds, as measured at NWS sites, for a four-state region centered on the Laramie Valley. At 0000 MDT (Fig. 3a) the surface winds in this region ranged from 2.5–4.5 m s⁻¹, with no distinct pattern of wind direction. By 0600 MDT (Fig. 3b) the surface winds were still light (2–4.5 m s⁻¹) and variable over most of the region, with hints of anticyclonic circulation centered at the extreme southwest corner of the Nebraska panhandle. By 1200 MDT (Fig. 3c) the wind speeds had generally increased (up to 6 m s⁻¹), with a distinct anticyclonic circulation centered in the southern portions of the panhandle of Nebraska.
and with corresponding southeasterly winds over southeast Wyoming, including the Laramie area. This 1200 MDT wind pattern agrees fully with the NWS surface pressure analysis at 1200 MDT, which showed the center of the surface high located over the Nebraska panhandle.

c. Valley winds

Figure 4 is a plot of surface winds in the Laramie Valley at 0000 MDT, as recorded with the stations described in section 2. Due to equipment failure, data from stations 2 and 3 were not available for this day.

At local midnight (0000 MDT, Fig. 4) distinct cross-valley drainage winds are indicated at stations 1 and 4–8, with westerly winds of about 2 m s\(^{-1}\) in the west half of the valley and easterly winds of 1–2 m s\(^{-1}\) in the east half of the valley. Down-valley, southeasterly drainage winds (1 m s\(^{-1}\)) were recorded at station 9.

Figure 5 shows the pattern of changes in wind speed and direction at three of the stations (5, 7 and 8), from 0000 to 1300 MDT. As mapped in Fig. 1, these three stations roughly form a west–east transect across the valley. The drainage pattern shown in Fig. 4 persisted until about 0700 MDT, with downslope winds at stations 5 and 8, and with light and variable winds on the valley floor (station 7).

Sunrise on 25 July occurred at about 0600 MDT. Between 0700 and 0800 MDT the winds at station 5 changed to upslope, following at least 1 h of surface heating. Station 5 was on an east-facing slope, and the upslope winds are probably similar in origin to those observed by Whiteman (1982), Banta and Cotton (1981), and Toth and Johnson (1985). By 0900 MDT the winds at station 8 had gained a slight upslope component, which became most pronounced at 1000 MDT.

At 1000 MDT, stations 5 and 7 both recorded light southeasterly winds, indicating that winds from above the BL had started to reach the surface by vertical mix-
Figure 7 contains a plot of potential temperature vs height (MSL) for the lower levels of the 0600 MDT Lander radiosonde. The North Platte sounding had fewer data points, but coincided exactly with the Lander sounding at 2000 and 4900 m MSL (no North Platte data at intervening levels). Further justification for using the Lander sounding stems from the fact that the strong inversion layer just above 3500 m MSL (about 1500 m AGL) coincides with the wind shear layer observed at 1500 m AGL in the pilot balloon observations at 0600 MDT (Fig. 8). Also plotted in Fig. 7 are hourly values of potential temperature at each of the three pilot balloon sites, from 0600 to 1100 MDT. The three different wind regimes are deduced from the pilot balloon data, as discussed below.

As shown in Fig. 7, the lowest levels of the atmosphere were stable (potential temperature increasing with height) at sunrise on 25 July (about 0600 MDT). As indicated by the potential temperature values at the three pilot balloon sites, the BL was very stable at sunrise—a condition conducive to maintaining drainage winds.

The time sequence of increasing potential temperatures at the three surface sites, when compared with the potential temperature sounding, gives a good indication of the cross-valley pattern of BL destabilization. The surface temperature measurements at the Sheep Mountain site between 0800 and 0900 MDT suggest that enough warming had occurred to allow BL destabilization and the start of downward mixing of winds from above the BL. As indicated by continued surface warming, the extent of vertical mixing probably continued to increase through the remainder of the observation period (until 1100 MDT). Surface warming at the Overland and Southeast Laramie sites lagged that at Sheep Mountain, suggesting that BL instability and consequent vertical mixing did not occur until between 0900 and 1000 MDT—about 1 h later than at Sheep Mountain.

Based on this interpretation of the potential temperature profile in Fig. 7, we would expect the breakdown of drainage flow patterns to begin along the west side of the valley and progress eastward across the valley, with at least 1 h lag between the west and east sides of the valley. This prediction is in full agreement with the surface wind patterns described above and plotted in Figs. 4–6. The appearance of southeasterly winds at the surface, matching the regional pattern, would be direct evidence of vertical mixing reaching through the entire BL. Such evidence appeared along the west side of the valley as early as 0800–0900 MDT, but did not appear along the east side of the valley until sometime between 1000 and 1100 MDT. Evidence of continued vertical mixing was also visible in the wind speed measurements, where the southeasterly surface winds in the valley increased in speed between 1100 and 1200 MDT.
e. Pilot balloon wind profiles

Pilot balloon releases on 25 July began at 0530 and ended at 1100 MDT, with balloons released every 30 min. Each balloon was tracked to about 1880 m AGL, with data recorded every 30 s (corresponding to 94 m intervals). Horizontal wind data from each release are presented in Fig. 8.

At the Sheep Mountain site, near the west-flank mountains, the downslope winds were about 400 m deep at 0530 and 0600 MDT (Fig. 8a). This downslope regime lasted until after 0700 MDT, in agreement with the surface measurements at station 5, when the wind direction switched to upslope. The winds remained upslope at Sheep Mountain until about 0930 MDT. By 1000 MDT southeasterly winds were present in the lowest levels.

On the opposite side of the valley, southeast of Laramie (Fig. 8c), the downslope winds were 350–400 m deep, and persisted until about 0800 MDT. After a transition period of about 1.5 h, distinct upslope winds were present at 0930 MDT, 1 to 2 h later than at the Sheep Mountain location and in agreement with the surface observations. The upslope winds lasted until after 1030 MDT, and southeasterly winds were present in the lowest levels by 1100 MDT.

In the center of the valley, at the Overland Trail site (Fig. 8b), the winds in the lowest 200 m were light and variable until about 1030 MDT. By 1100 MDT, as at the site southeast of Laramie, the winds at the lowest levels were southeasterly.

The winds in the lowest few 100 m of each set of pilot balloon observations (Fig. 8) were consistent with the corresponding surface wind observations (Figs. 4–6). The transitions from drainage to upslope and from upslope to southeasterly winds occurred first at the west side of the valley, then 1 to 2 h later at the center and east side of the valley. The deepest layer occupied by the drainage and upslope winds was about 400 m, as marked in Fig. 7.

An interesting pattern is visible in the strengths of the lowest-level southeasterly winds at each site at 1100
MDT. Along the west flank of the valley (Sheep Mountain), where vertical mixing had the longest duration, the southeasterly winds at 94 m AGL were about 7 m s\(^{-1}\). Moving eastward across the valley, corresponding to decreasing durations of surface heating and vertical mixing, the southeasterly, 94 m wind speeds decreased, with speeds of 2.5 m s\(^{-1}\) at the Overland Trail site and 1.5 m s\(^{-1}\) southeast of Laramie.

Further consistency in the data is noted in Fig. 7, where three different wind regimes are indicated, as suggested by the pilot balloon data at 0600 MDT. The first layer, from the valley surface up to 2600–2700 m MSL (about 400 m AGL) represents the apparent maximum vertical extent of the local drainage winds above the valley floor. This layer of drainage winds coincides with the local BL. The second layer, from about 2700 m to about 3600 m MSL, is the layer of southeasterly regional winds. During the nighttime hours, with a very stable BL (surface to 2700 m MSL), these winds remained decoupled from the surface. They later reached the surface during the day as solar heating generated instability and vertical mixing in the BL. The third layer (above 3600 m MSL or 1300–1500 m AGL) had westerly to northwesterly winds at 0600 MDT. As shown in Fig. 8, the winds in this upper layer gradually changed to southwesterly by the end of the observation period. Note that the transition between the second and third layers at 0600 MDT is marked by a zone of strong stability, allowing some decoupling of flows between the two layers. The zone of transition between layers 2 and 3 apparently lowered in height with time (Fig. 8). By 1100 MDT southeasterly winds extended from the surface to about 800 m AGL, while southwesterly winds extended from 800 m AGL to the top of the pilot balloon observations.

5. Conclusion

In the two cases presented above, the pattern of transition from drainage to regional winds was apparently "asymmetric," starting on the west side of the valley and progressing to the east. The most likely explanation for this asymmetry is based on the fact that morning surface heating would initially be strongest along the west side of the valley, with the degree and rate of heating enhanced by the east-facing slopes in that area. As surface heating induced vertical mixing and vertical transport of momentum, wind speeds and directions originally present above the stable BL would first be seen at the surface along the west side of the valley.

A second possible reason for the asymmetry would stem from mechanically induced mixing in the shear zone between the BL winds and the overlying regional winds. In this case the east side of the valley could be "shadowed" by the east-flank mountains, so that mechanically induced mixing would first result in surface wind changes away from these mountains. However, since the drainage flow at sunrise were about the same depth on both sides of the valley, i.e., the BL depth was uniform across the valley, one would expect surface heating to be the most important cause of the asymmetry.

A third possible explanation for the asymmetry could result from the differing heights of the west- and east-flank mountains. One might expect that radiational cooling on a higher mountain range could help maintain drainage winds for a longer time than for a lower mountain range. In the present case the highest mountains are on the west side of the valley, but the drainage lasts significantly longer on the east side—further evidence for the importance of surface radiational heating.

The pattern of BL wind transition observed over the Laramie Valley on 4 and 25 July was quite different from that observed and modeled for steep-sided, narrow mountain valleys (Whiteman 1982; Whiteman and McKee 1982; Bader and McKee 1983, 1985). In the steep-sided valleys, the night-to-day transition apparently involves two processes: erosion of the valley-filling inversion by heat-induced mixing near the surface, and subsidence of the inversion layer as heat-driven upslope winds develop on both sides of the valley. These two mechanisms work together, and result in a symmetric
Fig. 8. Profiles of pilot balloon wind measurements for 25 July 1985, at (a) the Sheep Mountain site (see Fig. 1). The data points are at 30 s (94 m) intervals, with the wind speed represented by the length of the barless wind flag (see scale at right). (b) As in (a), except for the Overland Trail pilot balloon site. (c) As in (a), except for the pilot balloon site southeast of Laramie.
removal of the inversion, relatively independent of valley width-to-depth ratio, valley orientation, and overlying wind shear. In the wider Laramie Valley, it appears that mixing induced by surface heating is the dominant transition process across the majority of the valley width, and the resulting inversion removal is asymmetric.

In general form, the pattern of inversion removal over the Laramie Valley is similar to that observed over South Park (Banta and Cotton 1981; Banta 1984). The major difference between the two locations is that the Laramie Valley opens, or drains, to the north, whereas the South Park Basin opens to the east-southeast. Thus, morning surface and BL processes observed along the west flanks of both the South Park Basin and the Laramie Valley are probably similar to each other and to the morning BL transitions observed along the Colorado front range (Toth and Johnson 1985). However, the cases described here, which indicate a delay in inversion removal along the east flank of the Laramie Valley, may have no analog at South Park, since that basin is not completely bounded by an east-flank mountain range. Asymmetric inversion removal at South Park was noted only in cases of westerly winds.

In contrast, the difference between the regional wind directions on 4 and 25 July suggests that the wide-valley, asymmetric inversion removal over the Laramie Valley may be independent of the overlying winds. With surface heating being dominant, and with the contrast between Laramie and South Park topography described above, it also appears that valley orientation should be important in determining the inversion erosion pattern. Modeling experiments will be needed to test that hypothesis.

Acknowledgments. Many members of the Department of Atmospheric Science participated and helped in the data-collection phase of this experiment (including station deployment and balloon launches): T. Parish, T. Northen, R. Clark, B. Martner, M. Politovich, L. Oolman, K. Waight, and S. Smutz. Thanks are also due to S. Allen for drafting all the figures. Many thanks are due to all the private citizens and landowners and to all the public, corporate, and university officials who assisted in the project by helping locate and/or by granting permission for use of the balloon and weather station sites.

This study was supported by a Grant-in-Aid from the Office of the Vice President for Research, the University of Wyoming.

REFERENCES


