Observations of the Evolution of Orographic Blocking

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ABSTRACT

The evolution of low-level flow upstream of the Continental Divide (Rocky Mountains) and the Wasatch Range from being unable to surmount the mountain range, to becoming unblocked and blocked again is studied observationally. During two months in the winter of 1991/92, a transect of three wind profilers measured the wind field every few minutes with unprecedented temporal detail.

The average state of that region during winter is blocked. A total of 47 blocked events were observed. A blocked flow event lasted on the average one and a half days, but the duration varied widely from a few hours to eight days controlled by the synoptic situation. The transition between the two states happened rapidly on the order of 1 h with a minimum of 20 min and a maximum of 4 h. The depth of the blocked layer during one blocking episode fluctuated considerably but reached on the average one-half to two-thirds of the barrier depth (depending on the location).

Previous research of idealized equilibrium situations focused on changes of the cross-barrier wind speed and stability as determining variables to build a mesoscale high over the barrier. Since their values were in the blocked range, other mechanisms had to trigger the transitions to an unblocked state.

A conceptual model proposes synoptic and radiative forcing to drive the blocking evolution. When the mountain-induced mesoscale high blocks the low-level flow, an opposing synoptic cross-barrier pressure gradient can negate the mesoscale high. Therefore unblocking happens most frequently when the trough axis of a short wave is immediately upstream of the barrier, but synoptic pressure gradients caused by contrasts in vorticity and differential temperature advection are sometimes also strong enough. The flow returns to its blocked state when the ridge behind the trough approaches the barrier so that the synoptic cross-barrier pressure gradient reinforces the mesoscale high.

For a lower barrier or stronger solar insolation, a well-mixed boundary layer can grow almost to the height of the barrier by afternoon and reconnect the blocked layer with the higher cross-barrier winds above the mountain. After sunset the thermal forcing changes sign as the radiative cooling stabilizes the lower atmosphere again and the transition back to the blocked state occurs.

1. Introduction

Will air that encounters an obstacle in its path go around, become stagnant, or flow over it? This question has been studied theoretically, numerically, and observationally in many locations of the world for several decades. The greatest wealth of observations exists for the Alps (e.g., Peppler 1928; Binder et al. 1989). But blocking of low-level air has also been reported for, for example, the Antarctic Peninsula (Schwerdtfeger 1975), Alaskan Peninsula (Lackmann and Overland 1989), Olympic Mountains (Mass and Ferber 1990), Sierra Nevada (Parish 1981), and Hawaii (Smolarkiewicz et al. 1988; Rasmussen et al. 1989). We use the term “blocked” to describe a situation where air anywhere along the obstacle below a certain level cannot surmount the obstacle but rather passes around it or becomes drawn into local recirculations. “Unblocked,” on the other hand, refers to a situation when—at least somewhere along the barrier—air can climb the mountain all the way.

Smith (1988) used the Bernoulli equation to show that the flow stagnates because heavier air piles up above the upstream slope. Numerical simulations for inviscid, nonrotating flow (Smolarkiewicz and Rotunno 1990) supported Smith’s result. They also found recirculation (flow reversal zones) on the upwind slope.

Rotation limits the upstream extent of the blocked layer to approximately one Rossby radius of deformation (Pierrehumbert and Wyman 1985). Theoretical and numerical studies of idealized flows (uniform up-
stream buoyancy frequency \( N \) and cross-barrier wind speed \( U \) identified the Froude number \( Fr = U/(Nh)^{-1} \), the Rossby number \( Ro = U/(\Omega L)^{-1} \), the Richardson number \( Ri = N^2(\partial U/\partial z)^{-2} \), and the shape of the obstacle to indicate the behavior of the flow (Smith 1989; Davies and Horn 1988). In the above definitions, \( h \) is the barrier height, \( \Omega \) the rotation rate of the earth, and \( f \) the Coriolis parameter.

Reisner and Smolarkiewicz (1994) included the effects of thermal forcing on uniform, frictionless, and dry flow neglecting earth’s rotation. Both parcel arguments and numerical simulations suggested that the flow is unblocked regardless of the Froude number when the magnitude of the thermal forcing,

\[
\Xi = \frac{L^*Q_0}{Uh(\partial U/\partial z)},
\]

exceeds unity. An average heating rate of \( Q_0 \) is assumed over a characteristic length \( L^* \). They confirmed their findings by comparison of numerical simulations with observations from the Hawaian Rainband Project.

Most observational, theoretical, numerical, and laboratory studies so far have dealt only with the causes for blocking of low-level air by mountains but have not attempted to explore the evolution of blocking, the whole cycle from an unblocked through a blocked state back to an unblocked one. How long does it take for the atmosphere to switch from one state to the other, how long are the blocked periods, how frequent is blocking, and what are the mechanisms for blocking and unblocking in the atmosphere? Do changes in cross-barrier speed and stability cause the atmosphere to switch between the two states or do, for example, synoptic or thermal forcings dominate? To answer these questions we deployed three wind profilers in a transect along the western slope of the Rocky Mountains (Colorado and Utah) during the winter of 1991/92.

The remainder of the paper is organized as follows. The experimental design and quality control of the profiler data are described in the next section. Observational results are presented in section 3, which leads to a conceptual model of the blocking evolution in section 4. Case studies in section 5 illustrate the conceptual model.

2. Design of experiment

a. Sites and instruments

The average height of the Continental Divide in Colorado is approximately 3600 m MSL, but some summits extend above 4000 m. However, farther north, in southern Wyoming, the barrier dips down to approximately 2500 m MSL. Air deflected at the barrier farther south or north can escape through this gap. Large mesas interspersed with valleys stretch westward from the Continental Divide to the next high barrier, the Wasatch Range and the Uinta Mountains (Fig. 1). The valleys are cut into the plateaus rather than walled-in by mountain ranges rising from a plain (e.g., Alps). Not the local valley circulations but the larger-scale flow systems are the focus of this study.

From December 1991 through February 1992, three wind profilers operated in a transect along the western slope of the Continental Divide. Table 1 summarizes their specifics. The height coverage of the profiler in Tabernash, closest to the Divide, varied from 4 to 7 km MSL, depending on turbulence, temperature, and humidity stratification of the atmosphere. Although the profiler in Meeker should theoretically have been able to measure winds up to the lower stratosphere, presumably ground clutter from a nearby hill in combination with the particular signal processing algorithms of the profiler limited the height coverage to below 6 km MSL. Reliable winds up to the tropopause were measured in Dugway.

The profiler in Meeker was at the edge of the theoretically expected upstream influence of the barrier, that is, one Rossby radius of deformation. By comparing data from Meeker with Tabernash, we were able to make some deductions about the horizontal extent of the blocked layer. Besides wind, the site in Meeker also measured virtual temperature with RASS (radio acoustic sounding system) during two short periods.

Although the profiler in Dugway was far enough removed from the Continental Divide to not feel its blocking influence, the flow there was subject to blocking effects from the Wasatch Range.

During three special observation periods (SOP), rawinsondes were launched frequently (two- to three-hourly) in Meeker and Tabernash to supplement wind with temperature and humidity measurements and allow a verification of the profiler winds. Microbarographs were unfortunately not available.

b. Local determination of blocking

Knowing only the local but not the total flow field makes it difficult to detect when and how deeply the low-level flow is blocked. Since blocking separates the flow into a layer that surmounts the mountain and another one that does not, quantities that differ as a consequence of that separation can be used to classify a situation as blocked. The SOPs provided data of the mass, wind, and humidity fields so that various methods could be compared. Five different methods that used all or just part of the available information were tested. All agreed when the flow was blocked, where they differed was the depth of the blocked layer. This was fortunate since only wind but neither temperature nor humidity were measured continuously. Careful subjective inspection of time–height series of cross-barrier and along-barrier components of the wind was used to determine the duration and depth of a blocked flow event. Though this classification is straightforward for the human brain, it had proved to be very difficult.
Fig. 1. Location of the three wind profiler sites in Tabernash (T), Meeker (M), and Dugway (D) and topography of western Colorado, Utah, and Wyoming. Being better known, Boulder (B) is also shown for orientation purposes. The lettering below the map indicates the location of the Wasatch Range (WR) and the Continental Divide (CD). Elevation contour interval is 500 m. The 2000-m MSL line is dashed, the 3000-m contour is bold, and terrain above 2500 m MSL is hatched.

to objectify and automate as is often the case in the field of pattern recognition. A situation with an extended transition zone between the blocked layer below and the unblocked flow above causes problems of exactly where to place the interface. The uncertainty, however, was usually not more than one gate length (250 m) in Dugway and Meeker and two gate lengths (202 m) in Tabernash.

Periods when the profilers were not on the upstream side of the barrier or when there was only a weak westerly cross-barrier component above mountaintop were counted among a separate, nonupwind class. Several blocked situations actually began or ended with a non-westerly flow aloft.

The transition time from unblocked to blocked was determined as the time from the onset of blocking in the lowest gate until the time the depth of the blocked layer had become quasi-stationary.

c. Quality control

Wind profilers inherently yield extremely weak return signals. Despite relatively long dwell times of ap-

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approximately 1 min, signal-processing techniques have to be pushed to the limit in order to maximize the data yield. May and Sträuch (1989), for example, report a signal-to-noise ratio as low as -35 dB, for which they could get reliable radial velocity estimates. Consequently, profiler wind observations may contain a high proportion of gross errors. Mountainous terrain causes additional problems with ground clutter. Special quality control procedures have to be used to recover a maximum of useful information from these data. Most currently implemented quality control schemes use only one part of the information provided by the signal-processing routine, namely the radial velocity. For this dataset, however, a threshold check was performed first using additional information from signal-to-noise ratio, absolute minimum value of signal strength, and relative minimum spectral width of the signal. The latter is the only objective threshold, the other limits had to be chosen somewhat ad hoc. The spectral width of a back-scattered signal is always finite due to turbulence and shear of the mean wind within the sampling volume and the finite width of the profiler beam (Nathanson 1991). Data with a spectral width smaller than the amount caused by the finite beam width are therefore bogus and have to be discarded.

Radial velocities of data that had passed were examined both temporally and vertically with a least median of squares (LMS) regression (Rousseeuw and Leroy 1987). LMS regression proved to be better at detecting errors (while still keeping good data) than the widely used random consensus averaging (Fischler and Bolles 1981).

3. Observational results

a. Data quality

For the SOPs, profiler winds could be compared with winds measured with rawinsondes to check the efficiency of the quality control. On average, the difference of the $u$ components was 0.8 m s$^{-1}$ with a standard deviation of 1.6 m s$^{-1}$; for the $v$ component these values were 0.4 m s$^{-1}$ and 1.7 m s$^{-1}$, respectively. Despite the complex terrain and ensuing problems with ground clutter, these values even surpass the results of previous, more extended comparison studies, which had been mostly for profiler locations on comparably level ground (e.g., Weber and Wuertz 1990). The standard deviations were also on the same order as the 2–3 m s$^{-1}$ found in the rawinsonde network (Daley 1991). The quality control algorithm succeeded not only in discarding most erroneous data but also in keeping good data, which had been a problem with the random consensus average algorithm (appendix of Dharssi et al. 1992; Brewster and Schlatter 1986, 1988).

b. Statistics

From the profiler measurements, 23 blocking periods were identified in Tabernash, 14 in Meeker, and 10 in Dugway (Table 2). The average blocking period lasted 1.5 days but varied from 3 to 187 h (nearly 8 days) so that the standard deviation is large.

The depth of the blocked layer varied greatly during the observational period (Fig. 2). A steady state was never achieved; even during one blocking event the depth of the blocked layer did not remain constant. Most frequently, however, the blocked layer reached at all three sites at least half the barrier height but rarely mountaintop. As expected, the blocked layer never extended above the height of the crest.

During the winter of 1991/92, a large number of cutoff lows were located upstream of the Continental Divide. Eight periods were observed in Tabernash and Dugway and seven in Meeker when the profilers were not on the upwind side of the barrier. Despite the similar number of occurrences, the duration of these periods as a fraction of total observation time in Dugway doubled those in Tabernash and Meeker (Table 2). When the profilers were on the upwind side of the obstacle, the atmosphere was normally blocked: barely more than half the time in Meeker but almost always (85%) in Dugway.

Overall, low-level air could not flow eastward out of the Great Basin over the mountains between 65% and 92% of the time (depending on the location), which means that although the air might exchange on a local level among valleys, the regional replenishing of low-level air is infrequent. Therefore, the implementation of large pollution sources in that region could result in the accumulation of a high concentration of pollutants.

c. Comparison of unblocked and blocked flows

Wind matrices (Cehak and Pichler 1968) combine the large quantity of data measured by the profilers into a compact picture and bring out the differences between the blocked and unblocked states.

Wind directions and cross-barrier speeds were separated into 20° and 2 m s$^{-1}$ bins, respectively. Then the joint probability mass function ("wind matrix") for wind direction and cross-barrier speed, respectively, between an undisturbed level above mountaintop and

| Table 2. Number of blocking events, their minimum, average, and maximum duration for the three profiler sites. |
|-------------------------------------------------|---------|---------|---------|
| Blocking events                               | Tabernash | Meeker | Dugway |
| Minimum                                       | 8       | 3       | 10      |
| Median                                        | 20      | 14      | 40      |
| Average duration (h)                          | 32      | 22      | 56      |
| Maximum                                       | 84      | 67      | 187     |
| Profiler not upwind (%)                       | 23.4    | 26.1    | 44.4    |
| Blocked when westerly (%)                     | 72.2    | 52.9    | 85.4    |
| No low-level W → E flow (%)                   | 78.7    | 65.2    | 91.9    |

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the gates below were computed. For cross-barrier speeds, summing
\[ \sum_{i=i+k}^{n-k} A_{i,j-k}, \quad -n + 1 \leq k \leq n - 1, \quad (2) \]
where \( n \) is the number of bins and \( A_{ij} \) the frequency of a certain speed occurring at the two gates \( i \) and \( j \), tells how likely a speed change of \( k \) times the bin width is between these two gates. Since wind direction is cyclic one needs to perform
\[ \sum_{i=1+k}^{n+k} A_{i,j-k}, \quad k = 1, \ldots, n - 1, \quad (3) \]
to obtain the frequency of a change in wind direction by \( k \) times the bin width between the gates \( i \) and \( j \).

Wind matrices at all three profiler sites are qualitatively similar and the one from Meeker may serve as an example: The reference gate was approximately at \( 1.7h_0 \), where \( h_0 \) is the height of the barrier.

1) Wind Direction

The wind directions at the reference level \( (1.7h_0) \) and above the crest were quite similar for both blocked and unblocked cases as the alignment of the peaks along the main diagonal in Fig. 3 shows. As one descends to the surface, the pattern gets more complicated and the two classes differ.

The joint probability mass function maximum for the unblocked cases (Fig. 3a) remains aligned along the main diagonal down to the lowest gate although it becomes wider. The success of a graph like Fig. 3a at
depicting a huge amount of information qualitatively comes at the expense of its quantitative usability. Table 3a serves to alleviate that shortcoming at least for a comparison of wind directions at 1.7$h_b$ and 0.3$h_b$ (reference and lowest gate, respectively). The marginal distributions indicate west as the most common wind direction afoil at 1.7$h_b$ and southwest at the lowest gate. The combination of a wind afoil from 270° with winds below from 210° to 270° had the highest frequency of any combination of wind directions.

A closer look at the turning of the wind with height (Fig. 4a) exemplifies that only slight turning of the horizontal wind with height characterized unblocked flow. More than half of the time the wind veered less than 60° from 0.3$h_b$ to 1.7$h_b$; most often by just 20°. This veering can be attributed to the influence of surface friction.

For the blocked cases, winds within the blocked layer came from all directions despite westerly flow afoil, visually signified by the change of orientation of the line of maximum joint probability from diagonal afoil to parallel near the surface in Fig. 3b. A minimum of northerly winds separated two types of blocked flow: one of flow deflection to the north (with a southerly component in the blocked layer) and one of flow reversal with an easterly wind component in the blocked layer. When an air parcel approaches the barrier, it is slowed down to subgeostrophic speeds and consequently deflected in the direction of the pressure-gradient force, which is to the north in our case. This explains the minimum of northerly low-level flow. A strong mountain-induced mesoscale pressure perturbation on the upwind side can result in reversed flow.

Blocked flow events had two preferred directions afoil, 290° and 330° (Table 3b), which is more northerly than for the unblocked cases. One is tempted to equate more northerly with a reduced cross-barrier component, which is not the case as will be shown in the next section. It rather corresponds to being upstream of a synoptic trough, whereas the low-level flow remained unblocked ahead of or under the trough.

Flow deflection (maximum of 17.5% from 210°) was preferred over flow reversal (maximum of 7.8%
Table 3. Joint probability mass function of wind direction (°) at 1.7$h_b$ and 0.3$h_b$ in units of 0.1% for (a) unblocked and (b) blocked flow. The marginal distributions are shown in the rightmost column and the last line, respectively. They do not add up to 100% since only part of the whole table is shown.

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From 130°, a more northerly wind aloft increased the likelihood of a flow reversal near the surface.

The orientation of the line of the joint probability maximum in Fig. 3b is parallel below two-thirds of the barrier height, but traces of that orientation can be seen up to the crest. One can conclude that the depth of the blocked layer generally did not extend above two-thirds of the barrier depth.

Like the unblocked flows the wind veered more often with height than it backed (Fig. 4b), but the veering was more pronounced than for unblocked cases as a consequence of the flow deflection: most frequently by 70°–110° (in 19.3% of all blocked cases) between the first and the reference gate, compared with only 10°–50° in the unblocked situations. Flow reversals contributed to the secondary maximum for a backing of approximately 140°.

2) Cross-barrier wind speeds

Blocking manifests itself in a large vertical gradient of horizontal cross-barrier wind. The most common cross-barrier speed at the reference gate (4739 m MSL) was 14 m s⁻¹, whereas at 0.3$h_b$ this component vanished or even changed sign (Table 4b). The low-level cross-barrier component was more likely to be directed away from the barrier when the upper-level component was weaker (6–8 m s⁻¹). For stronger flow aloft (12–14 m s⁻¹), mere flow deceleration outweighed flow reversals in accordance with Froude number considerations.
How big was the difference between cross-barrier flow aloft and below crest? Most frequently, 10 m s$^{-1}$ (Fig. 5b). A discontinuity in the maximum of the joint probability at two-thirds of barrier height marks the average depth of the blocked layer. A prevailing deceleration of 4 m s$^{-1}$ even slightly above the crest at 1.2$h_b$ compared with no deceleration for unblocked events shows that the effects of blocking were not just confined to below the crest.

Surprisingly, winds aloft were weaker for unblocked (Table 4a) than for blocked cases. Cross-barrier components of 8 m s$^{-1}$ (compared with 14 m s$^{-1}$ for unblocked events) prevailed. For uniform flow over a given barrier, cross-barrier component and stability control whether the flow is blocked or not. This would require a more than twofold decrease of static stability for a transition from a blocked to an unblocked state. Since the synoptic height and pressure fields of the observed events were not uniform, other mechanisms become possible. The fact that unblocked flow was less northerly than a blocked one makes a change of the synoptic pressure gradient accompanying the movement of a synoptic trough a more plausible explanation why unblocking occurred despite weaker cross-barrier winds aloft.

Most frequently, the difference between the cross-barrier components at 1.7$h_b$ and 0.3$h_b$ was 6 m s$^{-1}$; it decreased continuously to 0 m s$^{-1}$ at barrier height (Fig. 5a).

d. Transitions

It was not known a priori how rapidly the transition from blocked to unblocked flow and vice versa would occur. To capture the details of these transitional periods, the individual profiler soundings with one profile every 2–11 min (depending on the profiler) had to be used instead of the commonly used hourly averaged data. The 12-h interval between soundings of the regular rawinsonde network was too long to even capture all the blocked periods.

Figure 2 gives a visual impression of the swiftness of the transition. Blocking formed within 15 min to 2 h (an average of 40 min for all sites) and became destroyed almost as rapidly—within 20 min to 4 h (average of 1 h for all sites). To our knowledge no observations with such a high temporal resolution have been previously available.

Blocking did not always first appear close to the barrier (Tabernash) before it spread farther away (Meeker). Due to its proximity to the Continental Divide—not only horizontally but also vertically—a blocked layer might extend up to Meeker but be too shallow to reach the elevation of Tabernash. On the other hand, there were transitions, for example, on 23 January and 10 February (relative to UTC, which is 7 h ahead of local time), when Tabernash became blocked before Meeker did. In all these cases, blocking in Tabernash happened in the evening or early night.
TABLE 4. Joint probability mass function of cross-barrier wind speed (m s⁻¹) at 1.7h₀ and 0.3h₀ in units of 0.1% for (a) unblocked and (b) blocked flow. The marginal distributions are shown in the rightmost column and the last line, respectively. They do not add up to 100% since only part of the whole table is shown

(a) comp | -4 | -2 | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | ref
--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
10 | 0 | 0 | 0 | 1 | 2 | 3 | 3 | 0 | 1 | 1 | 2 | 1 | 0 | 0 | 14
8 | 0 | 0 | 0 | 1 | 2 | 1 | 5 | 3 | 1 | 2 | 1 | 0 | 0 | 32
6 | 0 | 0 | 0 | 2 | 8 | 13 | 3 | 3 | 1 | 2 | 1 | 4 | 2 | 0 | 98
4 | 1 | 5 | 5 | 9 | 23 | 29 | 43 | 50 | 26 | 7 | 1 | 0 | 0 | 1 | 225
2 | 3 | 19 | 22 | 19 | 23 | 30 | 27 | 24 | 10 | 13 | 3 | 4 | 1 | 0 | 187
0 | 5 | 13 | 15 | 19 | 23 | 30 | 27 | 24 | 10 | 13 | 3 | 4 | 1 | 0 | 230
-2 | 9 | 13 | 15 | 8 | 10 | 11 | 5 | 9 | 1 | 0 | 0 | 0 | 0 | 82
-4 | 1 | 0 | 0 | 2 | 3 | 2 | 5 | 3 | 1 | 0 | 0 | 0 | 0 | 24
-6 | 0 | 0 | 1 | 2 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9
15 | 51 | 62 | 69 | 105 | 138 | 154 | 149 | 101 | 73 | 23 | 18 | 10 | 3 | 971
(b) comp | -4 | -2 | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | ref
--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2
8 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 6
6 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 1 | 1 | 0 | 0 | 6
4 | 1 | 1 | 3 | 6 | 5 | 9 | 10 | 16 | 10 | 3 | 4 | 3 | 3 | 74
2 | 2 | 2 | 14 | 11 | 18 | 30 | 36 | 62 | 43 | 21 | 8 | 7 | 4 | 262
0 | 0 | 2 | 8 | 19 | 18 | 25 | 40 | 33 | 30 | 51 | 39 | 18 | 5 | 291
-2 | 3 | 3 | 19 | 23 | 40 | 47 | 26 | 23 | 40 | 27 | 7 | 3 | 1 | 262
-4 | 1 | 3 | 3 | 14 | 14 | 5 | 5 | 12 | 6 | 5 | 3 | 2 | 1 | 79
-6 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 3 | 1 | 0 | 2 | 1 | 0 | 13
3 | 10 | 21 | 61 | 76 | 103 | 134 | 112 | 149 | 152 | 98 | 42 | 22 | 12 | 995

which points to a possible radiative influence. Similarly, there were several unblocking events in the afternoons that could be observed only in Tabernash but not in Meeker. A good example is the period 27–29 January 1992, when the flow became unblocked shortly after noon and blocked again a few hours after sunset on all three days. This diurnal influence will be discussed in more detail in the next section.

A summary for the observational period of cross-barrier component at crest heights and buoyancy frequency N below from bidual rawinsondings in Grand Junction and Salt Lake City (the rawinsonde stations closest to Meeker and Dugway) for the times when they were on the upwind side yielded average values of approximately 6.5 and 0.015 s⁻¹, respectively, at both sites. The Froude number was, therefore, 0.2, so that the normal state of the low-level atmosphere from December 1991 through February 1992 was blocked.

To decide whether the transitions occurred because of a change of far-upstream cross-barrier speed and stability seems impossible since in our case there are no undisturbed far-upstream values and the profiles are far from uniform, so that it is not immediately clear which values to select. An example from the second SOP in Meeker shows that in the region affected by blocking the ratio of U( Nh)⁻¹ with values from above the crest (solid line in Fig. 6) changed only slightly during the transition from blocked to unblocked, whereas the increase of that ratio with values from the lowest six-tenths of the barrier height occurred mostly after the flow had become unblocked. A similar behavior was found for other unblocking events where stability data were available.

4. Toward a conceptual model of blocking

Since the observed flows did not abide by the restrictions of uniformity and stationarity imposed by most theoretical studies, more mechanisms than just changes of cross-barrier wind speed and stability can reinforce or negate the mountain-induced high-pressure and anticyclonic vorticity anomaly above the upwind slopes. Both three-dimensional numerical simulations (Mayr 1993) and microbarograph measurements (Mass and Ferber 1990) show that this excess pressure is only on the order of one hPa. Modulations of the pressure field by synoptic disturbances surpass that value and are, therefore, likely to interfere with the mountain-induced mesoscale high. Since the pressure and vorticity anomalies are confined to approximately one radius of deformation from the barrier, solely disturbances producing a strong enough gradient over that distance can push the low-level flow from being blocked to unblocked and vice versa; that is, short waves are preferred. When the trough axis itself approaches the barrier, its minimum in the pressure field can override the mountain-induced mesoscale high.

Cyclonic vorticity advection downstream of the trough axis opposes the high values of anticyclonic vorticity induced by the mountain. It generally also causes
the pressure to fall. Cold-air advection that decreases with height or warm advection that increases with height above the upwind slope have the same effect.

Besides synoptic disturbances, thermal forcing resulting in the growth and decay of a mixed boundary layer can trigger transitions between the blocked and unblocked states (Reisner and Smolarkiewicz 1994). If a mixed boundary layer grows to a height comparable with the obstacle height, the low-level flow can reconnect with the flow above.

**a. Classification of blocking events during the observational period**

Biday data from the regular rawinsonde network were analyzed and the initialized analyses of the National Weather Service Nested Grid Model consulted to evaluate the importance of the synoptic forcing. Wind and height data at 600 and 700 hPa were gridded by applying two passes of a Barnes objective analysis scheme (Achtert 1987), and advection of absolute vorticity and temperature were calculated. The 600-hPa level was chosen since it was approximately at the top of the highest peaks in the Rocky Mountains. Since the average horizontal distance between rawinsonde stations is more than 200 km, only disturbances at least 400 km wide can be reliably resolved. Vorticity and temperature advections pose even bigger problems since they involve the computation of derivatives. The 12-h interval from one sounding to the next adds to the difficulty in finding their exact location at the transition from blocked to unblocked. Except for the vorticity advection, all these difficulties were alleviated by the use of wind profiler data. The passage of the trough was deducted from time—height series of wind, and temperature advection was inferred from the vertical profile of the horizontal wind with the assumption that the turning of the actual and geostrophic wind was qualitatively similar.
1) UNBLOCKING

Synoptic forcing played a dominant role in unblocking. The most frequent favorable condition was the presence of a trough axis just upstream of the Continental Divide. In these situations the synoptic cross-barrier pressure gradient just upstream of the barrier opposed and overpowered the mesoscale, mountain-induced pressure gradient in the blocked layer above the upwind slope.

Half of the unblocking events had the favorable pattern of anticyclonic vorticity advection farther upstream (pressure rise, sinking motion aloft) and cyclonic vorticity advection just upstream of the divide (pressure fall, rising motion aloft), whereas the other half had no significant vorticity advection at all. Temperature advection did not significantly contribute to a change in pressure upstream of the barrier.

Six unblocking events occurred despite an unfavorable position of the trough axis downstream of the barrier. They all happened in the afternoon when the positive net radiation balance had been feeding energy into a sensible heat flux long enough to form a deep boundary layer. In January, however, only Tabernash became unblocked since the barrier there is 600 m shallower than in Meeker and additionally the tree coverage is higher, which—with snow cover on the ground—increases the sensible heat flux into the atmosphere during daytime.

The last unblocking event in February without a low at 600 hPa just upstream of the divide occurred in Meeker in the afternoon. By that time, the solar insolation was already greater and only patches of snow remained so that the sensible heat flux was obviously strong enough to grow the boundary layer deep enough to reconnect the blocked layer with the flow above.

Surface radiation, temperature, humidity, and wind measurements were used to calculate the sensible and latent heat fluxes applying the Penman-Monteith method (Stull 1988) assuming wet ground. The sensible heat flux between 0900 and 1500 LST provided enough energy to form an 1100-m-deep (i.e., three-fourths of the barrier depth) neutral layer. How does this compare with parcel considerations and numerical results by Reisner and Smolarkiewicz (1994)? Inserting the average heating rate of $Q_0 = 1.7 \text{ K h}^{-1}$ into (1) yields a magnitude of the thermal forcing $\Xi$ greater than 1, and the flow should—as it did—go over the barrier regardless of the Froude number.

Of the three profiler sites, Dugway faces the highest barrier: 2.2 km. During none of the unblocking events could a boundary layer grow deep enough to cause or assist the unblocking by reconnecting the blocked layer with the flow above mountain top.

Of course synoptic and radiative forcings did not only work separately but in some cases hand in hand.

2) BLOCKING

Synoptic forcing was even more dominant than for unblocking: it played a role in all observed events. The position of the 600-hPa low (trough) was downwind of the barrier so that the profilers lay downstream of a ridge, which supported the formation of a mesohigh. As in unblocking, vorticity advection was second to the presence of a 600-hPa height extremum just upstream of the barrier as a synoptic forcing mechanism leading to blocking and played a role in half of the events. Differential temperature advection, on the other hand, significantly contributed to pressure rise upstream of the barrier in one-third of the events.
Fig. 8. The 600-hPa height (m, dotted), advection of absolute vorticity (10^{-9} s^{-2}, solid), and temperature (10^{-3} K s^{-1}, dashed) on (a) 0500 LST 24 January 1992, (b) 1700 LST 24 January 1992, and (c) 0500 LST 25 January 1992.
Radiative forcing was never the sole but only an assisting factor favorable for blocking. As with unblocking, the radiative forcing was most effective in Tabernash where the barrier is relatively shallow.

A unique situation happened on 23 February 1992 in Meeker. The trough axis of a short wave approached the profiler site from the west instead of—as usual—from the northwest, thus causing a fall in the height of the 600-hPa pressure surface farther upstream, which made the height just upstream of the barrier relatively high enough to bring about a blocking. Since the short wave swept swiftly across western Colorado, that particular blocked situation lasted only the few hours it took the trough to reach the vicinity of the Continental Divide and thus reverse the pressure gradient.

(i) Unblocking

During winter the cross-barrier component of the wind above the Rocky Mountains in Colorado is usually small enough and the stability strong enough to put the atmosphere into the blocked part of the parameter space (Froude number less than approximately $2/3$). Denser air that piles up just upstream of the crest causes a mesoscale high above the upwind slope of the barrier. That mesohigh extends approximately one radius of deformation upstream. It is able to deflect the impinging low-level air to flow northward along and around the mountain so that the cross-barrier wind component is very small. The low-level flow separates from the air that can pass over the mountain. The way the atmosphere normally gets out of the blocked state is as follows.

A short wave approaches the Continental Divide from the northwest or west. Cyclonic vorticity advection precedes the trough axis leading to height falls and rising motion above the mountains. Cold-air advection also ahead of the trough axis decreases the overall stability of the lower troposphere, thus making a vertical displacement of the previously blocked air easier. The cold air advection is confined mostly to a layer at and immediately above the mountaintop and hence decreases with height causing the geopotential heights to fall. Temperature and vorticity advection therefore di-

b. Conceptual model of blocking evolution

The results of the previous section can be condensed into two prototypes of blocking evolution.

1) Synoptically driven blocking evolution

The preferred way of the atmosphere to become blocked and unblocked during low-sun season and for high barriers is through synoptic systems.
minish the positive pressure anomaly above the upwind slope and at the same time destabilize the lower troposphere.

When the trough axis is immediately upstream of the Continental Divide, the synoptic pressure minimum overwhelms the orographically caused pressure maximum, and with higher pressure farther upstream in the following ridge, the blocked air flushes out over the mountains. Winds pick up in the lower levels to a cross-barrier speed comparable to the one above the mountains. Vertical mixing decreases the stability of the previously blocked air. A short wave unblocks more likely than a wide trough because vorticity advection increases as the wavelength of a disturbance decreases and the pressure minimum at the trough axis extends over a horizontal distance comparable to the one of the mountain-induced mesoscale high.

(ii) Blocking

As the trough moves farther east out toward the Great Plains, anticyclonic vorticity advection and warm-air advection appear upstream of the Continental Divide. Anticyclonic vorticity advection causes the geopotential height to rise and also brings potentially warmer air down from the mid- and upper troposphere, thus increasing the overall stability of the lower atmosphere, which makes a vertical displacement of an air parcel more difficult. Warm air advection does the same, and since it usually decreases with height it also contributes to the geopotential height rise. This time the synoptic forcings work together with the orographic forcing in building the positive pressure anomaly above the upwind slope of the Continental Divide. As the height maximum of the flow aloft approaches the barrier, the air below the mountaintop becomes blocked again.

2) Radiatively Driven Blocking Evolution

(i) Unblocking

Even if a synoptic high pressure system (ridge) reinforces the mountain-induced positive pressure anomaly, the air near the ground can become coupled to the flow above mountaintop and thus unblock when at least one of the following conditions is fulfilled: the sensible heat flux is strong and directed from the ground to the
air above, or the barrier is shallow. Unblocking occurs in the following manner.

After sunrise the net radiation balance turns positive so that the sensible heat flux will be away from the ground (Fig. 7b). With snow on the ground the surface albedo is high and the radiation surplus small. Therefore, little energy is available for the sensible heat flux and only a very shallow boundary layer forms. Unless the barrier itself is also very shallow, the boundary layer will not reach high enough to reconnect to the flow above. Forested areas, however, have a lower albedo even with snow on the ground, and more energy will be available for the growth of the boundary layer. With continuing solar insolation, the nocturnal surface inversion weakens and finally—with sufficiently large sensible heat flux—gets destroyed. Now the boundary layer grows much faster and might come close to barrier top. Turbulent mixing brings the winds from higher up down close to the ground—unblocking (Fig. 7c)!

The barrier in Tabernash was low enough to make that unblocking mechanism work even during the time of minimum solar insolation. Toward the end of the observations, in February, an increase in solar insolation and the fact that not the whole surface was snow covered provided a strong enough sensible heat flux to grow a boundary layer deep enough to unblock even at Meeker where the barrier is 600 m higher than in Tabernash.

(ii) Blocking

Around sunset without solar insolation, the net radiation balance is negative, the surface cools radiatively, the sensible heat flux will reverse direction, and the air above the surface will cool and stabilize (Fig. 7d). Without synoptic conditions favorable to unblock-

5. Case studies

a. Synoptically driven evolution

At 0500 LST January 24 1992, Meeker and Tabernash were under strong northwesterly flow. A short wave lay with its axis over Montana at the edge of the map in Fig. 8a. Cyclonic vorticity advection was confined to the immediate vicinity of the trough. Cold air was advected in 600 hPa toward the Continental Divide. The short wave (vorticity maximum) moved rapidly to the southwest and had already reached the divide 12 h later (Fig. 8b). Vorticity and temperature advection over the location of the profilers was negligible. Another 12 h later, at 0500 LST January 25 1992, (Fig. 8c) the trough axis was over eastern Kansas, far downstream from the divide. Vorticity advection was insignificant and a diffuse zone of cold air advection lay over western Colorado.

How do the profilers in Meeker and Tabernash show these synoptic events? With the trough far to the northwest, both locations were blocked (Figs. 9a and 10). Meeker had along-barrier winds at the lowest two gates (Fig. 10), presenting a nice example of flow deflection, whereas the blocked layer in Tabernash was almost calm—only weak winds from varying directions. The trough started to pass Meeker about 2 h before noon (the wind turned more westerly) and Tabernash shortly afterward. The flow became unblocked in Tabernash (Figs. 9a, b) at 1227 LST and half an hour later in Meeker (Fig. 10) where low-level winds became more westerly and stronger at unblocking. Figure 9b captures the transition from a blocked to an unblocked state in Tabernash in minute detail: initially the blocked layer extended to 3200 m MSL. At 1154 LST, blocked air in Tabernash reached up to 3400 m MSL. Eleven minutes later, that depth had decreased to 3100 m MSL and another 22 min later, at 1227 LST, the strong winds reached down to the first gate of the profiler (152 m AGL), which means that the transition from blocked to unblocked state took only half an hour!

During the unblocked period, wind speeds at all levels differed little. Midtropospheric winds at Meeker started to turn more northerly again at around 1700 LST indicating that the upstream side of the trough was moving over the location. At 2030 LST, the low-level air in Meeker had again become blocked. Winds at Tabernash briefly followed that pattern before turning more westerly shortly before Meeker became blocked. This would indicate a second vorticity maximum that passed only over Tabernash but not Meeker. The transition back to the blocked state in Tabernash occurred
at 0200 LST January 25 1992, after that second vorticity maximum had passed. A close-up (Fig. 9c) reveals that within 20 min wind speeds in the lowest 500 m AGL changed from approximately 10 m s\(^{-1}\) to almost 0! The blocked layer in Meeker was initially almost calm but later had also flow approximately opposite to the higher level winds with speeds of up to 4 m s\(^{-1}\).

**b. Radiatively driven evolution**

On 28 January 1992, synoptic conditions favored a blocking of the low-level air: the region upstream of the Continental Divide was under a ridge for the whole day (Fig. 11). The trough axis lay over Kansas. At 0500 LST both vorticity and (differential) temperature advection over Meeker and Tabernash were small. During the day (not shown) the ridge moved slowly toward the Continental Divide and weakened, but the overall synoptic conditions did not change.

The favorable synoptic setting translated indeed into blocking in Meeker and Tabernash. Tabernash, however, did not remain blocked much longer. Figure 12 shows that the layer up to 3400 m MSL was blocked until the early afternoon at 1300 LST. Less than an hour later, at 1357 LST, it was unblocked. We hypothesize that the boundary layer had grown deep enough to mix the higher cross-barrier winds from above mountaintop down to the ground. Even though snow covered the ground on this day, the many conifer trees in the area created a strong enough sensible heat flux to form a several-hundred-meter-deep boundary layer, thus connecting it to the air flowing over the Continental Divide. Although we do not have temperature soundings for that particular day to give an exact depth of the boundary layer, the observation of a boundary layer that grew under clear conditions to approximately barrier height during a special observation period two weeks later supports this explanation.

At sunset around 1700 LST, the flow was still unblocked. Then the thermal forcing reversed its sign and an hour later, after the deep, well-mixed boundary layer had collapsed, the lowest layer up to 3000 m MSL became blocked again. The winds remained very weak, and the last sounding in Fig. 12 at 2100 LST even shows weak flow reversal: southeasterly flow in the blocked layer with northwesterly winds above.

**6. Conclusions**

The evolution of low-level flow upstream of the Continental Divide and the Wasatch Range in the Rocky Mountains from being blocked—that is, unable to surmount the barrier—to becoming unblocked and blocked again was studied observationally with previ-
Tabernash January 28, 1992 [LST]

Fig. 12. Horizontal wind vectors from profiler in Tabernash, 1211–2103 LST 28 January 1992. The bold line marks the top of the blocked layer. Some winds were discarded by the quality control and are therefore missing.

ously unavailable temporal resolution. During two months in the winter of 1991/92, a transect of three wind profilers measured the wind field every few minutes. Frequent radiosonde launches during three special observation periods supplemented these measurements.

The three wind profilers together observed a total of 47 blocking events. A blocked flow event lasted on the average 1.5 days, but the duration varied widely from a few hours to 8 days controlled mostly by the synoptic conditions. The depth of the blocked layer even during one blocking episode fluctuated considerably.

Surprisingly, the transition between the blocked and unblocked state did not happen gradually but rather rapidly on the order of 1 h with a minimum of 20 min and a maximum of 4 h.

Previous research of idealized situations had focused on the Froude number as determining variable to build the mesoscale high above the upwind slopes, which blocks the flow. According to the Froude number the normal state of the lower atmosphere in this region during winter was blocked. Synoptic and radiative forcings rather than changes in cross-barrier component and stability controlled the transitions between blocked and unblocked flow states. The prototypical synoptic forcing is as follows:

When the low-level flow is blocked by the mountain-induced mesoscale high, an opposing synoptic cross-barrier pressure gradient can negate the mesoscale gradient. Unblocking happens most frequently when the trough axis of a short wave is immediately upstream of the barrier, but synoptic cross-barrier pressure gradients caused by contrasts in vorticity and temperature advection on occasions are also strong enough to overpower the mesoscale pressure gradient. The flow returns to its blocked state when the trough has passed the barrier so that the synoptic cross-barrier pressure gradient reinforces the mesoscale one.

The radiative forcing is more important for low barriers or with strong solar insolation:

Under these conditions a well-mixed boundary layer can grow almost to the height of the barrier by afternoon and reconnect the blocked layer with the higher winds above the barrier and thus unblock it. Around sunset the net radiation balance turns negative, the sensible heat flux reverses, and the radiatively forced cooling stabilizes the lower atmosphere again, the transition back to blocked occurs, and completes the diurnal blocking cycle.

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