An Analysis of the Structure of Local Wind Systems in a Broad Mountain Basin

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ABSTRACT

In the traditional model of ridge-valley winds, there are typically two wind regimes on a dry day: a downslope, drainage wind at night due to cooling at the surface along the slopes, and an upslope wind during the day due to solar heating of the slopes. This study presents observations from South Park, a broad, flat basin in the Colorado Rockies. The observations consist of time sequences of surface observations, surface mesonet analyses, and vertical atmospheric soundings using a tethered balloon system. On a typical dry day in South Park, three wind regimes were observed: the downslope regime, the upslope regime, and a late morning or afternoon wind which corresponded in direction to the winds above the ridgetops. Because the gradient and ridgetop winds were most frequently from the west, we have called these winds the "afternoon westerlies."

The afternoon westerlies occur in conjunction with a deep (2–3 km or more) afternoon convective boundary layer in which momentum (and other properties) are well mixed all the way down to the surface. The appearance of the westerlies at the surface is thus a consequence of the strong turbulent mixing within the convective boundary layer.

Vertical tethered balloon soundings taken in mid-morning show that the upslope winds form within a shallow convective boundary layer, which develops beneath the nocturnal inversion in response to surface heating. This stable inversion layer inhibits downward mixing of the upper-level westerlies and allows easterly, upslope flow to establish itself near the surface. When the last remnant of the nocturnal inversion is erased by surface heating and other processes, the westerlies are free to mix downward, and afternoon westerlies are observed at the surface.

1. Introduction

The behavior of turbulence and the effects of local wind systems over mountainous terrain are of interest in a variety of applications. Diffusion and air quality studies focus on the movement and diffusion of tracer substances or pollutants. Forecasting cumulus and cumulonimbus formation in the mountains relies in part on the ability to determine the flow of low-level moisture. In forest-fire meteorology, an unforeseen wind shift can cost the lives of fire fighters. In each of these applications a knowledge of the behavior of local winds in the atmospheric boundary layer is indispensible.

In the present paper, the local wind systems in South Park, a broad, flat basin in the Colorado Rockies, are discussed. We describe the evolution of these wind systems on a typical, dry day in South Park, i.e., a day in which thermal forcing by local terrain features is not disturbed by large-scale pressure gradients or by circulations accompanying deep cumulus clouds. In this study, we show that the development of these local wind systems is intimately connected with the evolution of the daytime convective boundary layer (CBL) over the land. The data used in this study are horizontal surface charts from the Portable Automated Mesonet (PAM) system of the National Center for Atmospheric Research (NCAR), and vertical soundings using a tethersonde (tethered-balloon sounding system).

In this paper, we define three surface wind regimes which typically occur on a dry day in South Park. The downslope regime will refer to downslope and downvalley flow systems, i.e., winds which are forced by cooling at the earth's surface and which blow generally from higher to lower ground. Analogously, the upslope regime will refer to upslope and upvalley winds, which are ultimately forced by surface-based heating. These downslope and upslope wind regimes thus consist of wind systems described by Wagner (1938) and Defant (1951).

The third regime, which is due to convective mixing in the deep afternoon boundary layer, is an afternoon wind system which generally corresponds in direction with the winds above the ridgetops. The afternoon westerlies—as we shall call them, since the winds aloft were generally from the west—have many of the characteristics of the wind system described by Schroeder (1961) and Schroeder and Buck (1970, p. 121). The afternoon downslope winds in the latter case, however, occur in conjunction with many features not found in South Park, such as a marine inversion aloft, afternoon easterly winds

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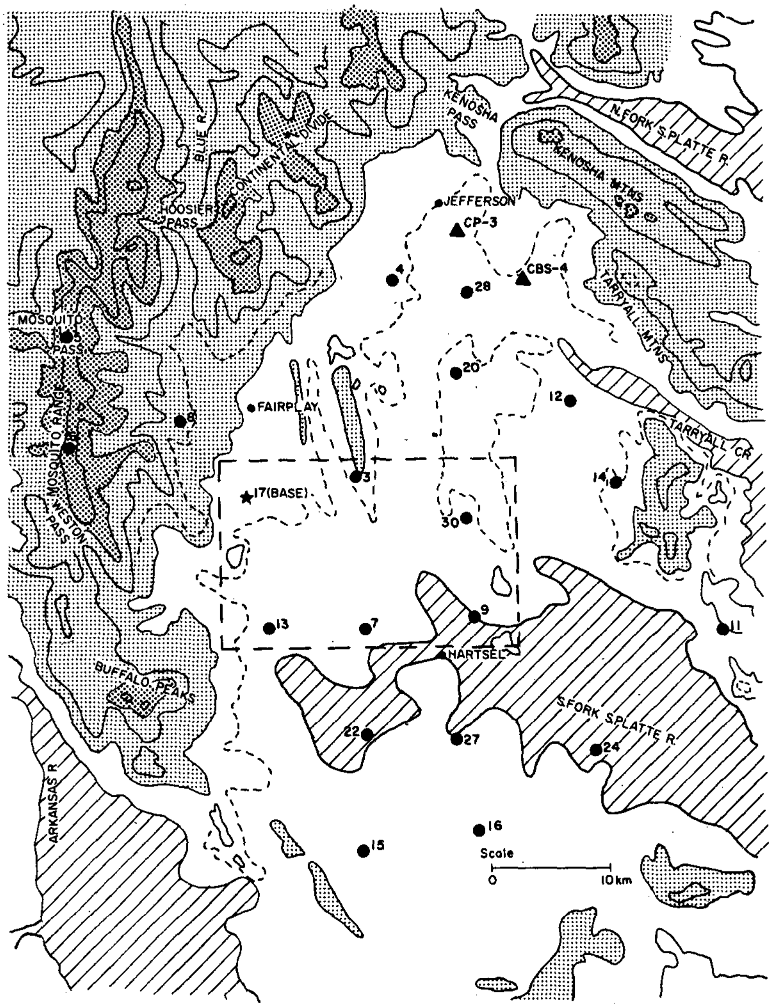


FIG. 1. Map of topography in South Park, Colorado. Regions below 9000 ft (2744 m) are cross-hatched; regions above 10 000 ft (3049 m) are lightly shaded; and regions above 12 000 ft (3659 m) are heavily shaded. The base site, indicated by the star, was located on terrain sloping upward toward the high mountains to the west. The triangles represent two of the weather radar sites, and the large circles represent the locations of PAM stations. The six central South Park stations are included within the dashed rectangle.

aloft, late afternoon upslope winds near the surface, etc. Thus, some of the physical mechanisms operating in Schroeder's California case differ from those operating in South Park.

2. Description of the topography

According to Webster's Dictionary, a mountain park is "a level valley between mountain ranges"; a more precise definition is "a broad, flat-bottomed basin surrounded by mountains."[1] South Park is a relatively wide park in the Colorado Rockies. Peaks of the continental divide rise to the west, while two rivers, the South Fork of the South Platte River and Tarryall Creek, flow through the mountains to the east. Thus South Park is a basin with several smaller river valleys running through it. It is the wide South Platte River valley—50 km east–west by 70 km north–south—where this study takes place.

The dashed rectangle in Fig. 1 surrounds six surface mesonet (PAM) observing stations. These stations will be referred to as the central South Park stations. Several streams flow through this region from north-northwest to south-southeast. Thus, downslope or downvalley winds in this rectangle are from northerly through westerly directions,

[1] The former definition is from Webster's *Third New International Dictionary*—Unabridged (G. & C. Merriam Co., Springfield, Mass., 1966). For the latter, we are indebted to an anonymous reviewer of this paper.

while upslope or upvalley winds blow from southerly through easterly directions. The base site, indicated by a star on Fig. 1, was at an elevation of 2930 m.

Several studies of ridge-valley circulations in and above narrower mountain valleys have appeared (e.g., Defant, 1951; Buettner and Thyer, 1966; Fosberg, 1967; MacHattie, 1968; Whiteman and McKee, 1977). Kao *et al.* (1975) studied the diurnal wind circulations over the broad Salt Lake valley, which is similar in dimension to the South Platte valley discussed here, although the valley orientation is opposite (the high ridges are to the south). The emphasis in Kao's study was on the horizontal variation of turbulent and mean kinetic energy as determined from a mesonet of surface observing stations, and on the diurnal variability of diffusion near the ground.

In a study over "relatively flat" terrain, Lenschow *et al.* (1979) found that the pooling of cool air in depressions in the topography had a significant impact on the evolution of the daytime CBL—in agreement with results to be presented in this paper. In that study, however, no upslope flow was ever observed. There are many reasons for upslope to be absent, the most obvious of which is that the slopes may not have been steep enough. Also, perhaps the protective influence of the mountains upwind of South Park, which allows upslope to form in their lee, was an effect missing in the case studied by Lenschow *et al.*

3. Instrumentation

The instrumentation used in this study included the NCAR portable automated mesonet of surface meterological observing stations and a tethered-balloon system for obtaining vertical atmospheric soundings. These instruments were deployed as a part of a much larger experiment, the South Park Area Cumulus Experiment, in July and August 1977 (SPACE-77). The present study is an outgrowth of a study of the development of the atmospheric boundary layer into the subcloud layer, when cumulus and cumulonimbus clouds form over the mountains. The instrumentation systems used in this study are described below.

The Portable Automated Mesonet (PAM) is a system of surface meteorological observing sites which are linked to a main base station by radio. The remote observing stations are equipped with wet- and dry-bulb thermistors, a pressure port, a wind vane and a cup anemometer mounted at 4 m, a tipping bucket raingage, and a transmitter with a directional antenna mounted at a height of 15 m. Mesoscale data were available in real time, and, in fact, the PAM illustrations in this paper are based on hard copies made in the field.

The locations of the 20 stations used in SPACE-77 are indicated on Fig. 1. A thorough discussion of the PAM system is given by Brock and Govind (1977).

Tethersonde[2] is the trademark of the tethered-balloon, atmospheric sounding system used in this experiment. Morris *et al.* (1975) have described the features of this system in detail.

The balloon carries aloft an instrument package which measures pressure, dry- and wet-bulb temperature, and wind direction and speed. The data are radioed to a ground station which records the data. Soundings are obtained by paying out line from a winch and allowing the balloon to carry the instrument package aloft, then reeling it in. The measured quantities are instantaneous values of temperature, humidity, etc., and are thus subject to sampling error in regions of turbulence. The variability resulting from this sampling error, however, can help to identify regions of turbulence, although it is not a totally reliable indicator.

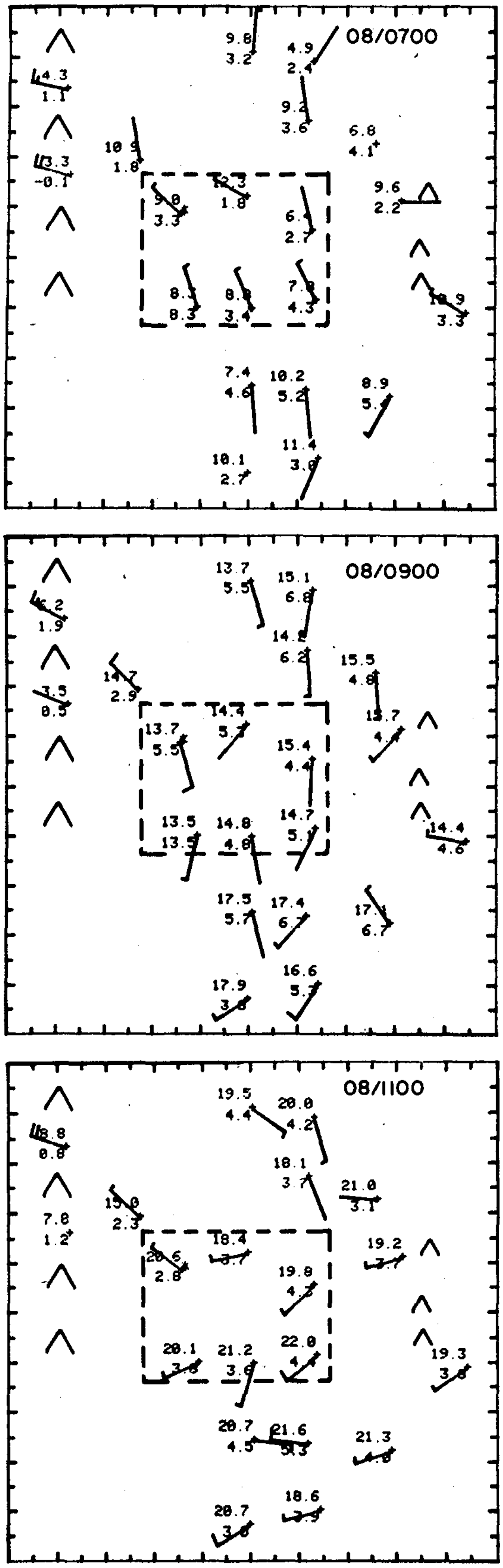
4. Results

In all, our data set consists of observations from more than 10 dry days in South Park. Of these, we have selected data from three days for presentation here. Records of PAM surface data obtained on 8 and 9 August are typical of those which we observed on many dry days. On 7 August, we obtained the best sequence of Tethersonde soundings. We would have preferred to present PAM data for 7 August to complement the sequence of Tethersonde soundings; unfortunately, no PAM data were available on that day until after 0900 MDT, which was after the upslope had begun. Thus, in order to present complete sets of PAM surface observations, it was necessary to use data from other days. The course of the surface winds on the two days selected, however, was very similar to that which occurred on 7 August.

a. PAM surface analyses: 8 August

A good example of the three diurnal wind regimes which occur in South Park was observed on 8 August 1977. One complication which occurred on this day was the presence of convective clouds in central South Park after 1130 (all times MDT), but this was after the afternoon westerlies had reached the surface. Thus, although there were afternoon showers in the Park, this does not contradict our definition of dry days, since cloud circulations did not inter-

[2] Tethersonde is a trademark of Atmospheric Instrumentation Research, Inc., Boulder, Colorado. NCAR's version of this system has been referred to as the Boundary-Layer Profiler (BLP or BP).



fere with the establishment of the three local wind regimes which we found to be characteristic of a dry day.

Fig. 2 shows the three wind regimes as revealed by PAM surface charts. The stations in the upper left are ridge-top stations (elevation 4000 and 4200 m), so they give an indication of the gradient-level winds. Fig. 2a shows a well-established drainage flow at 0700 in central South Park (in the dashed rectangle). The winds measured at the ridgetop stations are strong and westerly, while those in the Park are weaker and more northwesterly. By 0900 (Fig. 2b) upslope flow is well established in central South Park. The winds in the rectangle have reversed to a southerly direction and dew points have risen by ~2°C. Two hours later (Fig. 2c), the winds in the western part of central South Park have shifted to a westerly direction and the dew points have dropped by about 2°C. This is the beginning of the afternoon westerlies.

Time plots of temperature, mixing ratio, and winds from 0400 to 1200 on 8 August at the main base site are presented in Fig. 3. Before 0800 the wind direction is northwesterly (Fig. 3a) indicating drainage flow. Sunrise at this site was about 0620 on this day, and the temperature starts to rise at about 0630. Just before 0800 the wind speed drops to ~1 m s^{-1}.

After about 0830 the upslope winds blow from a south-southeasterly direction with speeds of 4–5 m s^{-1}. The temperature trace—shown on both Figs. 3a and 3b for reference—shows that the upslope air is *cooler* in this case than the drainage air mass it replaced; Fig. 3b shows that the upslope air is also moister. After 0845 the temperature begins to rise again.

Upslope flow continues until just before 1000, when the winds die off and the direction becomes variable again. After 1000 the winds settle into a westerly direction which lasts the remainder of the day—the afternoon westerly wind regime. The mixing ratio trace (Fig. 3b) shows that these afternoon (or late morning in this case) winds are drier than the upslope winds, while the speed trace (Fig. 3a) shows that they are also gustier (more turbulent). The temperature levels off at ~20°C.

Not all of the features revealed by the PAM on this day are characteristic of a typical dry day in South Park. To give some appreciation for the variability of some of these features, we present PAM

FIG. 2. PAM surface analyses for 8 August 1977. (a) Early morning drainage flow at 0700 MDT. (b) Midmorning upslope flow at 0900. (c) The beginning of "afternoon" (or late morning here) westerly flow in central South Park. Plotted are temperature and dew point (°C), and wind speeds as follows: a half flag represents 2.5 m s^{-1} (5 kt) and each full flag represents 5 m s^{-1} (10 kt).

data from a different day in the next section, this time with only brief explanation.

b. Further PAM data: 9 August

PAM surface charts of the three flow regimes for 9 August are presented in Fig. 4. On this day, the ridgetop winds are from a northwesterly direction. Time plots of winds, temperature and mixing ratio at the base site are presented in Fig. 5.

The winds (Fig. 5a) are northwesterly until after 0800, although the speed drops off and the direction becomes variable after 0700. The temperature (Fig. 5b) seems to increase in pulses and the humidity also increases from sunrise to 0800. The shift to upslope winds occurs abruptly at 0830; this wind shift was not always so sudden in South Park. It was accompanied by sharp minima in wind speed and mixing ratios. After the shift, the temperature dropped slightly, but not nearly so dramatically as in the previous case.

The afternoon wind shift was more gradual than on the previous day. At 1130 the wind direction became variable, and at noon the speed began to decrease. Meanwhile, the mixing ratio was gradually declining from values of 8 g kg^{-1}, which were characteristic of the upslope flow. The winds finally settled into a northwesterly direction after 1230, and the mixing ratios leveled off at <5 g kg^{-1}. Although the actual record is short after 1230, the afternoon westerlies are in fact more turbulent than any of the morning winds (in addition to further PAM observations, this was also determined from UVW anemometer data). Furthermore, we note that the afternoon winds are northwesterly, the same direction as the ridgetop winds.

c. Vertical tethersonde soundings: 7 August

Vertical soundings through the three wind regimes were obtained at the base site using the tethered-balloon system (Tethersonde). Soundings for 7 August are presented in Figs. 6a–6f; as shown, several of these soundings reached a height of nearly 500 m.

A sounding through the drainage flow was taken at about sunrise (Fig. 6a). The potential temperature (θ) profile shows a strong surface-based radiation inversion below 250 m, with a neutral (constant θ) layer aloft. This constant θ layer is a persistent feature in subsequent soundings, and we shall continue to refer to it as the *neutral layer aloft*. The θ value of this neutral layer is ~319 K. The drainage winds in the lower, stable region are strongest just above the surface and are from a northerly through northwesterly direction, while the gradient winds in the constant θ layer aloft are from a southwesterly direction. Thus the winds in the two vertical regions do not seem to be coupled.

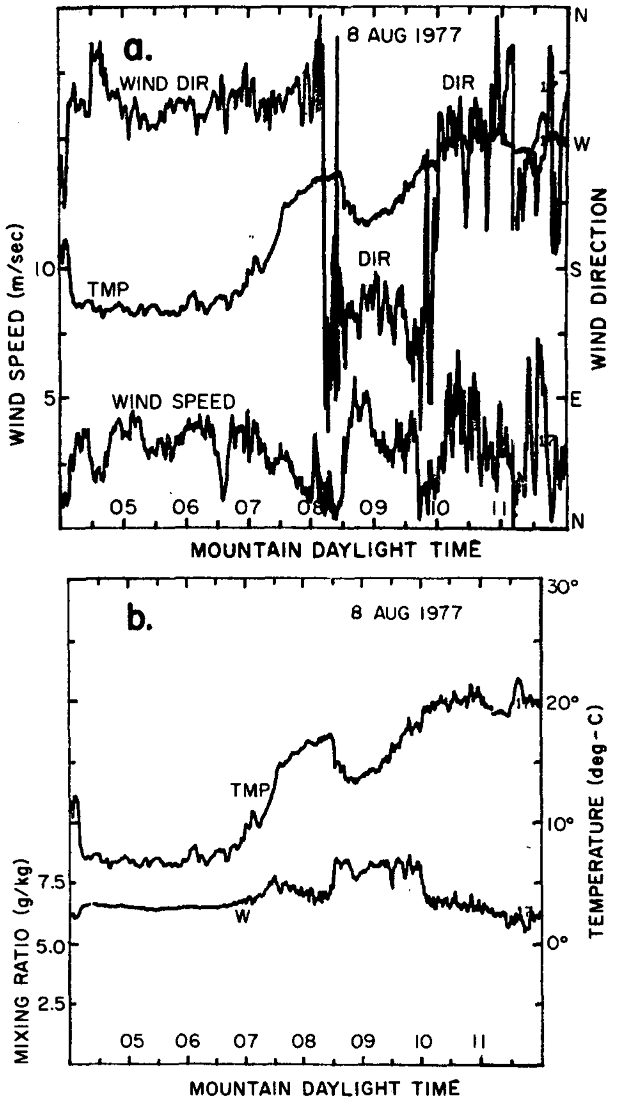


FIG. 3. PAM time plots of winds, temperature and mixing ratio for 8 August at the base site. (a) Winds before 0800 are northwesterly drainage winds; from 0830–1000, southeasterly upslope winds; and after 1000, afternoon westerlies. (b) Note that upslope flow is relatively cool and moist, while afternoon winds are dry.

Fig. 6b shows incipient upslope flow an hour later. The surface temperature has increased more than 10–14°C, and the light winds in the lowest levels are blowing up the local slope (refer to Fig. 1) from an easterly direction. At the top of the sounding the winds are still southwesterly, and the neutral layer aloft above 250 m persists, with a θ value of 319 K. The strange behavior of the θ trace just above 200 m could be due to a temporary intrusion of warm air at that level, to a discontinuity in the density interface (indicated by the large vertical θ gradient there) moving past the balloon, or perhaps to problems with the instrument system in this situation. The occurrence of rather strong upslope flow

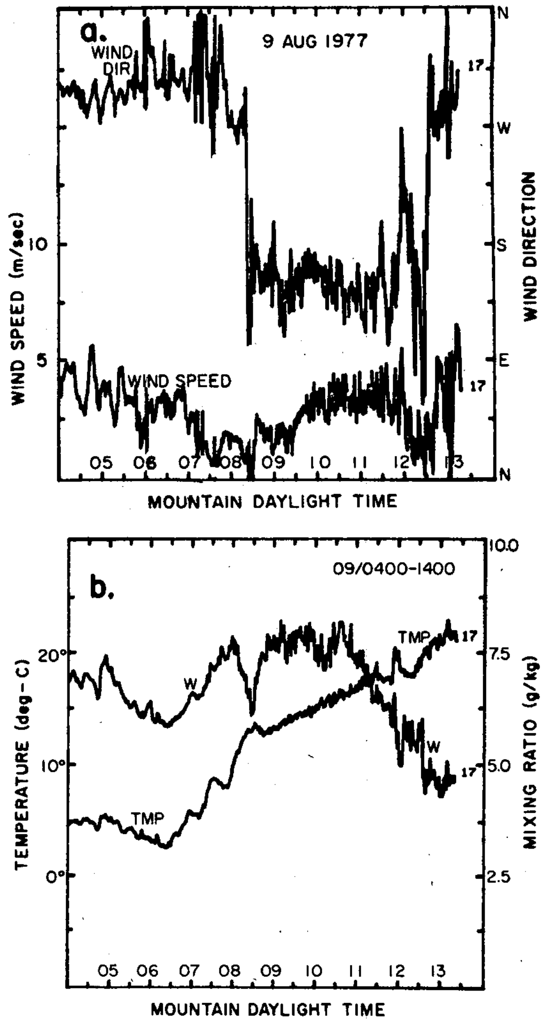


FIG. 5. PAM time plots of (a) wind direction and speed, and (b) temperature and mixing ratios for 9 August at the base site.

at this level—even stronger than at the surface—is a feature absent from most other days, although it did happen on some other occasions.

A feature which was evident on the θ profiles taken through incipient upslope on other days was a shallow, surface-based convective boundary layer (CBL) in the lowest 100–200 m. A CBL is not clearly evident on Fig. 6b, although one can discern some CBL features. In Section 5b of this paper we argue that the lack of a clearly definable CBL on individual soundings is a result of sampling error. Additionally, the CBL which forms beneath the nocturnal inversion is not very deep, especially when compared with the depth of the neutral layer aloft that may

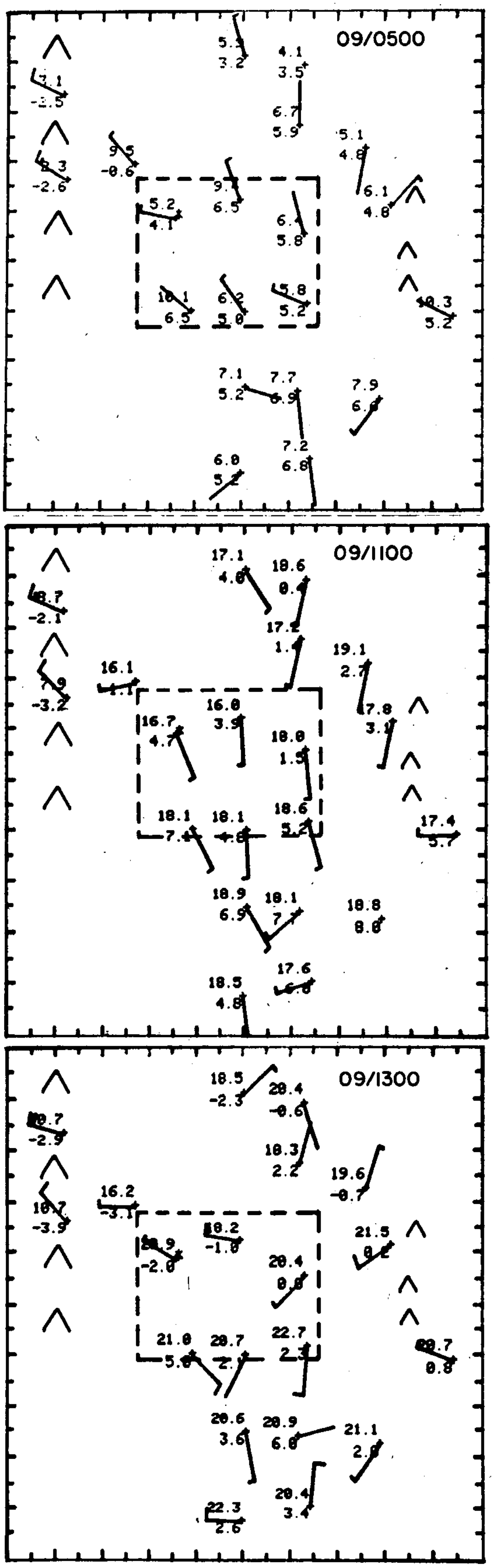


FIG. 4. PAM surface analyses for 9 August 1977: (a) drainage flow, (b) upslope flow, (c) incipient afternoon westerlies in the northwest sector of central South Park. Temperatures (top) and dew points are in °C, and wind speeds are represented the same as in Fig. 2.

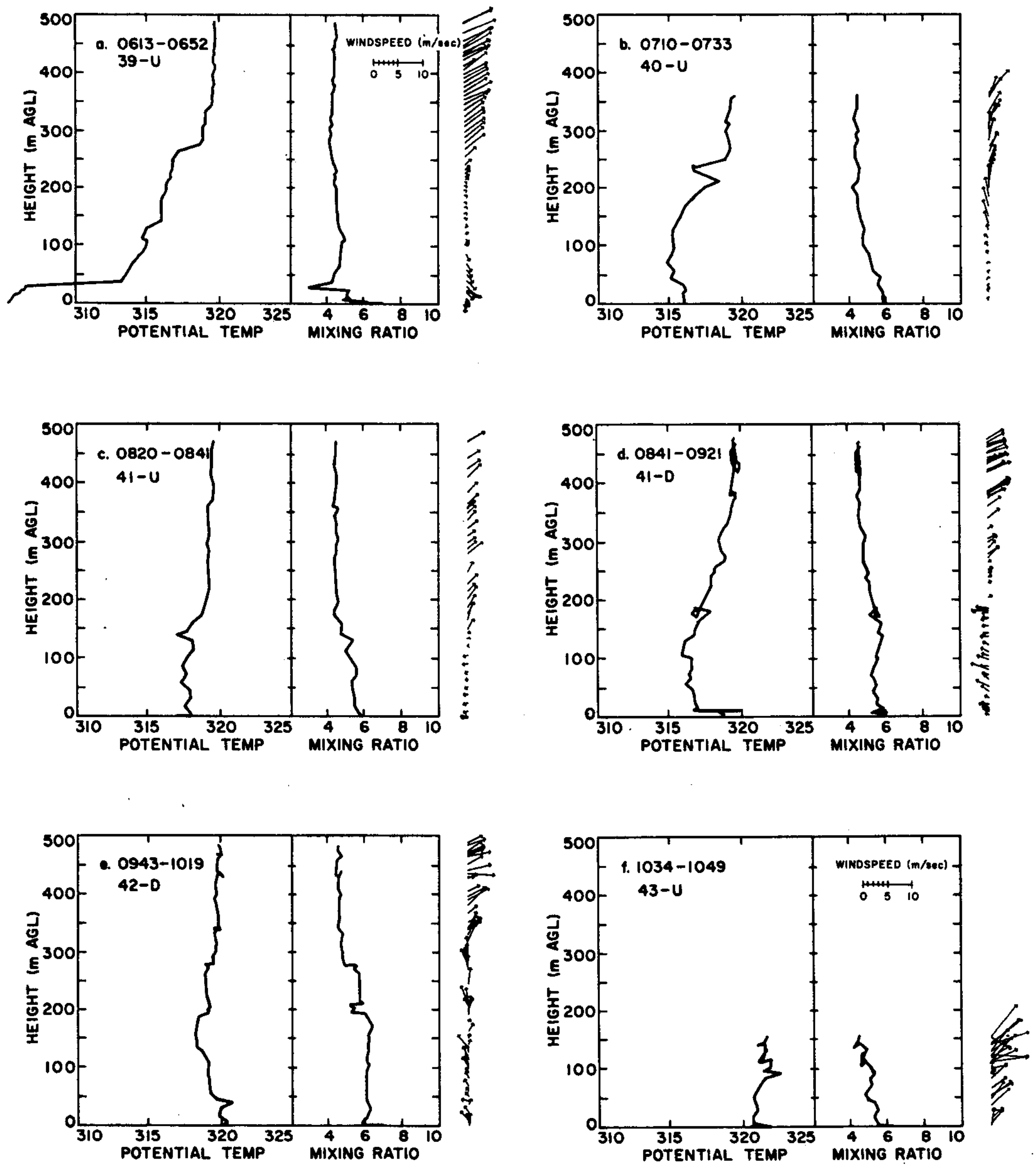


FIG. 6. Sequence of Tethersonde soundings for 7 August 1977: (a) up sounding (0613–0652 MDT), (b) up sounding (0710–0833 MDT), (c) up sounding (0820–0841 MDT), (d) down sounding (0841–0921 MDT), (e) down sounding (0943–1019 MDT), and (f) up sounding (1034–1049 MDT). Each sounding is labeled with times, sounding number, and whether it was the up (U) or down (D) sounding. Potential temperatures are in K and mixing ratios in g kg^{-1}. Arrows indicate wind direction, with north upward and east to the right, and length of arrow indicates speed. Wind speed scales are given on soundings (a) and (f). Note the development of a deeper and deeper layer of upslope flow on soundings (c), (d) and (e), and the turbulent westerly flow on sounding (f) down to near the surface.

extend to 3 km or more above the ground. For this reason (and for other reasons which we shall discuss later), we call this the *shallow CBL*.

The shallow CBL in Fig. 6c has grown to a height of 150 m, and in Fig. 6d, to a height of 200 m. In these soundings, the top of the shallow CBL is evident from the wind profile: there is easterly, upslope flow below the convective inversion, and southwesterly ridgetop-level flow above. The upper-level winds are still associated with the neutral layer aloft, with $\theta \approx 319$ K, and there is a stable region in the θ profile between this neutral layer and the shallow CBL.

Fig. 6e shows an interesting sounding. The moisture profile and the winds clearly show that the shallow CBL extends vertically to nearly 300 m. The

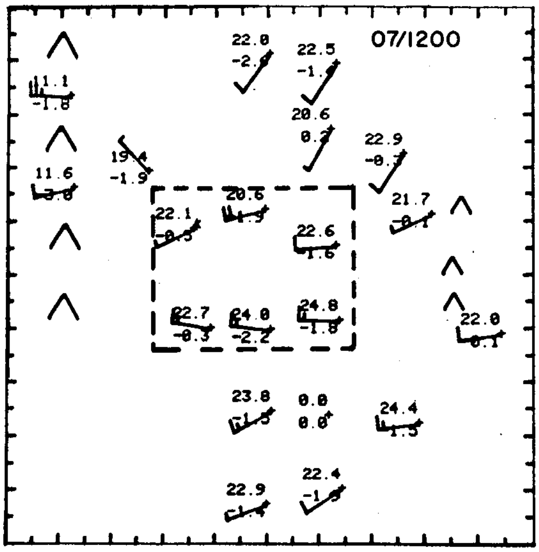


FIG. 7. PAM surface analysis for noon on 7 August. Note the strong westerly flow throughout South Park. This uniformity in surface wind direction all over South Park was observed on many dry afternoons when strong (4 m s^{-1} or more) ridgetop westerlies were present. Temperatures and dew points are given in °C, and wind speeds are represented the same as in Fig. 2.

moisture and θ profiles show that the CBL is discontinuous, with an intruding layer of warm, dry air near 200 m. The winds in the CBL are very gusty, and their direction is now from a southerly through southeasterly, *upvalley* direction, as opposed to the earlier *upslope* direction. The neutral layer aloft persists, but the temperature near the surface has warmed so that its potential temperature is greater than the 319 K of the upper neutral region. Moreover, the θ of the shallow CBL has nearly reached 319 K. Thus, with any further heating the two regions—the shallow CBL and the neutral layer aloft—should become convectively coupled.

The Tethersonde ascent in Fig. 6f, started 15 min after the previous sounding had been reeled in, shows that this indeed occurs. The balloon system, which was not designed to be used in winds of over 8 m s^{-1}, could barely be raised to a height of 150 m because of strong, turbulent westerlies. Fig. 6f shows that these westerlies were dry, and that they extended down to the surface. Fig. 7 is a PAM surface chart for noon on this day. It shows that dry, westerly winds have taken over all of South Park.

5. Discussion

a. *Onset of afternoon winds*

In the previous section, we attributed the appearance of the westerlies at the surface to convective coupling between the surface-based shallow CBL and the neutral layer aloft. In this subsection, we elaborate on the coupling process.

We start with the situation as depicted in Fig. 6e, where the shallow CBL and the neutral layer aloft are still distinct. They are still distinct because turbulent mixing between the upper neutral layer and the lower region (the shallow CBL) is inhibited by the presence of a weak stable layer just below 300 m, the last remnant of the nocturnal inversion. A little more heating erases the stable layer. When the stable layer is gone, this allows the turbulence of the CBL, generated by buoyancy in the warm surface layer (i.e., the lowest 10% of the CBL), to grow rapidly upward into the relatively quiescent, neutral layer aloft. Rapid mixing of the shallow CBL and the upper neutral region occurs. The result is a much deeper, well-mixed CBL which extends from the surface to the top of the old neutral layer aloft. In contrast to the shallow CBL, we call this the deep CBL or the deep afternoon CBL, since it persists all afternoon over South Park on a dry day.

The upper neutral layer was much deeper than the shallow CBL, as mentioned above. Since there was considerably more mass in the region aloft, its properties overwhelmed those of the shallow CBL when the mixing occurred. Thus, one sees dry, westerly flow throughout the new deep CBL; Fig. 6f shows the lowest 150 m of this deeper boundary layer.

The picture that one gets of the erosion of the nocturnal boundary layer from Fig. 6 is not new. It is very similar to that which has been observed over flat terrain. Deardorff (1974, 1978), for example, presents θ profiles where "explosive" growth of the CBL occurs into a neutral layer aloft, which was left over from the deep CBL of the previous day. Coulman (1980) found the same kind of behavior in the evolving subcloud layer (which *is* a dry CBL until clouds form). Additionally, acoustic sounder records have shown the phenomenon of mid- to late-morning explosive CBL growth (McAllister *et al.*, 1969; Russell *et al.*, 1974; Hall *et al.*, 1975).

Over flat land the nocturnal inversion seems to have little overall effect on the growth of the deep CBL, except to set the timing back a little [Tennekes (1973) calls it a "morning transient"]. Over South Park, however, we have seen that the presence of a strong stable layer between the shallow CBL below and the strong westerlies above is precisely the feature which allows upslope to form within the shallow CBL. Otherwise the westerlies would be free to mix down to the surface and no upslope would form at all. This stable layer is the nocturnal inversion.

b. *Comments on observed CBL structure*

As we remarked in Section 3, each Tethersonde observation is an instantaneous "snapshot" of conditions at that level. Traditional θ and q profiles in the CBL, like those discussed by Kaimal *et al.* (1976) and Deardorff (1978) or modelled by Ball (1960) and

Tennekes (1973), are based on values at each level that are averaged over 10–20 min or more. The averaging period is selected to be long enough to average over several "thermals" or "plumes" in the CBL. In the lowest part of the boundary layer, the surface layer, these plumes have an unstable, superadiabatic θ profile, but outside the plumes, the lapse rate is neutral down to very close to the ground (Kaimal and Businger, 1970). Thus a Tethersonde, which does not average its values, may be sampling inside or outside of a plume at any given moment. Profiles from the Tethersonde should reflect this variability, as well as variability from the fact that rising air inside of a plume tends to be warmer than the sinking air outside of a plume. In other words, Tethersonde observations in the presence of plume convection would be subject to a rather large sampling error.

Whether plumes are actually present in the CBL over South Park is a point which requires further discussion. Acoustic sounders have been used to identify plumes in the atmospheric boundary layer (McAllister *et al.*, 1969; Hall *et al.*, 1975). In South Park, two acoustic sounders were operated at various times at the base site, and both verified the presence of plume convection in the CBL. Moreover, data from micrometeorological towers were obtained at the base site, and data from an aircraft equipped with a gust probe were obtained over South Park. The temperature traces from these data showed characteristic plume "signatures" as described by Kaimal and Businger (1970). Thus, even in the presence of the upslope circulation in South Park, the large eddies in the CBL are plumes.

In view of the variability of the Tetersonde observations it is impractical to establish rigid criteria by which a CBL can be identified on an individual tethered-balloon sounding. Although observation-to-observation variability on a given sounding can aid in locating regions of turbulence—as was evident on many of the soundings presented in this paper—even this is not always a dependable indicator. What makes more sense in interpreting the soundings is to consider the entire sequence of soundings for a given day, as we have done in Section 4c. Individual soundings in the sequence should then be compared with soundings at a similar time in the evolution of the boundary layer on other days. This interpretation can then be improved by referring to data from other sources, such as rawinsonde, PAM, aircraft, acoustic sounder and towers equipped with micrometeorological wind and temperature sensors. These data sources were all available during SPACE-77.

Some general characteristics, which are *often* present on individual Tethersonde soundings of the CBL, can be identified. The bulk or central part of the CBL has a potential temperature and mixing ratio which are nearly constant with height, but which show considerable turbulent variability. The winds are from a similar direction in the CBL, but show random turbulent fluctuations in both direction and speed. In the lowest few tens of meters (the surface layer), the properties are highly variable—especially θ. If the balloon ascends outside of a thermal, the θ profile may be constant down to the lowest observation, as discussed above. If the balloon samples the inside of a plume, the θ profile may be superadiabatic at some levels. Because the Tethersonde may enter a plume at any level, the warmest temperatures do not necessarily show up at the ground. At the top of the CBL, where an inversion exists, one should find evidence of discontinuities in the θ, mixing ratio or wind profiles.

Since the variability in the Tethersonde soundings of the CBL arises largely through sampling error, we expect to find *some* soundings which should conform fairly well to the model of CBL structure. Fig. 8 shows a sounding through the upslope flow on 9 August. This profile reproduces the essential features of the lowest half of the model CBL, although the superadiabatic layer is rather shallow.

The typical sequence of soundings which emerges from considering several South Park sequences (like that presented in Fig. 6), as well as information obtained from other data sources, is depicted in Fig. 9. Fig. 9a represents a sounding taken through the early morning drainage flow (marked D), with the drainage wind shown blowing in a direction somewhat different from the upper-level gradient winds. Fig. 9b shows incidient upslope flow (marked U) forming beneath the nocturnal inversion, within a shallow turbulent CBL. Fig. 9c shows upslope flow (marked U) still decoupled from the winds aloft. The direction of the winds in the lower level could have been shown from a southerly or southwesterly *upvalley* direction instead of the easterly *upslope* direction indicated. Finally, Fig. 9d shows the deep CBL and the afternoon wind regime, with winds characteristic of the ridgetop level all the way down to the surface.

c. *General comments on afternoon winds in the mountains*

In this paper, we have described the events leading to the erosion of the nocturnal cold pool in a wide, flat basin in the Rocky Mountains, and the consequent surfacing of the upper-level winds. We have looked at this problem from the point of view of a mesoscale network of surface observing stations, and in somewhat greater detail, from the point of view of vertical atmospheric soundings taken from a station along the western slope of the valley. We have found that the dynamics of a convective inversion, similar to the kind of inversion which is found over flat terrain, are an important aspect

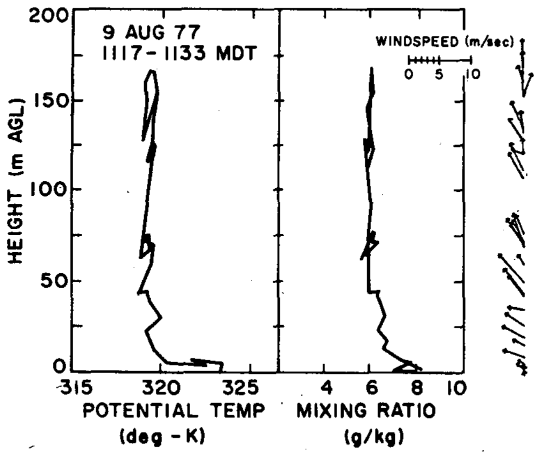


FIG. 8. Tethersonde sounding for 9 August showing typical structure for lower part of convective boundary layer (CBL). The upper part of the sounding shows a neutral, turbulent, convective region, while the lowest 30 m or so shows a moist, superadiabatic surface layer.

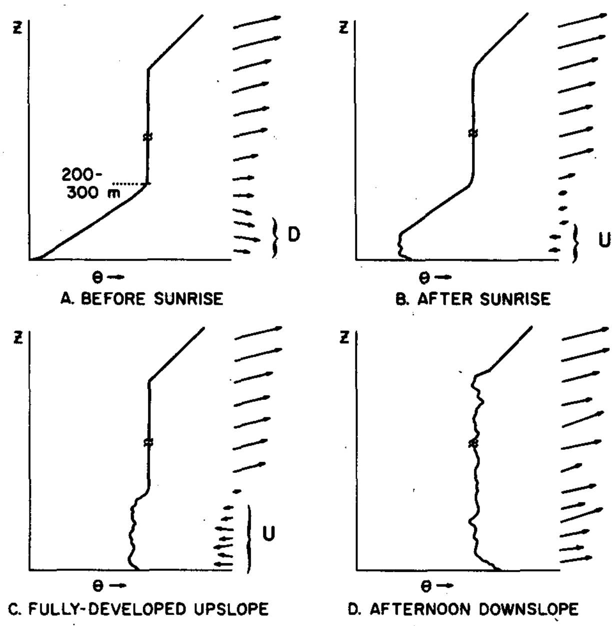


FIG. 9. Typical sequence of soundings which occurs on a dry day for a station along an east-facing slope. (a) The nocturnal inversion with drainage flow (D) becomes (b) a shallow CBL with incipient upslope flow (U). (c) Upslope layer (U) and CBL deepen until the last remnant of nocturnal inversion is erased, and (d) deep, well-mixed CBL forms. The break in the neutral layer is to indicate that this layer is much deeper than depicted, as discussed in the text.

of the physical processes leading to both upslope and afternoon winds.

One reason why the afternoon wind regime is so obvious in South Park is that the valley drains to the east. Thus, the upslope winds and the gradient-level winds are from quite opposite directions, and when the afternoon regime takes over, there is a noticeable wind shift. If the valley had drained toward the west, so that both the upslope and the gradient winds were westerly, then the transition to afternoon winds would have been much less noticeable. In fact, on days with easterly winds aloft in South Park, easterlies persisted at the surface all afternoon.

In narrow mountain valleys, the occurrence of an afternoon wind regime is not a well-documented feature. This may be due in part to the strong channeling effect exerted by a valley on the winds within. One documented case, however, is the study of Schroeder (1961), who studied the wind systems in a canyon in the coastal mountains near San Diego, California. The canyon opened to the east, so that downcanyon winds would be from the west. Schroeder identified two different situations in which afternoon downslope occurred. The first was observed during cool, humid weather and the second during hot, dry weather. The latter type could be similar to what we observed in South Park, although both of Schroeder's types were strongly influenced by a marine inversion and by an overriding sea breeze circulation. From this it is evident that there are different physical mechanisms by which afternoon wind shifts can be produced in the mountains.

A second study, which took place in a river valley in the Canadian Rocky Mountains, is that of MacHattie (1968). Using data from surface stations which were averaged over several dry summer days, he found evidence for a late-morning or afternoon wind which blew down the valley. He inferred, in agreement with our results presented here, that these winds were due to the downward mixing of gradient-level winds aloft. (Additionally, he found a late-afternoon tendency for the flow to return to an *upvalley* direction—a feature which Schroeder (1961) also observed in California.)

d. Mechanisms which dissolve the nocturnal inversion layer

One of the conclusions of this paper is that dissolution of the ground-based, nocturnal inversion layer in South Park occurs mostly through the upward growth of the shallow CBL which forms at the underside of the layer. Other mechanisms have been suggested to account for the dissolution of the inversion layer in valleys. Some of these other mechanisms will be discussed briefly in the following section.

A number of studies have shown that the top of the inversion layer sinks during morning heating. Davidson and Rao[3] and Ayer (1961) attributed this to the

[3] Davidson, B., and P. K. Rao, 1958: Preliminary report on valley wind studies in Vermont, 1957. New York University, College of Engineering, Department of Meteorology and Oceanography.

erosion of the inversion layer from above by turbulent mixing at the top of the layer. Whiteman and McKee (1977) found that the sinking of the inversion layer was in response to the fact that the upslope flow, blowing up the sidewalls of the valley, evacuates mass from the central portions of the valley. The observations in all of these studies were taken in relatively narrow valleys—considerably narrower than South Park.

Using our South Park data, an inspection of rawinsonde and Tethersonde soundings taken on dry days revealed no consistent tendency for the top of the nocturnal inversion layer to lower during the course of the morning. Thus the mechanisms described above seem to have little effect on the eventual dissolution of the inversion layer in South Park.

A different mechanism was proposed by Lenschow *et al.* (1979), who studied the dissolution of cool pockets which formed at night in topographical depressions in the relatively flat terrain of the high plains of eastern Colorado. They found that when a certain "slope Richardson number" exceeds its critical value, the turbulent Reynolds' stress (i.e., drag force) at the top of the cold air layer is sufficient to pull the cold air out of the depression. Once the cold air is out of the low region, it eventually commingles with the turbulent air of the deep, daytime CBL.

In addition to their studies over relatively flat terrain, Lenschow *et al.* also used some of our South Park data to show that a similar phenomenon occurs in mountainous terrain. Thus their mechanism has been shown to be an important one in South Park. The relative importance of the mechanism proposed by Lenschow *et al.* (as opposed to the growth of the shallow CBL discussed in this paper) to the destruction of the inversion layer, is a subject which is currently under investigation.

6. Conclusion

The results presented in this paper have demonstrated the importance of the daytime evolution of the vertical stability profile (given by the potential-temperature profile) to the establishment of the local wind regimes in a broad mountain valley. By sunrise, a stable layer has formed next to the ground, resulting from nighttime radiational cooling of the surface and from cool air drainage. With heating of the surface by the sun after sunrise, a shallow CBL forms beneath the nighttime stable layer. Within this CBL, upslope winds develop. Finally, when the nighttime stable layer has competely eroded, a very deep, turbulent CBL forms. The vertical turbulent mixing in this deep CBL transports momentum from the strong ridgetop-level winds aloft (when present) all the way down to the surface. This effectively overwhelms any local-scale (mountain-valley) winds which may be trying to form in the afternoon.

These processes add a new wrinkle to the traditional view of slope winds, which was expressed by Cramer (1972, p. 48): ". . . on sunlit slopes, θ values are highest next to the slope and flow tends to be up the slope." Our study shows that over South Park (unlike the Pacific Coast where Cramer's study took place), this statement is true so long as upper-level winds are prevented from mixing downward to the surface. When the deep, turbulent, afternoon CBL forms, however, the surface winds tend to conform to the upper-level winds, owing to the strong vertical mixing which is present in the CBL.

The presence of a very deep afternoon CBL over the mountains has been documented by several authors (e.g., Holzworth, 1964; Cramer, 1972). The focus of this study, on the other hand, has been on the "mini-CBL" which forms beneath the stable remnant of the nocturnal inversion—the "morning transient" of Tennekes (1973). Although this layer is quite shallow compared with the deep afternoon CBL, this study has shown that processes occurring within the layer have a very important effect on the diurnal cycle of winds at (and just above) the surface.

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