Aspects of Regional-Scale Flows in Mountainous Terrain

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ABSTRACT

Mountaintop data from remote stations in the central Rocky Mountains have been used to analyze terrain-induced regional (meso-β to meso-α) scale circulation patterns. The circulation consists of a diurnally oscillating wind regime, varying between daytime inflow toward, and nocturnal outflow from, the highest terrain. Both individual case days and longer term averages reveal these circulation characteristics. The persistence and broadscale organization of nocturnal outflow at mountaintop, well removed from valley drainage processes, demonstrates that this flow is part of a distinct regime within the hierarchy of terrain-induced wind systems.

The diurnal cycle of summertime convective storm development imparts a strong influence upon regional-scale circulation patterns. Subcloud cooling processes, associated with deep moist convection, alter the circulation by producing early and abrupt shifts in the regional winds from an inflow to outflow direction. These wind events occur frequently when moist conditions prevail over the central Rocky Mountains. Atmospheric soundings suggest that significant differences occur in the vertical profile of the topographically influenced layer, depending upon the dominant role of either latent or radiative forcing.

1. Introduction

Recent research efforts within the Department of Energy's ASCOT program have been directed at understanding the nature of atmospheric transport in complex terrain. The problem is especially interesting at night, when systematic, terrain-induced winds accomplish much of the low-level transport. The daily cycle of solar heating and longwave radiative cooling over mountainous terrain produces a hierarchy of interrelated flow regimes. As a result, diurnally reversing circulations are generated on spatial scales (see Orlanski 1975) ranging from individual mountain slopes (meso-γ scale) and mountain valleys (meso-γ to meso-β scale), up to the mountain-plain slope (meso-β to meso-α scale), and across large plateau areas (meso-α to synoptic scale). While many observational and theoretical aspects of this topographic forcing have been known for some time (Defant 1951), few studies describe circulations on scales greater than the mountain-valley (e.g., Atkinson 1980, p. 249; Barry 1981, p. 148).

Several examples of terrain-induced flows on the meso-β scale and above include Buettner and Thyer (1966), who noted the presence of antivalley winds above a mountain–valley circulation in western Washington. Using pilot balloons, Tyson and Preston-Whyte (1972) observed a mountain–plain circulation in a distinct layer above the mountain-valley winds. (Note: The difference between the terms "mountain-plain" and "regional-scale" exists only in number of dimensions considered; whereas mountain-plain refers to two-dimensional aspects, regional-scale implies a three-dimensional flow.) Others have discussed the spatial characteristics of regional-scale circulation patterns in different geographical settings. Mass (1982) described diurnally reversing flows in the Puget Sound area of western Washington in summer and winter, whereas Toth and Johnson (1985) observed the development of a similar circulation along the Colorado Front Range during July 1981. Numerical simulations of the diurnal evolution of the mountain-to-plain boundary layer, across both the western and eastern slopes of the Colorado Rocky Mountains, have also been conducted (Dirks 1969; Banta 1986; Bader et al. 1987; and Tripoli and Cotton 1989a,b). On the largest scales, Reiter and Tang (1984) have shown the presence of diurnally forced circulations over the Western Plateau of North America.

The primary focus of the ASCOT program has been the study of nocturnal valley drainage flows. One of the factors controlling the development of valley drainage is the speed and direction of the ridgetop winds (Orgill and Barr 1987). Winds immediately above the valley can differ from geostrophic flow, due to the effects of thermal forcing and topographic channeling on spatial dimensions between the mountain-valley and synoptic scales. This paper provides an analysis of wind systems in complex terrain on this regional (meso-β to meso-α) scale. To facilitate this study, selected mountaintop locations have been instrumented over

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four summers (1984–87) as part of the Rocky Mountain Peaks Experiment (ROMPEX). Data from these networks provide more extensive observations on the meso-β to meso-α scale than have previously been available. The analyses show that regional-scale circulations, driven by thermal forcing of the mountain-to-plain slope, are significantly altered by moist convective processes.

2. Data sources

In the summer of 1985, the most ambitious phase of the 4-year ROMPEX field program was undertaken. The experiment included 19 high mountain stations located primarily in Colorado, but extending also into southern Wyoming and northern New Mexico. The configuration of observing systems and various types of data collected during the 1984–86 ROMPEX field programs have been described at length by Sheaffer and Reiter (1987) and by Reiter et al. (1987). Since 1985, the field program has focused upon investigating regional flows within the smaller domain of northcentral Colorado. The most recent 1987 ROMPEX surface network consisted of 9 stations operated by various agencies, 8 in high mountain locations, and one valley site (see Fig. 1 and Table 1). The stations are located in a northwest to southeast transect across the Continental Divide, with 6 stations west of the Divide and 2 to the east. Data from the ROMPEX stations have been supplemented with surface and upper air data from the National Weather Service. Lightning strike data from the Boise Interagency Fire Center were also acquired to indicate convective storm activity over mountainous regions where radar coverage is often poor. Airsonde equipment from the National Center for Atmospheric Research was used to take vertical soundings of temperature, humidity, and pressure during selected periods of the 1986 and 1987 experiments. The ascents were tracked by optical theodolite.

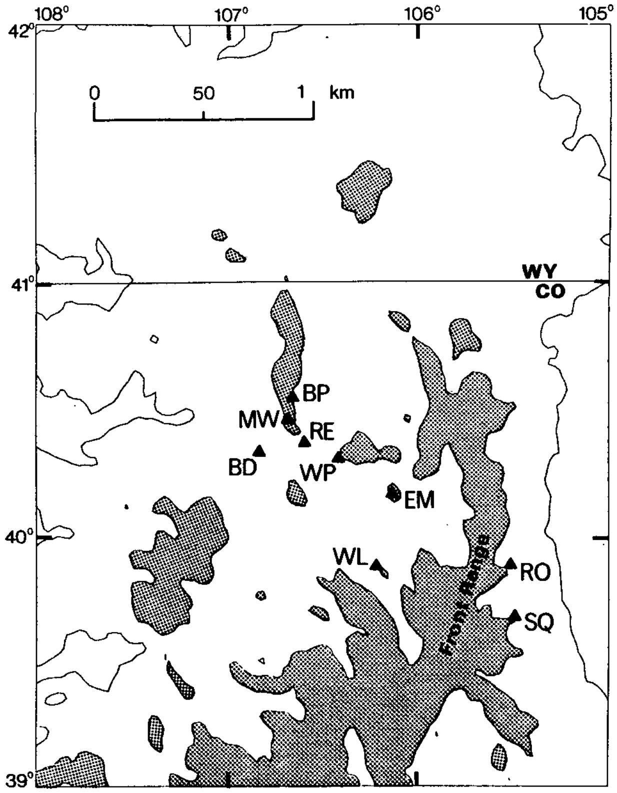


FIG. 1. ROMPEX 1987 station locations and two-letter identifiers. (See Table 1 for further details.) Geographic location relative to larger central Rocky Mountain region is denoted by dotted line in Fig. 2a. Topographic contours are 2000 and 3000 msl. Areas above 3000 msl are shaded to depict high terrain.

3. Thermally driven regional-scale flows

Thermally forced circulations are most easily observed during dry conditions with strong solar forcing, and quiescent synoptic-scale flow. Over the central Rocky Mountains, such an environment occurs intermittently during the summer months. In this section, the emphasis is placed on describing regional-scale flows which develop in these radiatively driven conditions.

a. Undisturbed diurnal wind cycle

An example of an organized, thermally driven meso-β to meso-α scale circulation is shown in Fig. 2. Upper level charts for this day (26 August 1985) show a strengthening anticyclone centered in the Four Corners area at 50 kPa. Over Colorado, this pattern brought weak, very dry northwesterly flow. Resultant mountaintop wind vectors for the afternoon of 26 August 1985 (Fig. 2a) show west to northwest flow on the west side of the high mountain barrier, with east to southeast flow on the east side. The resulting convergent flow pattern toward the highest terrain is referred to as "inflow", and arises in response to solar heating of the mountain-to-plain slope.

The nocturnal phase of this circulation is given in Fig. 2b. Resultant winds show that divergent outflow from the mountain divide has replaced the inflow of the previous afternoon. The observation of organized outflow winds at mountaintop shows that pressure systems resulting from longwave radiative cooling can force a direct wind field response on the mountain-to-plain scale. Schematically, this nocturnal wind regime appears to be similar to that described by Tyson and Preston-Whyte (1972) (their Fig. 3), who illustrate the regional-scale outflow from the Drakensburg Plateau, flowing above the individual mountain-valley wind regimes toward the Indian Ocean in South Africa. Here, the outflow develops between the high mountain terrain near the Continental Divide and the lower elevation plains to the east and the intermontane basins to the west.

TABLE 1. Monitoring sites for ROMPEX 1987.

Station	(ID)	Elevation (msl)	In operation	Instrumentation*	Agency**
Buffalo Pass	(BP)	3219	June–Sept.	WS, WD, T, RH, P, RF	BOR
Brunner Draw	(BD)	2110	17 Aug.–2 Oct.	Energy Budget	CSU
Elk Mountain	(EM)	3481	8 July–10 Sept.	UVW Winds, T, RH	CSU
Mt. Werner	(MW)	3207	8 June–2 Oct.	Energy Budget	CSU
Rabbit Ears	(RE)	3017	June–Oct.	Energy Budget	USGS
Rollinsville	(RO)	2749	June–Sept.	WS, WD, T, RH, P, RF, K	PROFS
Squaw Mt.	(SQ)	3505	June–Sept.	WS, WD, T, RH, P, RF, K	PROFS
Whiteley Pk.	(WP)	3081	9 July–11 Sept.	UVW Winds, T, RH	CSU
Williams Pk.	(WL)	3300	7 July–10 Sept.	UVW Winds, T, RH	CSU

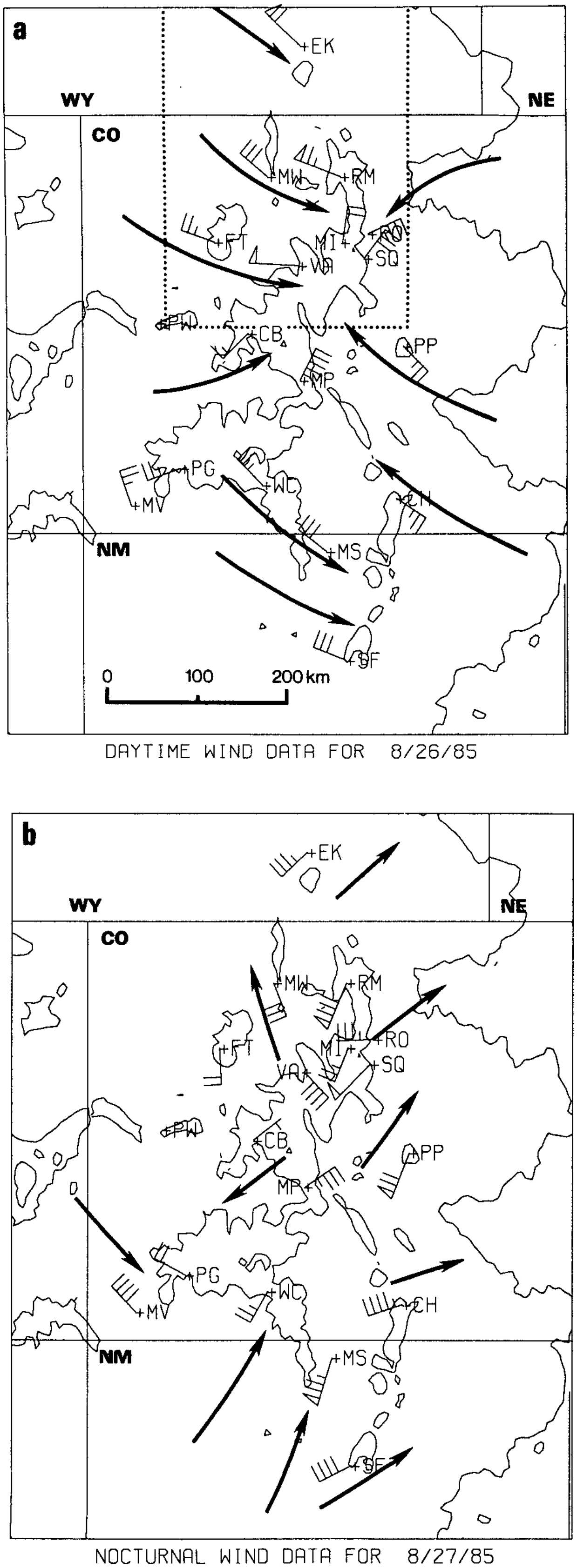
* Abbreviations: WS, wind speed; WD, wind direction; T, temperature; RH, relative humidity; P, pressure; RF, rainfall; UVW, three-dimensional wind components; K, solar radiation.
** Abbreviations: CSU, Colo. St. University; USGS, US Geological Survey; BOR, Bureau of Reclamation; PROFS, Program for Regional Observing and Forecasting Services.

b. *Time-averaged diurnal wind cycles*

The time-averaged effects of thermal forcing on the regional-scale are demonstrated with mean diurnal wind cycle data, selectively chosen to include only days where relatively unobstructed daytime solar heating and nocturnal longwave cooling predominate over the high terrain. This data stratification allows the examination of thermal effects without the complicating influences of strong convective or synoptic forcing. Observations from 47 clear days during the summers of 1985, 1986, and 1987 are included in this analysis. Selection of these days was subjectively based on several factors including a lack of lightning strikes and radar echoes, weak upper level flow, low humidity values, and nearly constant outgoing nocturnal infrared radiation values, which are indicative of clear skies. Hourly averaged wind cycles for the 47 days are shown as wind hodographs for the Squaw Mountain and Mount Werner stations (SQ and MW in Fig. 1) in Figs. 3a and 3b, respectively. The hodographs show the time of maximum west–east velocity (i.e., u-component) at the east slope (SQ) and the west slope station (MW) to be completely out of phase, demonstrating the inflow/outflow signature illustrated in Fig. 2. Common to both hodographs is an elliptical structure characteristic of wind regimes affected by a diurnally oscillating pressure field (Mass 1982). Orientation of the major axes and the elongated nature of the hodograph ellipses, particularly evident at MW, appear to reflect topographical constraints imposed upon the regional-scale flow even at these mountaintop sites. The clustering of points near the ends of the major axes represent the daytime and nocturnal flow regimes. This clustering effect results from two quasi-equilibrium states which develop between the forces driving the inflow and outflow winds (Staley 1957).

The strong velocities noted in the MW hodograph during both the steady daytime northwesterly and nocturnal southeasterly flow regime attests to the persistence of the inflow and outflow cycle under thermal forcing. At SQ, however, only the nocturnal outflow shows this marked regime steadiness. The proximity of the SQ station to the crest of the Front Range places this site near the western edge of the daytime easterly inflow solenoid. Consequently, the strength and timing of inflow winds are more variable at the station. Downward transport of westerly momentum from aloft through a deep mixed layer (Banta 1984) may also play an important role in this wind variability. As a result, relatively weak velocities are found in the hodograph due to the tendency for either easterly inflow or westerly outflow during the afternoon hours. This produces a cancellation effect in the resultant wind averages comprising the hodograph. The transition between each quasi-steady diurnal wind regime at SQ and MW takes approximately 6 to 7 hours (1900–0200 MST at SQ; 1800–0100 MST at MW) for daytime to nocturnal, and approximately 4 to 5 hours (0600–1100 MST at SQ; 0800–1300 MST at MW) from nocturnal to daytime. Turning of the winds in a clockwise sense at both stations during these transition periods is in response to Coriolis influence.

The SQ and MW mountaintop stations are representative of regional-scale wind conditions on each slope of the mountain barrier in northern Colorado. This can be demonstrated by examining the hodographs from two additional stations (Fig. 4) which were constructed from hourly averages over 63 summer days spanning 9 July–10 September 1987. The hodograph for Rollinsville (Fig. 4a; RO in Fig. 1), an exposed east slope station 25 km northwest of SQ, shows diurnal wind behavior similar to SQ. The winds exhibit clockwise rotation between a steady nocturnal southwesterly outflow regime and a less steady inflow regime. On the western slope of the mountain-plain topography lies Whiteley Peak (Fig. 4b; WP in Fig. 1), 25 km southeast of MW. The structure of the WP hodograph is more complicated than MW, but reveals similar characteristics of a well-defined daytime northwesterly inflow



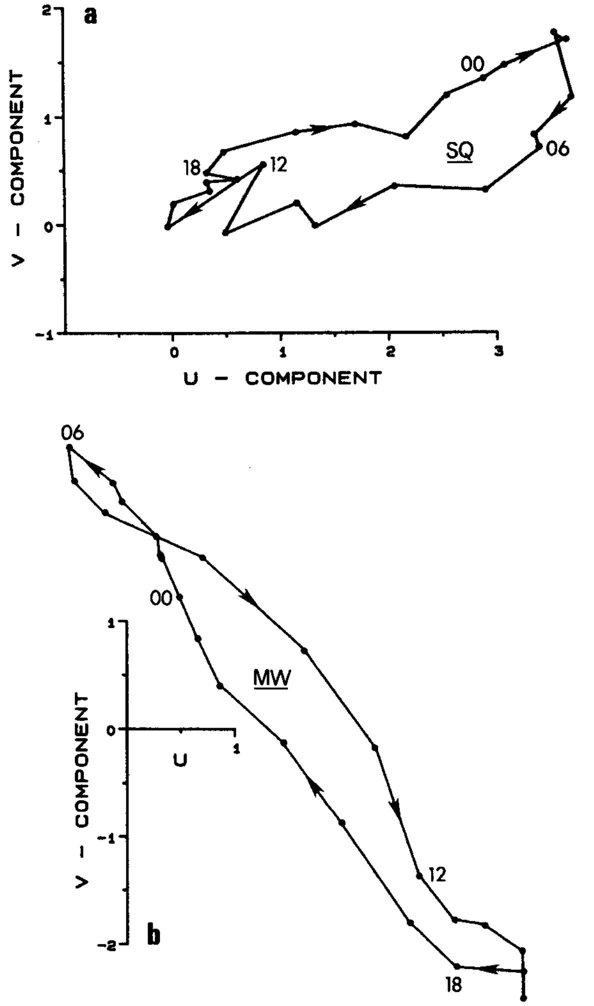


FIG. 3. Averaged wind hodographs for 47 clear days at (a) Squaw Mountain (SQ) and (b) Mount Werner (MW) (see Fig. 1 and Table 1). Labeled times are midnight (00), 0600 (06), 1200 (12) and 1800 (18) MST. Axes are horizontal wind component speeds in m s^{-1}.

and nocturnal southerly outflow. The curved nature of the WP hodograph reflects constraints on the stratified nocturnal outflow due to nearby topography. Counterclockwise rotation of the WP hodograph after 0500 MST appears to be caused by localized early morning heating effects, and is also noticeable in the MW hodograph.

c. *Vertical structure*

In late September and early October of 1987, nocturnal soundings were obtained during a period of an-

FIG. 2. Averaged resultant winds over the ROMPEX 1985 station network for (a) 1200 through 1500 Mountain Standard Time (MST = UTC − 7) 26 August 1985, and (b) 0000 through 0300 MST 27 August 1985. Barb represents 1 m s^{-1} wind speed, flag represents 5 m s^{-1}. Topographic contours are 1500 and 3000 msl.

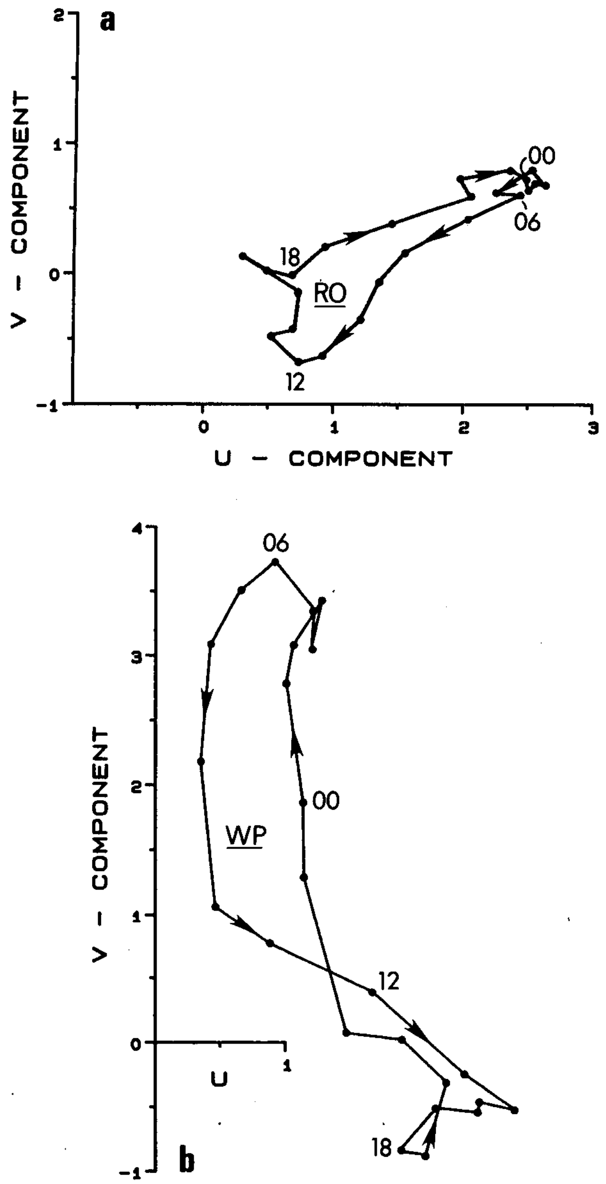


FIG. 4. As in Fig. 3, but for the period 9 July 1987–10 September 1987 at (a) Rollinsville (RO) and (b) Whiteley Peak (WP) (see Fig. 1 and Table 1).

ticyclonic conditions in Colorado, well-suited to observing dry, thermally driven outflows. One such sounding (Fig. 5) was taken in clear conditions at 0600 MST on 1 October 1987, from a valley site (~2010 msl) at the base of MW. The sounding shows a very strong surface-based inversion which developed through a 500 m layer (2010–2500 msl) as a cumulative result of nocturnal radiative cooling. Winds are light and variable within this layer. Two other distinct stable layers are found between the surface-based inversion and the nearly neutral conditions above 3300 msl. In the first layer, located between 2525 and 2850 msl, light southerly down-valley winds shift to stronger westerlies. In the second, which ranges from 2850–3250 msl, strong (~10 m s^{-1}) westerlies prevail. The abrupt change in the flow structure between the surface-based inversion and the first and second transition layers shows that decoupling of the flow has occurred within the elevated stable layers. It is important to note that this discrete stable layering extended above the surrounding ridgeline, located at approximately 3100–3200 msl. During the night prior to this dawn sounding, mountaintop winds at MW (located near the top of the second transition layer) were from the west-northwest, due to the penetration of fairly strong synoptic winds from above the mountaintop.

The following evening had similar anticyclonic conditions but with weaker synoptic winds, allowing a pronounced regional-scale outflow structure to evolve. This flow is clearly shown in a vertical profile from the top of MW taken at 2300 MST 1 October 1987 (Fig. 6). The sounding reveals the presence of an 8 m s^{-1} northeasterly jet located 30 m above the mountaintop surface, within a very stable and shallow (100 m) layer. The sounding also shows weaker surface winds at MW, from the northeast at 2.7 m s^{-1}. A later sounding taken at midnight (not shown) displayed southeasterly winds (~5 m s^{-1}) in this same shallow layer and weaker southeasterlies at the surface, which persisted throughout the night.

4. Convective processes on the regional-scale

The prevalence of summer convective storms over the central Rocky Mountains has been well documented (i.e., Klitch et al. 1985; Lopez and Holle 1986; Banta and Schaaf 1987). It is important to consider possible connections between the diurnal evolution of the convective storm cycle and the concurrent generation of regional-scale inflow and outflow. To accomplish this, the averaged effects of convective activity are examined for 9–31 July 1985. This 23-day period includes the most persistent daily occurrence of thunderstorms over the high terrain of Colorado during the ROMPEX experiments. It therefore provides a good example, in a time-averaged sense, of convective influence on regional-scale circulations.

a. Characteristics of storm development

The temporal features of cloud development on each slope of the mountain barrier can be demonstrated by observing the average incoming radiation at the MW and SQ stations over the July period. The MW station is located 100 km to the west, and SQ 30 km to the east, of this barrier (see Fig. 1). The 23-day hourly averaged solar radiation cycles at both stations (Fig. 7) are similar from sunrise (~0500 MST) until 1000 MST, when clouds at SQ reduce the incoming radiation. At MW, insolation continues to intensify until 1200 MST, after which some slight cloud effects are

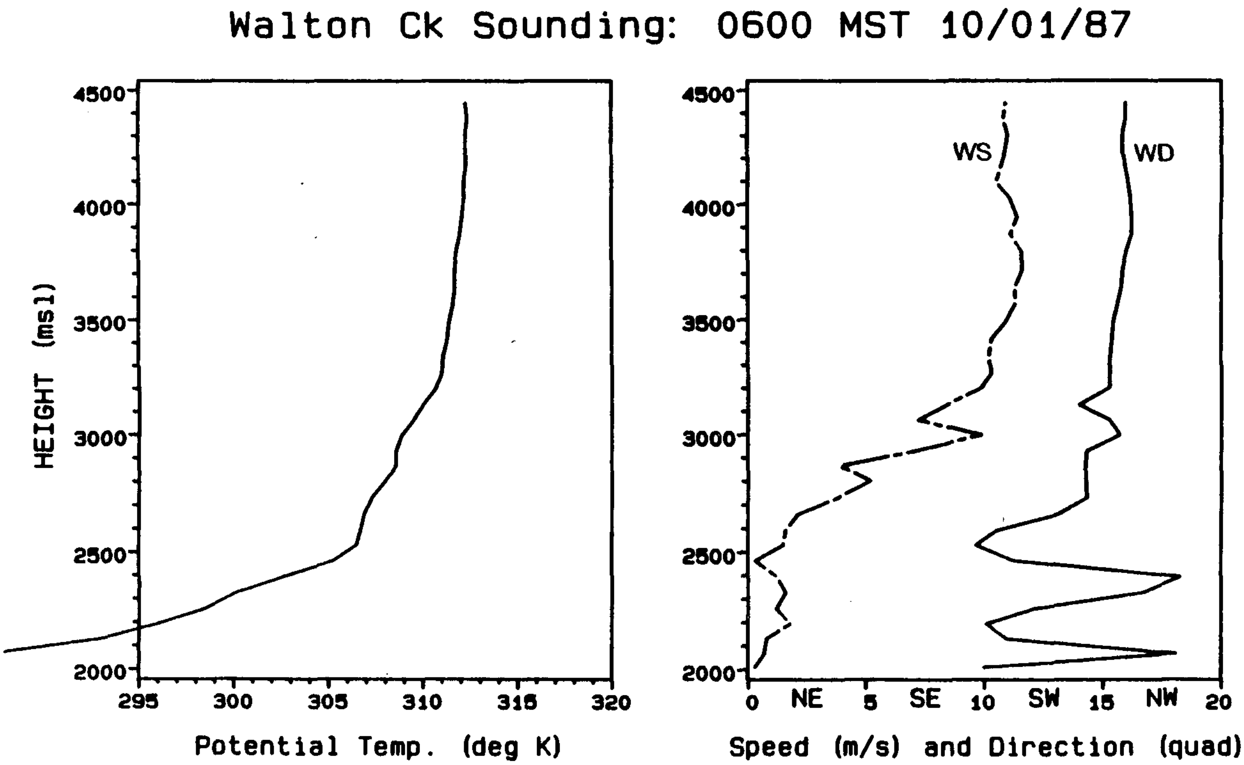


FIG. 5. Vertical sounding of potential temperature, wind speed, and wind direction from Walton Creek, Colorado (elev. 2010 m) at 0600 MST 1 October 1987.

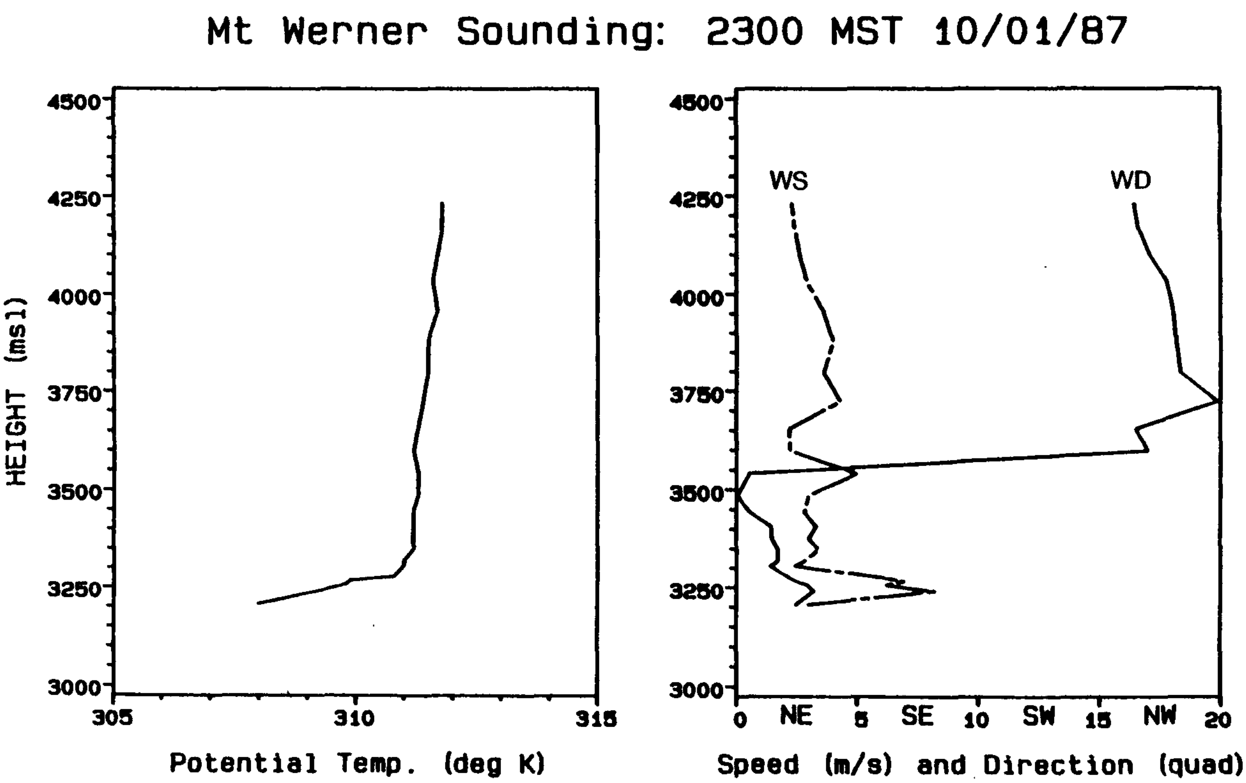


FIG. 6. As in Fig. 5, but from Mt. Werner, Colorado (elev. 3207 m) at 2300 MST 1 October 1987.

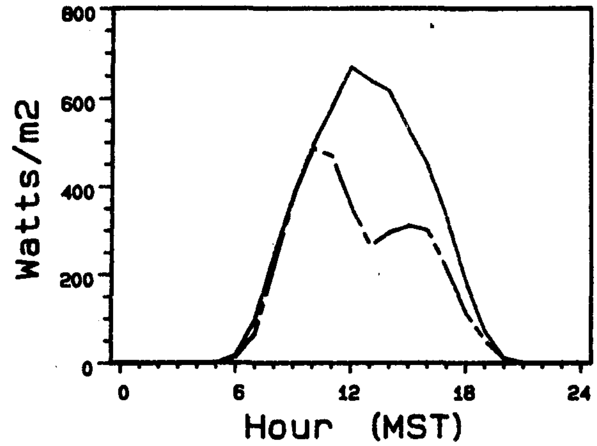


FIG. 7. Hourly averaged total downward solar radiation at Mt. Werner (solid line) and Squaw Mountain (dashed line) in W m^{-2}, for the period 9–31 July 1985.

observed. Cloudiness continues to decrease the incoming radiation at SQ until 1300 MST, after which the insolation remains fairly steady, although at substantially reduced values when compared with MW. This early and persistent cloudiness at SQ leads to a temperature maximum at 1200 MST and a 1400 MST maximum in precipitation frequency (not shown). The maxima of these parameters occur later at MW: 1500 MST for temperature and 1800 MST for precipitation. Earlier heating of the east slope relative to the west slope may account for some of this variation in cloud development between the two stations.

Hourly averaged lightning strike data for this 23-day period further demonstrate the characteristics of convective development. In Fig. 8a contours of lightning strikes between 1200 and 1300 MST, corresponding to the period of strongly decreasing insolation at SQ, are shown for the northern portion of the ROMPEX network. Lightning activity tends to be concentrated along the Front Range, with a relative maximum just north of SQ. Cloud shading effects from these storms are responsible for the low insolation values noted at SQ in Fig. 7. A band of heavy strike activity also extends westward from the Front Range following high terrain. Few strikes are noted in the vicinity of MW, in agreement with radiation data. A similar figure for 1800–1900 MST is given in Fig. 8b, showing that most of the active storms are now located west of the Front Range over the mountains and lower mesas of western Colorado. Considerable convective activity also occurs well to the east of the Front Range over the high plains of Colorado (not shown).

b. Convective influence on the regional-scale diurnal wind

Averaged diurnal wind cycles for the 9–31 July 1985 period at both SQ and MW (Fig. 9a) show a gradual morning transition from outflow to inflow between sunrise, at 0500 MST, and 1200 MST. This transition is followed by the steady inflow regime which is disrupted by an abrupt wind shift in the afternoon. Wind direction shifts over 100° at SQ between 1400 and 1500 MST from an easterly inflow to westerly outflow direction. An even more dramatic reversal from inflow to outflow (~135°) occurs at MW between 1700 and 1800 MST. The timing of this flow reversal was found by Bossert and Reiter (1987) to be highly correlated between the west slope stations of MW and Vail Mountain (VA in Fig. 2) for a 10-day portion of this July period, indicating the large horizontal extent of this effect. These sudden wind shifts were not apparent at either MW or SQ in the wind hodographs of Fig. 3, composed of days without significant convective storm activity. The corresponding diurnally averaged wind speeds (Fig. 9b) reveal a weak bimodal signature at both stations. Lowest speeds occur during the morning transition, followed by gradually increasing speeds during the daytime inflow phase. A brief decrease in velocity occurs with the inflow to outflow transition, followed by another gradual increase towards peak outflow speeds, which occur during the early morning hours at each station.

An evaluation of meteorological data from the MW station, encompassing 206 days over the four summers of 1984–1987, reveals that approximately 27 percent of the days experience sudden wind shifts from an inflow to outflow direction. These events are particularly recurrent with moist southerly to southwesterly flow which favors the development of strong convective storms. Following Betts (1984), thermodynamic data have been used to analyze a typical wind shift event which occurred at MW on 13 August 1986. This analysis (Fig. 10) is presented in the form of an equivalent potential temperature (θ_e) versus mixing ratio (q) diagram using hourly averaged data. Wind shifts usually occur in late afternoon at MW, and often exhibit gust front properties (Charba 1974), with a wind direction shift, gust surge, and temperature drop. In Fig. 10, heating and evaporation of surface moisture produce a linear increase in both thermodynamic quantities during the morning. Heating continues through midday, but the well-mixed properties of the airmass keep q constant. After 1400 MST, the effects of cloud cover and advection of drier air act to decrease both θ_e and q. Between 1600 and 1700 MST a large drop in θ_e occurs, without a significant increase in q. This trend continues, although with less amplitude, until 1800 MST. Drying of the airmass is noted after 1800 MST, with only a slight decrease in θ_e.

The change in θ_e between 1600 and 1700 MST signals the arrival of a convectively modified airmass advecting past the mountaintop (Betts 1982). Inspection of 15-minute data for this period shows that the wind shift from westerly to southeasterly occurred at 1545 MST. The southeasterlies ushered in the colder air that

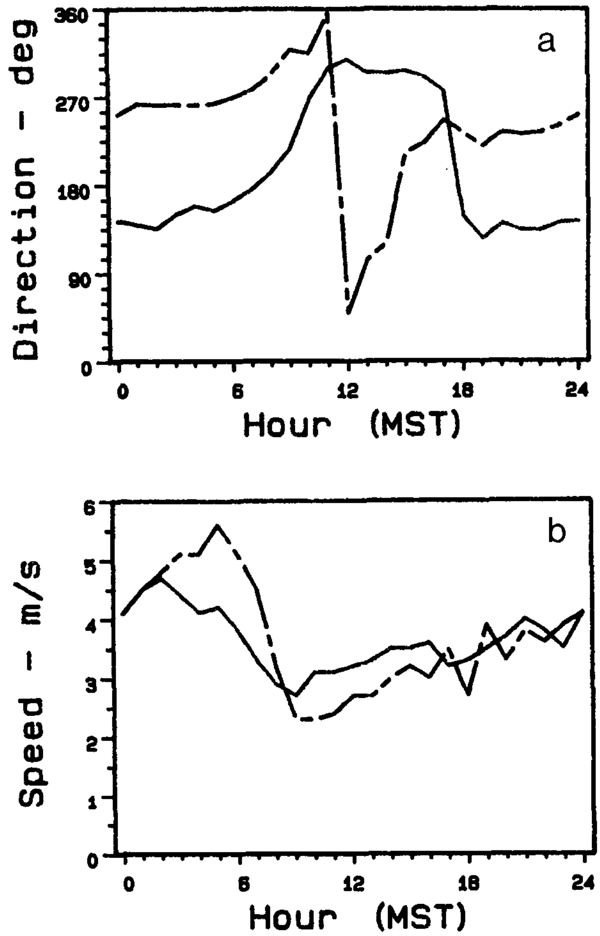


FIG. 9. Hourly averaged (a) wind direction and (b) wind speed at Mt. Werner (solid line) and Squaw Mountain (dashed line) for the period 9–31 July 1985.

initially arrived at 1600 MST. Lightning strike data show thunderstorm development in a line northeast to southwest of MW during this hour, with a brief shower at MW recorded at 1630 MST. The southeasterly winds reached 15-minute average speeds of 9 m s^{-1} at 1645 MST with gusts to 16 m s^{-1}, and persisted at speeds of 6–7 m s^{-1} until 0200 MST 14 August 1986, when a gradual transition to westerly flow began.

c. *Convective influence on the vertical structure*

Figure 11 shows a vertical sounding taken at 2300 MST 22 August 1987 from the valley site at the base

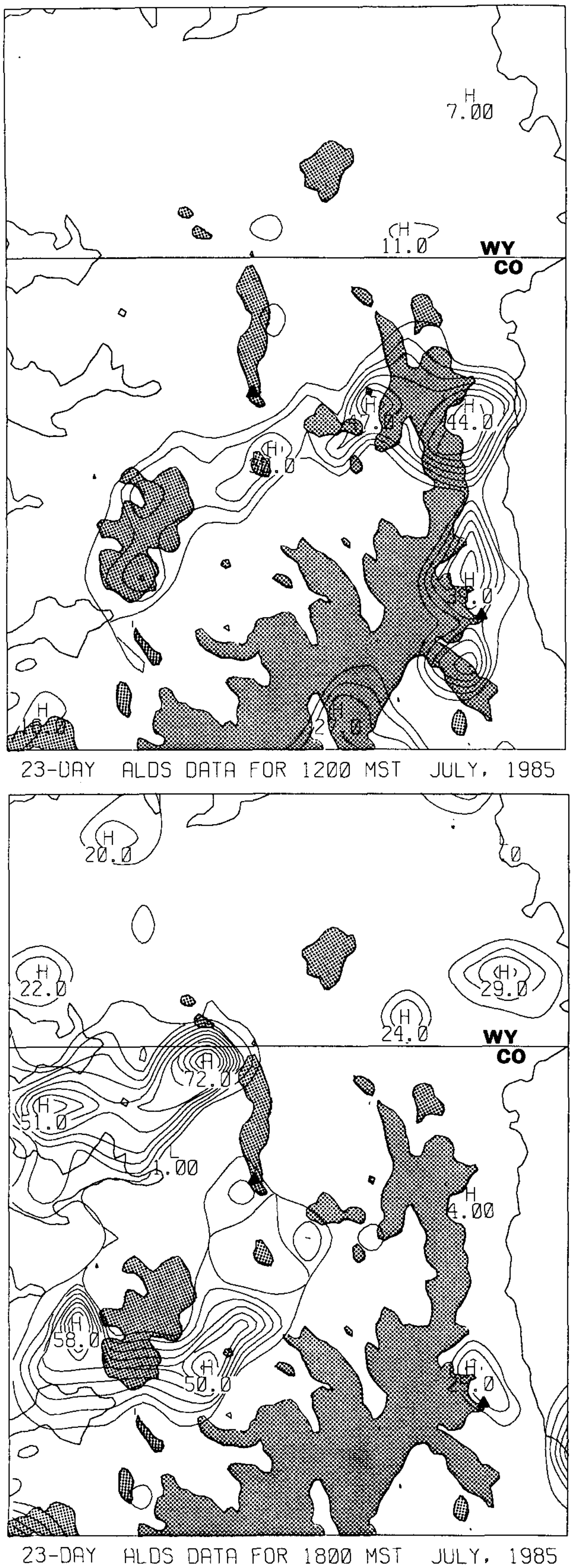


FIG. 8. Contours of total lightning strikes in each 0.167 degrees of latitude and longitude, for (a) 1200–1300 MST and (b) 1800–1900 MST 9–31 July 1985. Contouring begins at 10 strikes per 0.167 degrees, with a 5 strike interval thereafter. Geographic region is identical to Fig. 1, and triangles denote the Mount Werner and Squaw Mountain stations. Topographic contours are 2000 msl and 3000 msl.

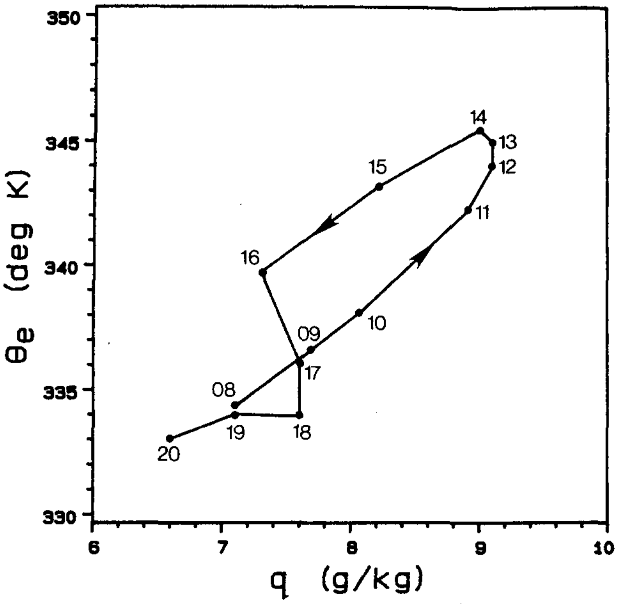


FIG. 10. Hourly averaged values at Mt. Werner of equivalent potential temperature versus mixing ratio for the labeled hours of 0800–2000 MST 13 August 1986.

of MW. The sounding represents conditions approximately 6 hours after the abrupt onset of southeasterly outflow winds at MW, associated with regional afternoon thunderstorm activity. The vertical profile shows light and variable winds with a surface-based inversion of 5°C between 2010 and 2500 m MSL. Above the inversion, deep southeasterly outflow prevails through an 1800 m layer which has a nearly constant stable stratification of 0.3°C/100 m. The outflow reaches a maximum speed of 8 m s^{-1} near ridgetop (~3100 m MSL). Winds at the MW station during this sounding were from the southeast at approximately 6 m s^{-1}. The outflow layer appears to be the result of convective modification of the subcloud layer. Other soundings launched in post-convective conditions have exhibited a similar vertical structure.

5. Discussion

The data analyses have emphasized the distinctive characteristics of regional-scale flows due to radiative (thermal) and latent (convective) forcing. Of course on many days when these flows are observed, we expect to find a significant contribution from both of these diabatic processes. In this section we further examine each process separately, however, in order to highlight the physical differences associated with each type of forcing mechanism.

The prolonged transition from inflow to outflow and later onset of outflow winds associated with radiative forcing stands in marked contrast to the abrupt wind

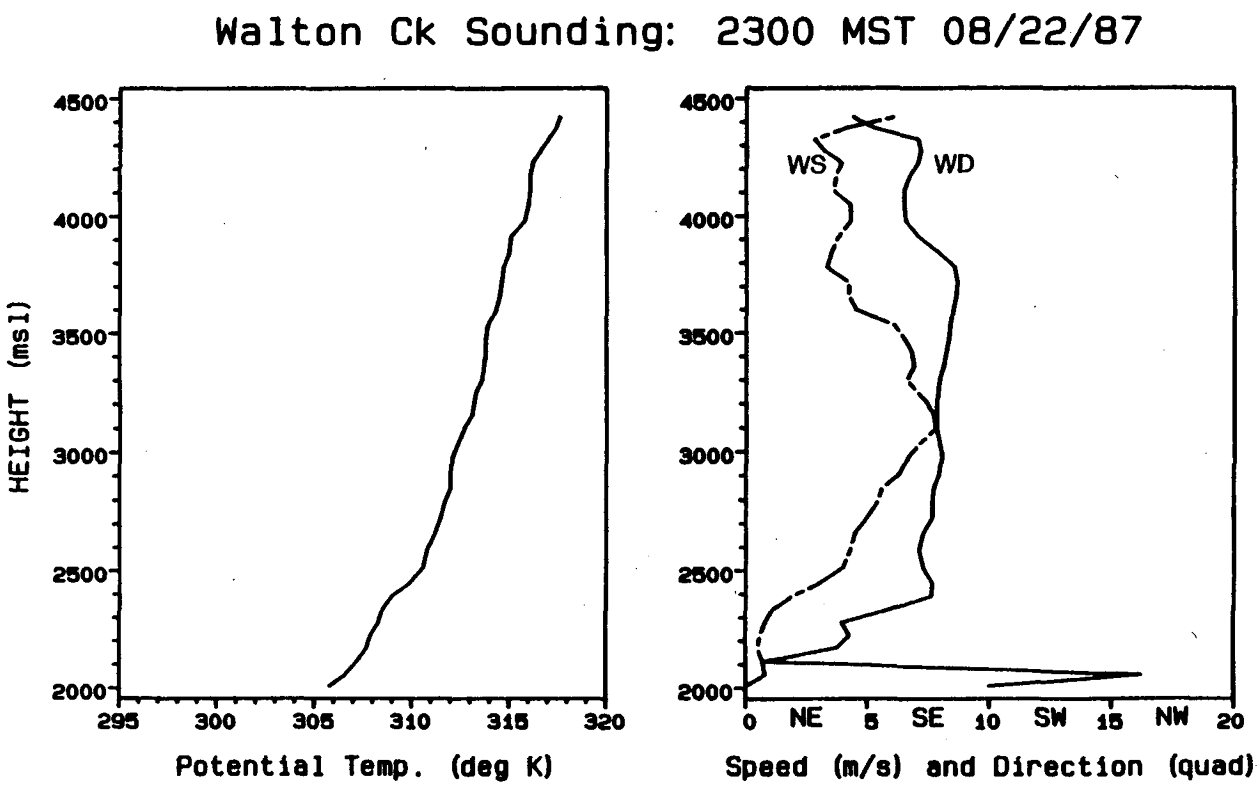


FIG. 11. Vertical sounding of potential temperature, wind speed, and wind direction from Walton Creek, Colorado (elev. 2010 m) at 2300 MST 22 August 1987.

transition noted on highly convective days. The vertical soundings taken in clear, dry conditions (Figs. 5 and 6) show that regional-scale nocturnal outflow occurs within a shallow stratified layer at the mountaintop level, above a deep, radiatively induced stable layer in the surrounding valleys. The explicit physical processes controlling the evolution of this distinctive outflow layer at mountaintop await further observational and numerical study. Bader et al. (1987) have reported that shear-induced upward mixing of colder air from near the surface can produce a deep (800 m) stable layer within a 4-hour time period, well within the average transition time between the regional-scale daytime and nocturnal flow regimes noted in section 3b. This type of turbulent mixing process may be important in producing a stable layer deep enough to allow outflow to be observed at mountaintop. Due to the complexity of the terrain and wide variety of upper-level flow conditions over the ROMPEX study area, however, many additional factors are undoubtedly important in the generation of these rather systematic outflows.

The development of regional-scale outflows under highly convective conditions differs from that shown for thermal forcing. In northern Colorado, initial convective storm development occurs primarily over the Front Range. This initial phase is often followed by the dissipation of these storms and the redevelopment of active convection toward the east and west (see Fig. 8). This sequence of diurnal convection has been shown to produce an abrupt transition in regional-scale circulation patterns (Fig. 9). An important process within this convective cycle is the evaporation of precipitation and unsaturated downdrafts (Leary 1980; Knupp 1987) from thunderstorms over the high terrain, which can produce a rapid transformation of the subcloud layer. Through this process a stable, cold airmass is generated that has a strong thermal contrast with the undisturbed, well-mixed boundary layer air. As this modified airmass moves down the terrain gradient on both the west and east slopes, it could be an important forcing mechanism in the regeneration of storm activity away from the high terrain, which will further modify the boundary layer airmass. The thermodynamic characteristics of such an airmass are consistent with those detailed in Fig. 10, which occurred with the sudden shift in wind regime at MW.

Propagation of convective storms eastward from the Front Range toward the high plains has been described by Cotton et al. (1983) and simulated with a sophisticated mesoscale model by Tripoli and Cotton (1989a,b). These studies indicate that the details of storm propagation away from the high terrain of Colorado are quite complicated. At present we lack sufficient observational data to discuss the storm propagation process in detail, particularly on the western slope of the mountain barrier. The observations presented herein, however, indicate that outflow from deep convection forces the abrupt flow reversal between diurnal regimes, as shown in Fig. 9. The persistence of this outflow regime long after the cessation of convective storm activity (see discussion of Figs. 9 and 10) is a frequent occurrence. The production of the convectively modified layer in the latter stages of the diurnal heating cycle, when the energy available for turbulent destruction of the airmass is greatly reduced, appears to be an important factor in the duration of these outflow events.

One final aspect of this paper involves separating the regional-scale nocturnal outflow regime from flow of synoptic origins. This distinction can be illustrated with data from MW and WP, two stations within the same outflow region. Winds at these two sites tend to be highly correlated, particularly during periods of strong nocturnal outflow. The elevation of MW is 125 m higher than WP (25 km to the southeast) and hence the potential temperature difference between the two exposed mountaintop sites provides a first approximation of the low-level, regional-scale thermal stratification. Figure 12 shows the potential temperature difference between MW and WP during periods of strong nocturnal flow as a function of hourly averaged wind direction at WP. Two prominent wind regimes are observed with strong speeds at WP. The most recurrent regime is from the south, and exhibits strong thermal stability, averaging 2°C cooler at WP than at MW. The unidirectional nature and large number of points within this stable outflow regime at WP attests to its persistence under widely varying synoptic conditions.

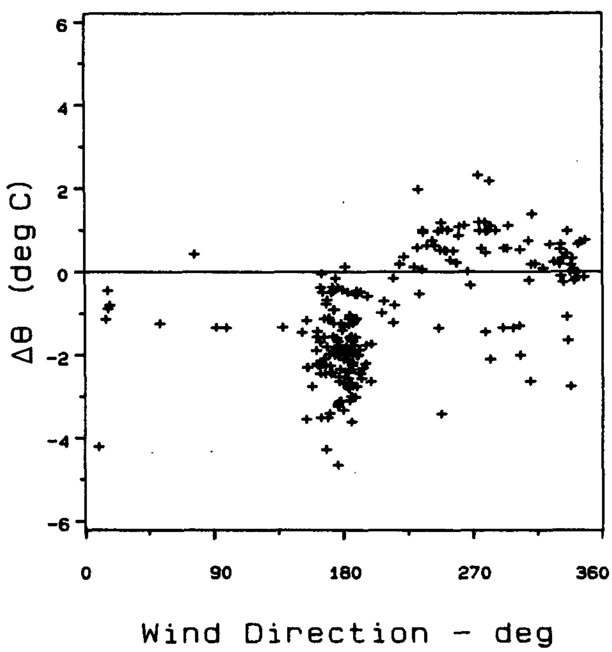


FIG. 12. Potential temperature difference between Whiteley Peak (WP) and Mt. Werner (MW) (WP − MW), versus wind direction at WP for hourly averaged data from 2100–0500 MST 9 July–10 September 1987 with wind speeds at WP of 5 m s^{-1} or greater.

In contrast to the southerly outflow, the other recurrent nocturnal regime at WP with strong velocities is from the southwest to northwest, and reveals a neutral to slightly unstable vertical profile between the two stations. This distinctive change in thermal stratification, depending upon wind direction, illustrates the differences in atmospheric structure between stable southerly nocturnal outflow and neutral westerly flow of synoptic origins.

6. Conclusions

Data collected over four summers (1984–1987) at mountaintop locations in Colorado have demonstrated the presence of recurrent circulation features forced by the diurnal cycle of solar heating and longwave cooling of the mountain-to-plain slope. These regional-scale flows are readily observable in the time-averaged diurnal wind cycles at mountaintop, particularly during periods of weak synoptic forcing. The response of the wind cycle to this forcing consists of convergent daytime inflow toward the north–south oriented mountain barrier, and divergent nocturnal outflow in a layer extending well above localized valley flows.

The cycle of convective storm development and collapse is closely associated with the inflow and outflow phases of regional-scale circulation patterns. Lightning strike data indicate the movement of convective activity both eastward and westward from its origins over the Colorado Front Range. Abrupt transitions between the daytime inflow and nocturnal outflow occur regularly during days when widespread, strong thunderstorms develop and move outward from the high terrain. The thermodynamic characteristics of the airmass associated with these sudden transitions show evidence of significant modification from convective processes. In contrast, days without this moist convective component have more gradual transitions between diurnal regimes.

Atmospheric soundings taken within the higher terrain areas indicate that significant differences may exist in the vertical profile of the topographically influenced layer when either convective or radiative forcing dominates. In the convectively modified environment, deep outflows with a nearly constant vertical stratification have been found above a weaker surface-based inversion. Comparatively dry radiative conditions produce a more layered atmosphere with strong decoupling of regional-scale flow from surface-based influences. The observations reported here have attempted to more clearly define various aspects of regional-scale winds. Knowledge of these wind systems is an important component in the study of transport processes in complex terrain, and is of fundamental importance to understanding the hierarchical structure of terrain-induced flows.

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