Summer Surface Flow Characteristics over Northeast Colorado

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ABSTRACT

Surface wind data from the Program for Regional Observing and Forecasting Services (PROFS) have been analyzed to investigate the diurnal wind flow pattern over the broad drainage area of the South Platte River in northeast Colorado. A consistent diurnal pattern appears in monthly averages as well as on most undisturbed individual days, and is similar to the classic descriptions of mountain–valley wind flows. It is observed that rather than occurring simultaneously at all elevations, downslope-to-upslope and upslope-to-downslope surface flow transitions along the Front Range of northeast Colorado begin near the foothills of the Rocky Mountains and propagate eastward across the plains.

During the summer months, local confluence is found at midday along major east–west ridges in the region (e.g., Cheyenne Ridge and Palmer Lake Divide). Consequently, in addition to the north–south Continental Divide, these east–west ridges are preferred regions for initial afternoon thunderstorm development. The late afternoon transition to downslope flow often appears to be associated with the propagation of thunderstorms from the mountains and ridges eastward to the plains.

1. Introduction

The mountains of the western United States, as well as the sloping Great Plains to the east, interact with the atmosphere on a wide range of horizontal scales. Establishment of the Program for Regional Observing and Forecasting Services (PROFS: Beran and Little, 1979; Reynolds, 1983) in northeast Colorado has provided new sources of data, useful for studying the development of weather systems at and near the interface between the mountains and the plains. This area includes the PROFS surface mesonetwork, which extends eastward from the Continental Divide ~150 km into the plains. Here we focus on the normal diurnal flow development over the PROFS region. The persistence of a diurnal upslope–downslope pattern, particularly during the summer months, has motivated the composite, climatological approach adopted in this study.

Recently, several mesoscale case studies (Smith and McKee, 1983; Schlatter *et al.*, 1983; Johnson *et al.*, 1984; Szoke *et al.*, 1984) have utilized data from the PROFS mesonet. Szoke *et al.* also discuss the frequent development of a surface convergence-vorticity zone centered near Denver (DEN, Fig. 1) when south to southeasterly gradient winds exist over the area. This zone, which often takes the form of a closed circulation, appears to be caused by terrain blocking, although the precise causal mechanism awaits further investigation. Our analysis suggests that, while the composite flows we present may include this cyclonic circulation to some extent, the diurnal variations in the composite flows are caused primarily by terrain heating.

The diurnal wind evolution in a mountain valley has been summarized by Defant (1951). He identifies two interrelated systems of wind flow: the slope winds, on a scale considerably smaller than the along-valley dimension; and a larger-scale mountain–valley wind. Although such a valley is often considered to have horizontal dimensions of only several kilometers, the same model can be applied to the larger-scale PROFS region. On this larger scale, the valley is the entire South Platte River basin (Fig. 1), enclosed by the Cheyenne Ridge to the north, the Palmer Lake Divide to the south, and the Continental Divide to the west.

Banta (1984) defines a third wind regime over South Park, Colorado, a broad mountain-surrounded basin approximately 100 km southwest of the PROFS area. In addition to the upslope and downslope flows described earlier, a convective mixing regime develops during the late morning. This latter flow feature occurs on the east-facing mountain slopes and is a consequence of westerly ridge-top winds mixing down to the surface. A leeside convergence zone forms as the convectively mixed westerly winds meet the easterly upslope winds. The convergence zone moves eastward and eventually the upslope regime is eliminated.

In relating the convective mixing regime to flows observed in the PROFS region, several differences between the PROFS area and South Park should be noted. South Park extends east–west ~50 km, with mountains on both sides, whereas the PROFS area extends east–west in excess of 100 km, with mountains only on the western side. South Park is about 1 km higher than the lowland PROFS stations, and so the peak-to-valley

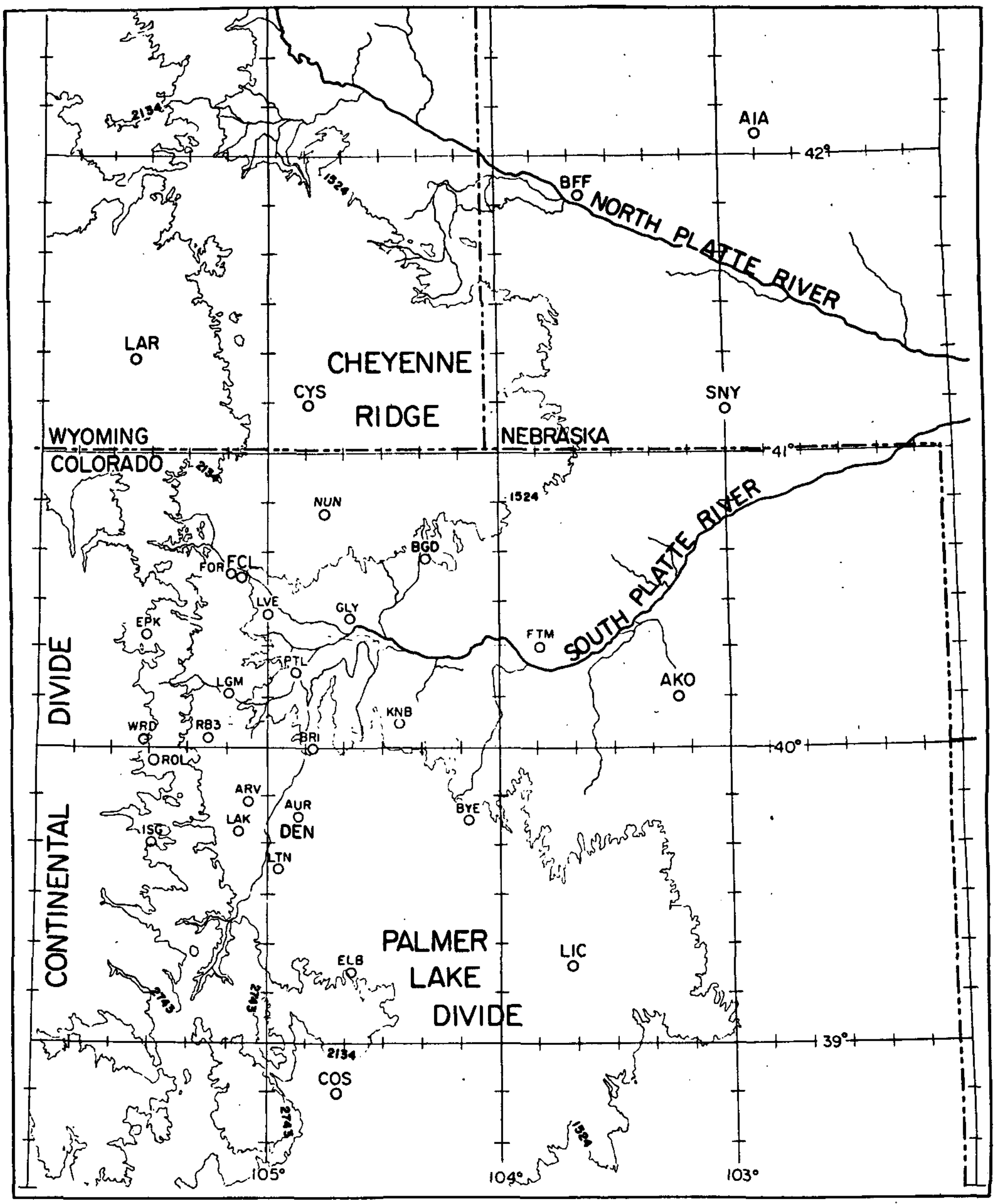

FIG. 1. PROFS mesonetwork stations (small letters) and surrounding conventional stations (large letters). Major geographical features are identified. Elevation contours are in meters (1524 m = 5000 ft, 2134 m = 7000 ft, 2734 m = 9000 ft).

elevation difference is ~2 km over the PROFS mesonet vs ~1 km over South Park. Nevertheless, it will be shown that a similar convergence zone usually develops within the PROFS area (although at a later time), and its possible relationship to the convective mixing regime will also be discussed.

Until recently, the PROFS mesonetwork data provided only surface information. Analysis of data from the newer network of vertical Profilers (Hogg *et al.*, 1983) should in the future provide valuable information on the vertical structure of the diurnal circulation. The vertical structure of the boundary layer in the western portion of the PROFS region is now being continuously sampled by the Boulder Atmospheric Observatory (BAO) 300 m meteorological tower near Erie, Colorado (Kaimal and Gaynor, 1983). Valuable information, such as the depth and characteristics of natural drainage flows (Hahn, 1981; Hootman and Blumen, 1983), has been obtained from the BAO tower, which can be coupled with observations of mesoscale circulations in the PROFS area.

Information on the vertical structure of the diurnal wind flow over the remainder of the PROFS area has been limited to rawinsonde data available routinely and in connection with special field experiments. Dirks (1969) composited upper air soundings from Denver as well as from stations east of Colorado. Based on this analysis and on numerical simulations, he proposed a two-dimensional, two-celled, daytime circulation over the plains. Upslope flow develops near the Continental Divide, reversing direction near mountain top level, leading to a subsidence area approximately 100 km east of the Continental Divide. Further east, a weaker but more extensive circulation cell develops over the slightly sloping plains. In his numerical simulations, Dirks found that surface flows of a few meters per second developed over the plains, while an unrealistically large 20 m s^{-1} flow developed near the Continental Divide.

Modahl (1979) composited upper air soundings obtained by the National Hail Research Experiment, conducted near Briggsdale (BGD, Fig. 1). He shows a diurnal oscillation of the east–west component of the wind with amplitude ~1 m s^{-1} from the surface through mean cloud base (200 mb above the surface). On hail days, the diurnal amplitude at the surface is roughly twice as large, but the amplitude at mean cloud base shows little change.

Some regional surface flow studies in the Denver area have been carried out in recent years, many for the purpose of examining air pollution problems in that urban area (e.g., Riehl and Herkhof, 1972; Haagenson, 1979). The PROFS data provide information on a considerably larger scale that are potentially of great value in assessing pollution impacts in the South Platte River drainage basin of northeast Colorado.

The effects within Colorado of the diurnal wind pattern on summer moist convection have been examined through composite studies of radar data (Wetzel, 1973; Henz, 1974; Karr and Wooten, 1976) and satellite data (Klitch *et al.,* 1985). All these studies point out that 1) on most days there is a progression of showers from the mountains to the plains, and 2) there are preferred locations for convective development, particularly along the east–west ridges that jut into the plains (Fig. 1). Cotton *et al.* (1983) have documented the evolution of convective precipitation cells as they move from the mountains of South Park across the foothills toward the high plains. The results reported in this study will highlight the important relationship between the diurnally varying boundary-layer flows and convective activity. We will also discuss possible interactions between terrain heating effects and the convergence zone described by Szoke *et al.* (1984).

2. Data and analysis procedures

Data for the summer of 1981, and for portions of July of 1982 and 1983 have been analyzed. Only the July 1981 mean flows will be presented.

a. Surface data

The PROFS surface mesonetwork consists of 21 automated stations at variable density tending to correspond to the population density of northeast Colorado. A map of these stations (small letters) and surrounding conventional stations (large letters) is shown in Fig. 1. All mesonet stations are within a 100 km radius of station BRI (Brighton). Note that the surface terrain variations over the plains are dominated by features on the scale of ~100 km.

A listing of the surface stations, identifiers, and elevations is provided in Table 1. The mesonet includes mountain stations [EPK, WRD, ROL, ISG] and ELB (near the crest of the Palmer Lake Divide) which range from 2146 m to 3505 m. The remaining 16 mesonet stations, which will be referred to as the lowland stations, are at 1615 ± 245 m. It should be noted that mesonet station BGD was not installed until November 1981. The surrounding National Weather Service (NWS) stations range from 1206 m at BFF (Scottsbluff, Nebraska) to 2217 m at LAR (Laramie, Wyoming).

The following observations are available from the mesonet stations every five minutes: total amount of

TABLE 1. Station identifiers and elevation.

Identifier	Name	Elevation (m)
	PROFS *mesonetwork stations*	
ARV	Arvada	1643
AUR	Aurora	1625
RB3	Boulder	1609
BGD	Briggsdale	1483
BRI	Brighton	1518
BYE	Byers	1554
ELB	Elbert	2146
EPK	Estes Park	2377
FOR	Fort Collins (Foothills Campus)	1609
FTM	Fort Morgan	1372
GLY	Greeley	1414
ISG	Idaho Springs	3505
KNB	Keenesburg	1521
LAK	Lakewood	1832
LIT	Littleton	1750
LGM	Longmont	1533
LVE	Loveland	1512
NUN	Nunn	1634
PTL	Platteville	1457
ROL	Rollinsville	2749
WRD	Ward	3048
	Conventional stations	
AKO	Akron	1421
BFF	Scottsbluff	1206
COS	Colorado Springs	1856
CYS	Cheyenne	1865
DEN	Denver (Colocated with AUR)	1625
FCL	Fort Collins (Main Campus)	1525
LAR	Laramie	2217
LIC	Limon	1695
SNY	Sidney	1313

precipitation; average, maximum, and minimum values of temperature, dewpoint, wind speed and direction; station pressure; insolation; and (at some stations) visual range. We will present only wind analyses using the average wind for the five minutes preceding each hour. The wind speed and direction are averaged independently from 30 samples taken during the five-minute period, with the wind direction treated as a unit vector; hence, the five-minute average wind is not a resultant wind (Panofsky and Brier, 1968), although in most instances it is probably very close to it.

To enable documentation of the flow field beyond the PROFS mesonetwork, observations from manned stations (LAR, CYS, BFF, SNY, AKO, LIC, COS) have been included when available. Generally, hourly observations are recorded. Some stations report every three hours; others close at night. The reported winds at these stations are subjective, one-minute averages.

b. Analyses procedures

For July 1981, the mesonet data were available in hard copy format only. The winds at each hour were vector-averaged (resultant wind), following the removal of observations with wind speeds greater than two standard deviations from the mean. The intent of this procedure was to exclude from the averages anomalous wind events such as thunderstorm wind gusts, etc. The occurrence of strong wind events in the data sample was rare, and analyses with and without application of the removal procedure are virtually identical.

Our average flows include contributions from the diurnal component of the wind as well as from mean gradient winds. For July 1981, the averaging procedure reduces the gradient wind component to a small contribution (with the exception of a southerly gradient wind at the easternmost stations: LIC, AKO, FTM) in comparison to the large diurnal component.

We have found subjective streamline analyses of the average winds to be the most effective way to present the data. (Wind roses provide more information for a single station, but are awkward for presenting the flow over the entire PROFS region.) Where stations are widely separated, we have analyzed for a flow consistent with upslope and drainage winds. The divergence ($\partial u/\partial x + \partial v/\partial y$) of the average wind over the lowland area was calculated from an evenly spaced (20 km) grid obtained using a bi-cubic spline subroutine fitted to the average u-component and v-component of the wind (each component independently) at each station.

3. Summer climatology

Our initial analyses (Johnson and Toth, 1982) were done for the month of July 1981. Later analyses of the diurnal flow for other periods are very similar to our results for this particular month. In Fig. 2, the mean surface flow at 3-hour intervals is shown. Maps on many individual days look like those shown for July. For reference, the reader should note that for July the average sunrise is at 0445 MST and sunset at 1930 MST.

During the early morning hours (0200, 0500 MST, Figs. 2a, b, respectively) there is flow off the Cheyenne Ridge and Palmer Lake Divide into the river basins to their north and south, consistent with drainage flow into a broad valley. During this period, a confluent flow exists along the South Platte River basin and maintains the same general character with only minor variations. (A reviewer has suggested blocking of a large-scale southerly flow by the Palmer Lake Divide as an alternative explanation for the northerly wind at COS. Although blocking effects are certainly present, we believe the flow there can be primarily attributed to drainage off the higher terrain to the north.) Data from PROFS provide no information on the depth of the surface drainage flow over the region. However, some information on its vertical structure may be obtained from the studies by Hahn (1981) and Hootman and Blumen (1983). Based on an analysis of BAO tower data from September 1978, Hahn determines that the nocturnal drainage flow near Erie, Colorado (approximately halfway between RB3 and BRI in Fig. 1) is generally confined to a depth of 100 m. A mapping of the vertical structure of the drainage flow over the entire PROFS region clearly requires further observational study.

By 0800 MST (Fig. 2c), weak upslope flow begins in the western part of the network, consistent with the effects of insolation on the east slope of the Continental Divide. Surface upslope flow has been generated over much of the region to the west of Denver (DEN) (not at the highest stations, however), while downslope flow persists to the east over most of the east–west ridges. By 1100 MST (Fig. 2d), upslope flow has developed over nearly the entire region, finally extending by 1300 MST to the level of the highest stations. Upslope flow over most of the region continues through 1400 MST (Fig. 2e). By 1600 MST, there is an indication of a reversal to downslope flow at several of the westernmost stations (not shown). This reversal extends to the foothills stations by 1700 MST (Fig. 2f) with westerly flow meeting easterly flow along a north–south line near Denver's longitude. The confluence line marking the onset of downslope flow progresses eastward for the next ~4–5 hours (Fig. 2g). The transition zone often becomes diffuse and difficult to track once it passes KNB. The typical drainage flow pattern returns over the western stations by late evening (Fig. 2h); however, a mean southerly flow still prevails at this time at the easternmost stations. It may be that the transition zone is in the vicinity of FTM at 2300, but, if so, its position is difficult to determine from the July-average mesonetwork winds. Drainage flow becomes well established at the eastern stations over the next 1–4 hours.

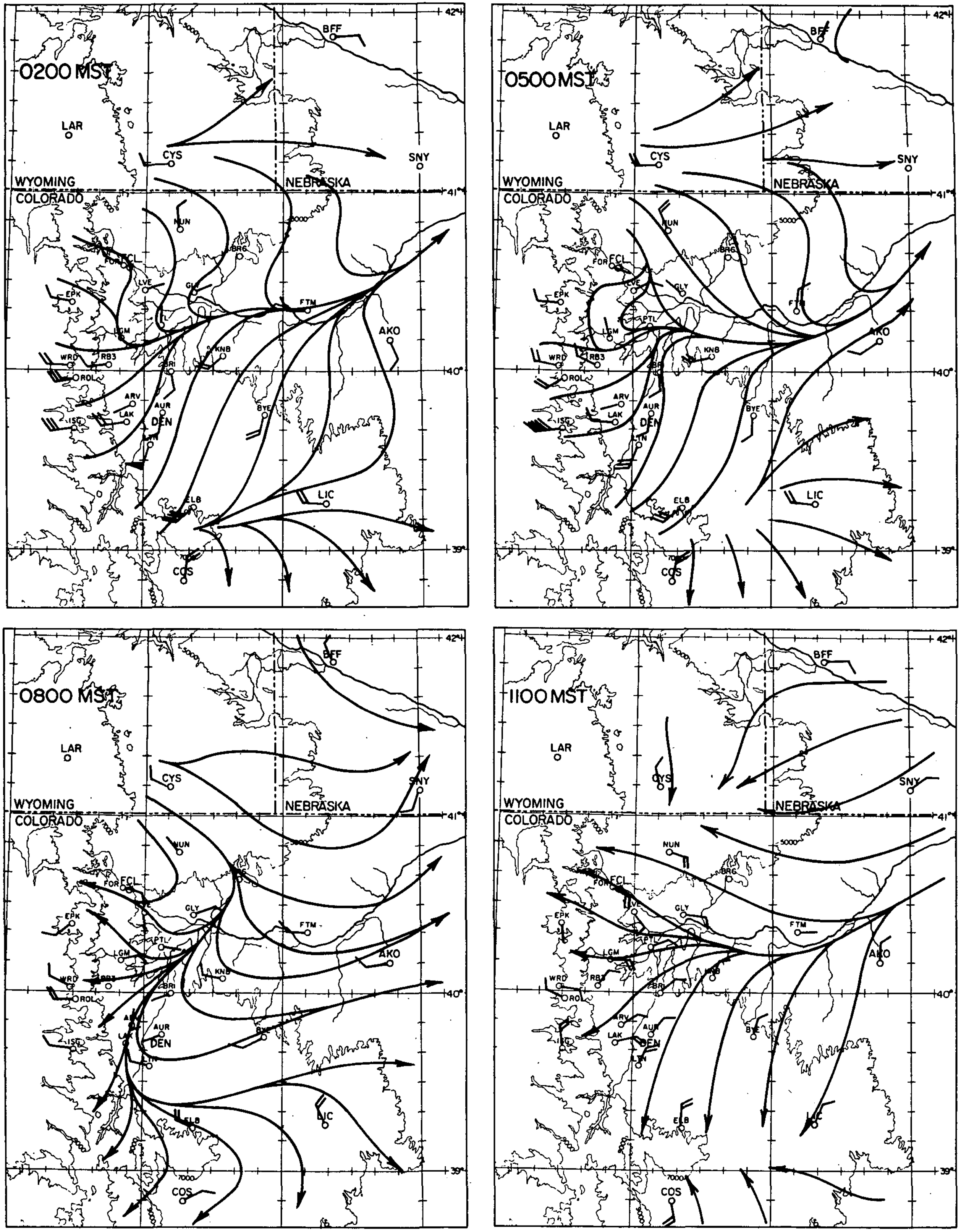

FIG. 2. Surface streamline analyses for July 1981 (a) 0200 Mountain Standard Time (MST) (b) 0500 MST (c) 0800 MST (d) 1100 MST (e) 1400 MST (f) 1700 MST (g) 2000 MST (h) 2300 MST. Plotted winds are in meters per second (one full barb = 1 m s^{-1}).

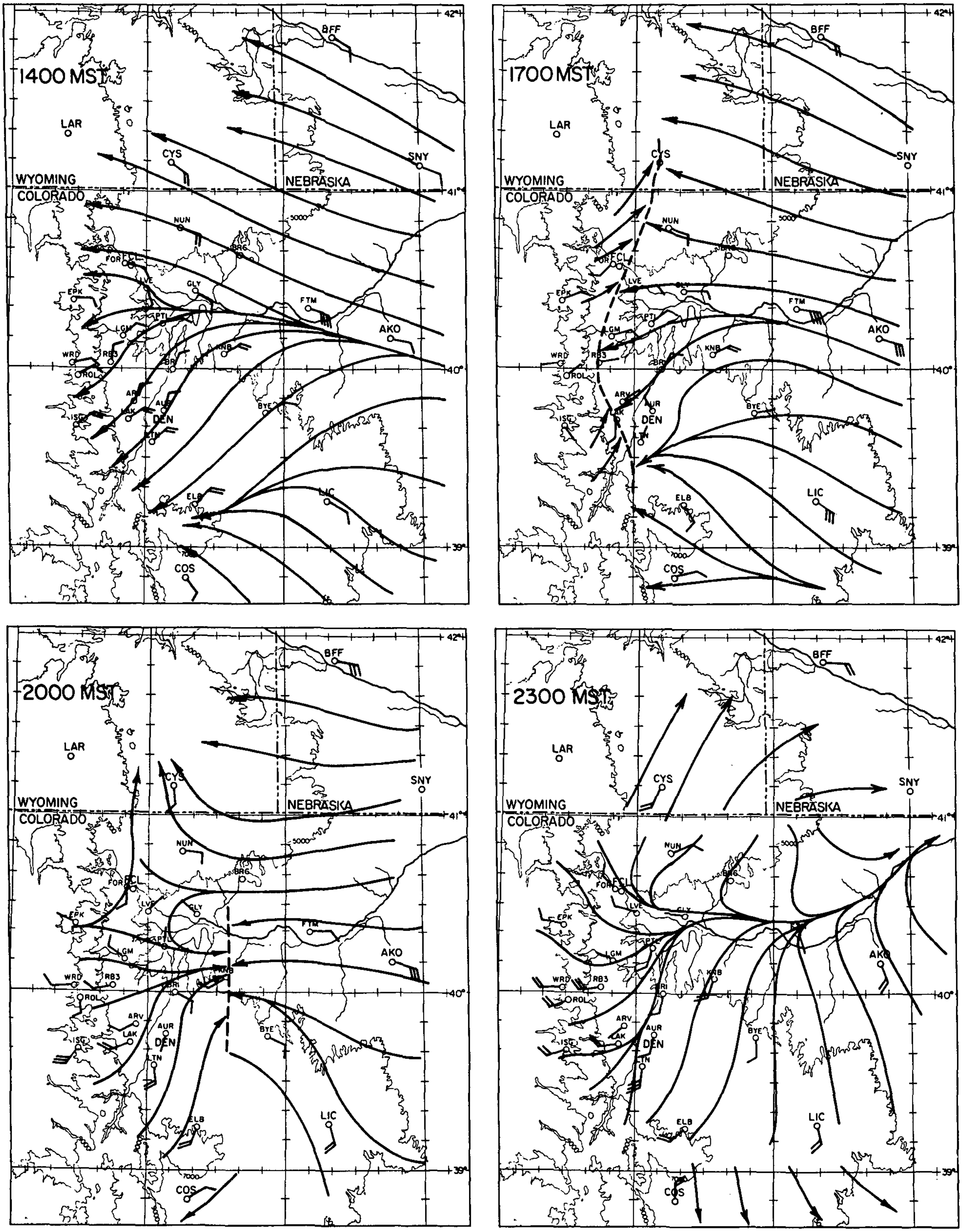

FIG. 2. (*Continued*)

An interesting character of the transition between downslope and upslope flows emerges from the results of this study. From the full hourly sequence of analyses, we find along the front range of eastern Colorado that rather than occurring simultaneously at all elevations, the downslope-to-upslope and upslope-to-downslope transitions begin at the foothills of the Rocky Mountains and propagate eastward toward the plains. The period of time for the transition from downslope to upslope during July mornings is ~3 h and from upslope to downslope ~4–5 h. This pattern is seen not only in the July composite, but on most individual days.

The beginning of the transition periods, however, varies from day to day and also in the composites calculated for other summer periods. This timing variation implies that a particular station's wind at the transition time has a bimodal character, i.e., on some days there is upslope, on others there is downslope flow. Furthermore, no particular significance should be attached to the direction of the very light winds at the transition zone.

The upslope-to-downslope transition (convergence zone) during the summer months is complicated by the effects of deep convection present at that time on most days. There also may be interactions with other convergence zones. Szoke *et al.* (1984) discuss the frequent presence of a convergence zone, sometimes accompanied by a cyclonic circulation, over the lowland region (generally west of BYE) and its impact on convective storms. The exact way in which the terrain generates this feature has not been determined. It is probably due to blocking of synoptic scale southeasterly winds by the Palmer Lake Divide and Continental Divide.

Circulations associated with terrain heating also contribute to a cyclonic circulation northeast of DEN (Figs. 2d–f). This cyclonic turning arises from the combined effects of the mountain–plains circulation and the Palmer Lake Divide upslope flow. The mean flow contributes to surface divergence out of the South Platte valley over the lowlands west of BYE (a rectangle having NUN, BYE, ELB and RB3 on its boundaries) from 0800–1400 MST (Table 2). The convergence zone analyzed within this area on many summer days by Szoke *et al.* (1984) is not reflected in these valley-scale July averages, at least prior to 1400 MST (Table 2). Convergent flow over the lowlands into the South Platte Valley increases during the late afternoon and early evening hours, reaching a peak during the late night and early morning hours, as can also be seen in Figs. 2h, 2a, and 2b.

The impact of small-scale convective circulations on the mean flow field can be inferred by considering the persistence of the wind. The persistence is defined as the speed of the resultant wind divided by the mean wind speed (Panofsky and Brier, 1968). In Fig. 3, the average persistence for all four mountain stations and for all sixteen lowland stations has been plotted at each hour of the day.

TABLE 2. Average surface divergence ($\times 10^{-5}$ s^{-1}) for the lowland region west of BYE (as described in text).

Hour (MST)	Divergence	Hour (MST)	Divergence
00	−3.2	12	+1.2
01	−3.5	13	+1.6
02	−3.5	14	+0.9
03	−3.6	15	−0.3
04	−3.4	16	−0.3
05	−2.6	17	−1.0
06	−2.2	18	−1.2
07	−0.9	19	−1.8
08	+0.9	20	−1.7
09	+1.4	21	−2.0
10	+2.0	22	−3.1
11	+2.1	23	−2.5

The persistence is higher at night for both station categories. The lower persistence during the daylight hours is probably a consequence of 1) boundary layer dry convection (e.g., thermals), and 2) daytime cloudiness and thunderstorm activity. In addition to the lower persistence during the day, the upslope–downslope transitions near sunrise and sunset are characterized by a very low persistence due to the bimodal nature of the transition-time winds. This combined daytime period of low persistence is fairly narrow for the mountain stations. Over the lowlands, a maximum in persistence appears near noon, just before convection begins moving from the mountains to the lowlands.

Another distinct feature in Fig. 3, the much larger increase in persistence at the mountain stations at night (to near 0.9), can be explained by two factors. First, two of the mountain stations (EPK and WRD) are located in high valleys where the nocturnal downslope flows are highly persistent and well-shielded from the weak synoptic-scale disturbances of summer. In addition, the other two mountain stations (ISG and ROL) are near peaks which are well exposed to the midlevel (700 mb) winds. These winds are also highly persistent in summer, as evidenced by the early morning (0500 MST) Denver sounding (persistence of 0.73 at 700 mb for the July 1982 period).

Averaged over the entire mesonet for all hours of the day, the persistence is low compared to studies of diurnal flows in areas dominated by persistent surface synoptic patterns (e.g., Skibin and Hod, 1979). The surface synoptic pattern in the PROFS area, even during the summer, is not highly persistent. Also, frequent afternoon and evening thunderstorms lower the persistence. In this area, the differences in persistence between the wind regimes and between the two distinct station areas (mountain vs lowland) are significant, and need to be kept in mind when interpreting the results. Although the persistence is low, the upslope and

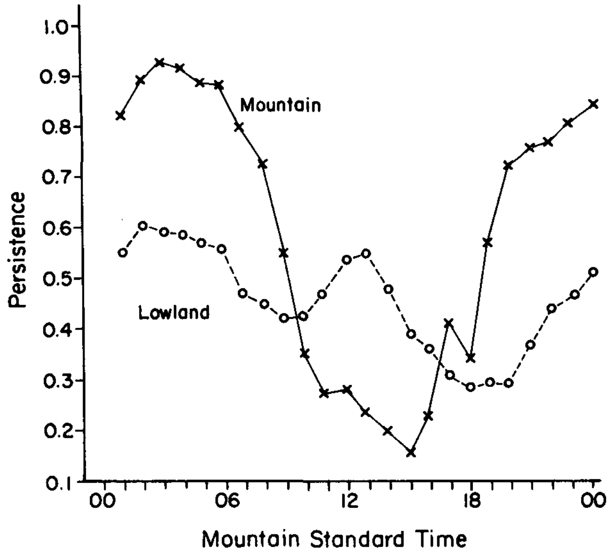

FIG. 3. Average persistence of the wind for each hour. The average for the 4 mountain stations is indicated by an "x", and for the 16 lowland stations by a circle.

downslope patterns (away from the transition periods) are extremely consistent from month to month and year to year (Toth, 1983).

Wind hodographs provide additional insight into the diurnal evolution of the flow. Selected hodographs for four stations are presented in Fig. 4. Corresponding hourly persistences for the four stations are shown in Table 3. The persistence is extremely low when the mean wind speed is <1 m s^{-1}. Conversely, the persistence is generally >0.5 when the mean wind speed is >2 m s^{-1}. Several stations, particularly those in the southern portion of the South Platte River Basin (LTN and ELB in Fig. 4), have a prominent clockwise rotation of the wind vector with time. In the Northern Hemisphere, clockwise turning is to be expected because of the Coriolis force. On the other hand, counterclockwise rotation requires a horizontal forcing that turns counterclockwise with time (Kusuda and Alpert, 1983; Mass, 1982). The only well-defined counterclockwise rotation is at FTM, (one of the stations north of the South Platte River in Fig. 4), and even then for only part of the day. Other stations near the Cheyenne Ridge (e.g., NUN, Fig. 4) and to the north of the South Platte River, although not actually counterclockwise, do have a much reduced clockwise rotation.

The behavior of the hodographs suggests that the flow evolves similarly to a typical mountain valley. Initially, upslope flow develops towards the Cheyenne Ridge and the Palmer Lake Divide, and then later the flow turns more toward the Continental Divide. The counterclockwise rotation of the wind associated with this thermal forcing north of the South Platte competes with clockwise Coriolis turning and yields narrow, elongated hodographs. On the other hand, the clockwise turning of both effects to the south of the river basin produces more open or oval-shaped hodographs at the southern stations. It is clear from the hodograph presentation that the amplitude of the diurnal wind oscillation varies considerably from station to station. This variation is likely a consequence of differing station siting and local terrain characteristics, in addition to the variable net wind forcing described previously.

Attempts to stratify the average pattern according to various synoptic situations met with little success. The average diurnal flow was determined for July specifically because strong synoptic forcing is relatively infrequent during that month. The diurnally varying component of the wind was always found to behave similarly to the pattern we described for July 1981. For various summer periods in 1981 and 1982, and for stratifications based on the speed of both the ridgetop winds and the gradient winds over the plains and also on the degree of convective activity, upslope and downslope wind components and transition zones evolved as for July 1981. Only the timing of the transition from upslope to downslope changed significantly, occurring 1–2 h earlier with stronger westerly winds aloft or with stronger convective activity. Otherwise, the diurnal component of the wind generally appeared to be superimposed on the surface synoptic flow. The easternmost stations (FTM, AKO, LIC), however, appear to be more susceptible to synoptic-scale effects and less under the control of diurnal circulations. This behavior was also noted by Smith and McKee (1983).

4. Relationship of mean flow patterns to thunderstorm activity

During July, most precipitation which occurs over the region of this study can be attributed to afternoon thunderstorms. Typically, the first showers of the day develop along the Continental Divide or in certain preferred regions along the foothills or ridges extending into the plains. Wetzel (1973), Henz (1974), and Karr and Wooten (1976) prepared climatologies of radar echoes based on data from the WSR-57 10-cm radar at Limon, Colorado. The frequency of radar echoes (0900–2100 MST) over the region presented by Wetzel as a percent deviation from the azimuthally averaged mean at each radius from Limon is shown in Fig. 5 for the summers of 1971 and 1972. Three favored regions for echo occurrence appear: 1) the eastern slopes of the Continental Divide; 2) the Palmer Lake Divide, and 3) the Cheyenne Ridge. Henz (1974) obtains similar results and finds the average time of maximum thunderstorm echo-generation in the preferred regions to be between 1200 and 1300 MST. Karr and Wooten (1976) also present similar findings. When southeast gradient flow is present over the plains, Szoke *et al.* (1984) suggest another area of enhanced thunderstorm initiation is over the lowlands north of Denver.

In Fig. 5, the mean surface flow at 1100 for July

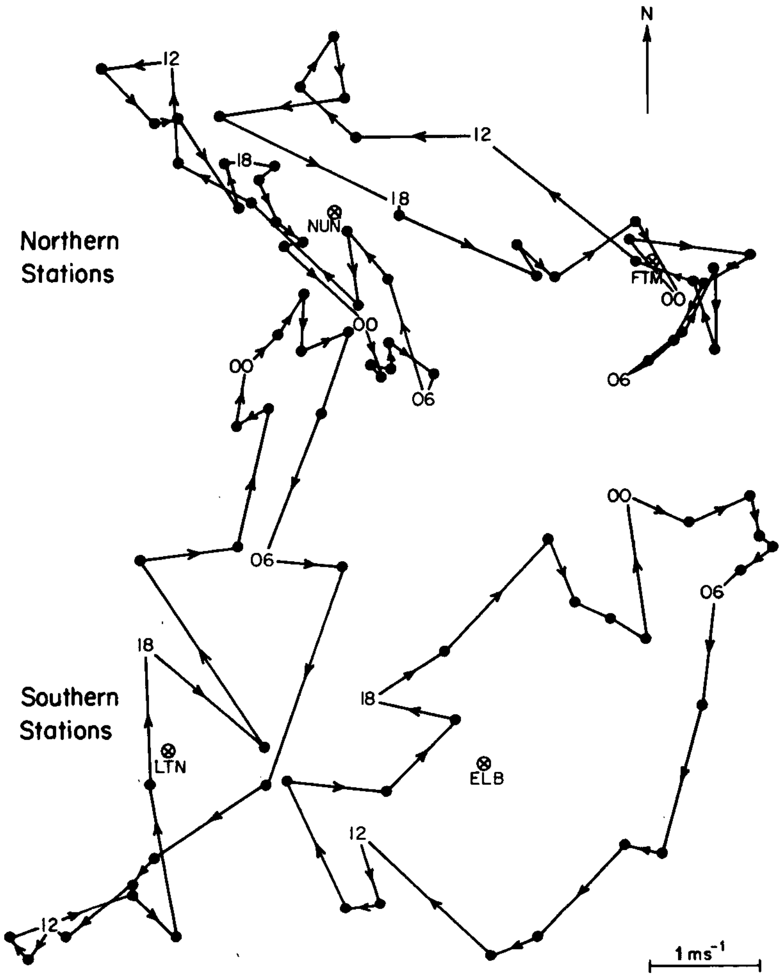

FIG. 4. Selected surface wind hodographs for July 1981. The wind vector end points are labeled at midnight (00), 0600 (06), 1200 (12) and 1800 (18) MST. Stations NUN and FTM are on the north side of the South Platte basin (see Fig. 1); LTN and ELB are on the south side.

1981 is superimposed upon the radar climatology for the summers of 1971 and 1972. Despite the fact that the two analyses are for different periods of time, there is a strong suggestion that the preferred regions for development coincide in most instances with zones of maximum surface confluence (and convergence) 1–2 h earlier. Moreover, these zones coincide reasonably well with the crests of the Cheyenne Ridge and the Palmer Lake Divide, features which provide for elevated heat sources that also help to determine preferred initial locations for convection. The character of the surface flow, which is strongly controlled by surface heating and topographic effects, does vary under different synoptic conditions. For example, as a surface high pressure system builds down from the northern plains it produces at first a more northerly and then later a more southerly component of the wind and, hence, different locations of preferred thunderstorm development.

The study by Wetzel (1973) indicates that there normally occur over north central Colorado two cycles of convective activity during the day. He finds that the first major storms that develop appear along the Cheyenne Ridge and the Palmer Lake Divide in the early afternoon and later propagate eastward out of the region. A secondary maximum appears later in the early evening in the upper reaches of the South Platte River basin. The eastward progression of this secondary feature coincides very well with eastward movement of the surface confluence line after 1700 MST (Fig. 2g). The fact that these two studies are based on analyses from different years and months and yet show consistent patterns in terms of radar echo tracks and surface flow fields strikingly illustrates the persistence and dominance of diurnal and terrain forcing in the region. Further work is needed, however, to better describe this flow feature and establish the mechanisms for its development.

TABLE 3. Hourly persistence (%) for selected stations.

Hour (MST)	Identifier				Hour (MST)	Identifier			
	ELB	FTM	LTN	NUN		ELB	FTM	LTN	NUN
00	66	13	92	42	12	23	42	69	27
01	73	14	88	53	13	13	52	55	34
02	81	20	93	63	14	18	63	49	31
03	84	16	90	88	15	24	62	31	30
04	81	31	90	91	16	7	57	7	12
05	71	38	91	96	17	11	57	11	11
06	66	44	83	92	18	14	58	22	10
07	52	32	55	68	19	39	53	40	20
08	44	16	39	56	20	51	17	41	19
09	38	22	25	41	21	46	10	59	8
10	33	17	72	19	22	52	12	73	15
11	33	20	65	30	23	54	6	76	17

As stated earlier, mean flows constructed for various summer periods all showed that the transition to downslope flow behaved similarly to the July 1981 results. The eastward propagation of the transition zone occurred in all cases. Only the timing and speed of propagation varied. Although convection is present

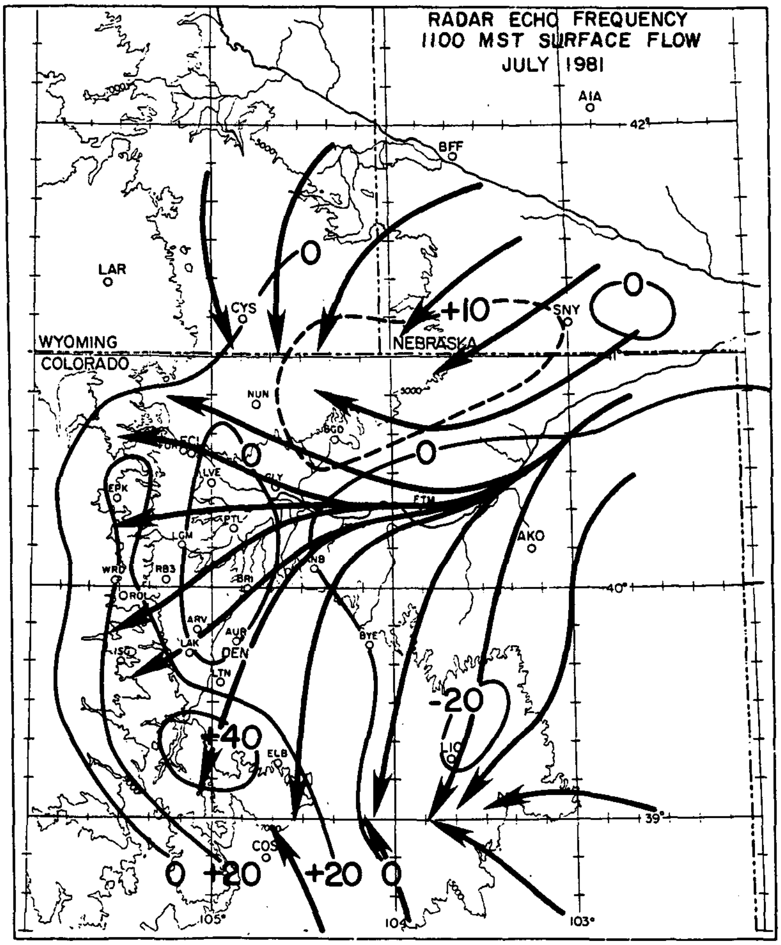

FIG. 5. Radar echo frequency, as determined by Limon, CO, WSR-57 radar, given as percent deviation from azimuthally-averaged mean at each radius from Limon (reproduced from Wetzel, 1973). Surface streamlines are shown for 1100 MST. Dashed line is intermediate contour.

along the Front Range on most summer days, the days with less convective activity appear to have a later transition to downslope flow. This finding implies that the Banta (1984) mechanism of downward mixing of westerly momentum from aloft by the growth of the convective boundary layer to ridgetop elevations may be a plausible explanation for the downslope onset that occurs before sunset. Other factors, however, such as shading of the east slopes of the Continental Divide by early afternoon convection, may help to explain the timing of this circulation feature. Blocking effects described by Szoke *et al.* (1984) may also contribute to variations in the timing and location of a mean convergence zone. It may be that an enhancement of surface westerlies, perhaps related to the downward transport of westerly momentum by cumulonimbus downdrafts (Erbes, 1978), contributes to an earlier eastward advancement of the downslope onset. The role this eastward-propagating confluence line plays in initiating or modulating the early evening thunderstorm maximum (Wetzel, 1973) is not clear and further study is needed.

5. Summary and conclusions

Analyses of summer surface winds over northeast Colorado, using data from the PROFS mesonetwork, revealed a diurnal wind flow pattern similar to those documented in other mountain–plains regions of the world. However, the mesonetwork data permitted distinctive features of the flow to be studied that are likely unique to Rocky Mountain eastern slope environments.

The late-night downslope flows and the late-morning through midafternoon upslope flows are consistent from month to month. The early-morning downslope-to-upslope transition zones begin near the foothills and propagate eastward across the plains. Winds within the morning transition zones are light and, even after averaging, vary considerably from month to month. The upslope flow through midafternoon develops according to classic descriptions of upslope and valley winds. At stations on the south side of the South Platte River, the wind vector rotates clockwise through the afternoon, while at stations on the north side the wind vector exhibits little turning or even slight counterclockwise turning. This behavior is consistent with solenoidal forcing by the three-dimensional sloping terrain; however, the importance of contributions by blocking effects and boundary layer growth in conjunction with moderate gradient winds is unknown.

Local confluence is found at midday along major east–west ridges in the region (e.g., Cheyenne Ridge and Palmer Lake Divide) and, consequently, these ridges are preferred regions for afternoon thunderstorm activity. Late in the afternoon, there is a preferred development of thunderstorms just west of the upper reaches of the South Platte River basin, followed by propagation toward eastern Colorado later in the evening. This pattern of thunderstorm development and movement is evident in the mean streamline patterns for the summer months of 1981. The extent to which this circulation feature is a consequence of downward mixing of westerly momentum by the growth of the convective boundary layer (Banta, 1984), or is somehow caused by the early afternoon development of cumulonimbus along the Continental Divide, is not fully known and further study is required.

Increased understanding of diurnal flow patterns in mountainous areas should improve forecasting in those regions. We have concentrated on the summer season because that is a time of year when large-scale synoptic forcing is weak. Diurnal effects over northeast Colorado are important at other times of the year, but analysis of their interaction with the synoptic features will likely be more complex.

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