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James J. Toth and Richard H. Johnson

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Cooperative Institute for Research in the Atmosphere

Colorado State University
Foothills Campus
Fort Collins, Colorado 80523

Colorado State University / National Oceanic and Atmospheric Administration

# AN OBSERVATIONAL STUDY OF SUMMER SURFACE WIND FLOW OVER NORTHEAST COLORADO

by

James J. Toth
and
Richard H. Johnson

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ABSTRACT

Analysis of summer surface winds over northeast Colorado, using data from the Program for Regional Observing and Forecasting Services (PROFS), has been carried out to investigate the diurnal wind flow pattern over the broad drainage area of the South Platte River. The pattern, similar to the classic descriptions of valley wind flows, appears in monthly averages as well as on most individual days. Unique features of the flow are documented, in particular the upslope/downslope transitions which begin near the foothills of the Front Range of the Rocky Mountains and propagate eastward.

Previous conceptual models of the afternoon and evening wind flow over northeast Colorado are verified. The afternoon upslope flow is often responsible for enhanced convective cloud cover in preferred locations during the summer. It is suggested that the development of moist convection modifies the diurnal flow and contributes to the late afternoon and early evening transition to downslope flow. This study has pointed out the need for further investigations of this problem.

## ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

PAGE

# I. 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. This study deals with the diurnal evolution of the surface wind flow at and near the interface between the mountains and the plains. Increased interest in this and other types of sub-synoptic-scale and mesoscale phenomena stems in part from the introduction of new or improved methods to collect, process, and display meteorological data. The establishment of the Program for Regional Observing and Forecasting Services (PROFS) provides an opportunity for using these new methods to study the development of weather systems in northeastern Colorado. This area includes the PROFS surface mesonetwork, which extends eastward, roughly 150 km, from near the Continental Divide well into the plains.

In this chapter, the motivation and objectives for this research are outlined and supported by providing background information on PROFS and previous investigations of mountain/slope flows.

## A. Purpose of this Study

Many previous studies, some of which will be reviewed later, have documented the diurnal mountain/plain wind flow around this area. However, few have considered the details of the flow evolution just east of the mountains. This mountain/plain interface is an area of large contrasts in observed weather, and has recently been explored in more detail using the data available from PROFS. One of several types of data gathered by PROFS is the set of observations from a surface mesonet consisting of 22 automated stations. The spacing of the stations is irregular, but features on the scale of 100 km can be resolved fairly well. The surface terrain variations (discussed later in this section) are dominated by features on this scale. The surface diurnal wind flow has been documented in a previous, preliminary report (Johnson and Toth, 1982) using averaged, July 1981, hourly winds from the mesonet and from several, conventional National Weather Service stations. In this study, a similar analysis of the PROFS surface mesonetwork data for June and August, 1981, and a more detailed analysis of the July 1982 data will be carried out. An attempt will be made to expand on the conceptual models of the physical mechanisms involved. Of particular interest is the afternoon wind transition along the Colorado Front Range which is involved in organizing late afternoon and evening convective storms into larger-scale systems (Cotton, 1983).

On individual days, deviations from the climatological wind field are present due to the background synoptic and subsynoptic forcing. A few relatively "undisturbed" days will be examined in an attempt to isolate the diurnal winds and their effects.

B. PROFS

The National Oceanic and Atmospheric Administrations's PROFS group (Beran and Little, 1979), headquartered in Boulder, has developed an operational workstation (Reynolds, 1983) as part of a continuing effort to improve short-term (0 to 6 h) mesoscale forecasts. New data sources and techniques are continually being incorporated into the workstation.

Table 1 shows the products which were being routinely collected and transmitted to the Denver Weather Service Forecast Office (WSFO) as of 1982. The mesonet and the Limon (LIC) radar data are transmitted to the Colorado State University (CSU) Department of Atmospheric Science on a near real-time basis (0.5 to 1.5 h after the observation). Digital satellite data are received directly at CSU. Naturally, these data sources are integrated with what may be the best observational instrument available--the human eye. A more detailed summary of data sources used in this study is given in the next chapter.

Short-term forecasting, obviously, is not the only use of the PROFS data; it has important research applications. Also, the summer convective season is not the only time of important weather developments in northeastern Colorado. Lilly (1981) and Schlatter et al. (1983) studied winter snowstorms in this area. In both cases, the investigators had available unconventional upper air data which they combined with the PROFS mesonet data to develop a three-dimensional view of the storms. Lilly used Doppler radar derived winds, and Schlatter included data from the Wave Propagation Lab's Profiler (Hogg et al., 1983). Johnson et al. (1983) show how the contrast between snow-covered and snow-free ground can generate a mesoscale circulation leading to a localized area of showers. A potential use of the mesonet winds would be to extend the previous studies of Front Range air pollution trouble-spots (e.g., Riehl and Herkhof, 1972) to include a considerably larger area.

Here I will only present data from the summer months. This is a time of year when the diurnal forcing exceeds, although it does not completely overwhelm the synoptic forcing. Also, in northeastern Colorado, summer thunderstorms are an almost daily occurrence. The

Table 1. 1982 real-time product list (from Reynolds, 1983).

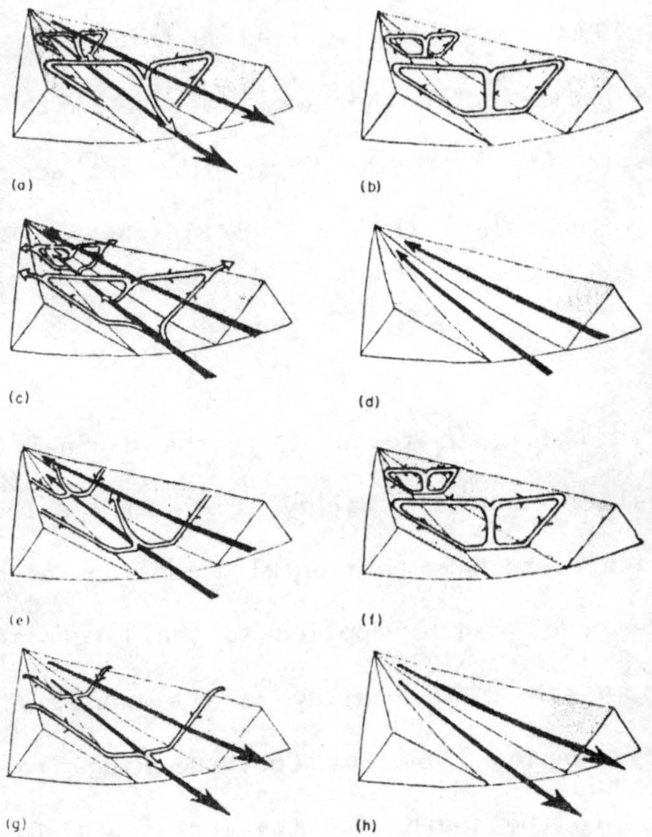
| Product description | Data resolution | Temporal resolution |
|---|---|---|
| Images | | |
| Visible satellite/GOES-W | 1 km | 30 min |
| Infrared satellite/GOES-W | 8 km | 30 min |
| LIC, CYS, CP-2 radar mosaic | 2 km | 5 min |
| Radar mosaic and visible satellite | 1 km | 30 min |
| CP-2 radar | 1 km | 5 min |
| Gray-scale topography; state, county, city, drainage, basin maps | 1 km | once |
| Graphics | | |
| Surface station model plot | -- | 1 h |
| Surface station contours | -- | 1 h |
| Satellite IR temperature contours corrected for parallax | 8 km | 30 min |
| Denver skew/T plot | -- | 12 h |
| Lightning data | -- | 5 min |
| Mesonet plot | -- | 5 min |
| Mesonet station contours | -- | 5 min |

surface flow, dominated by the diurnal cycle, is important in the development of these storms. Days with severe thunderstorms over the High Plains are noteworthy because of the frequent absence of well-defined upper-air features (Doswell, 1980) traditionally used to forecast severe weather further east. PROFS has selected the summer season, with it's convective weather, to measure the improvements in forecast accuracy obtainable through the PROFS technology (Haugen and Lipschutz, 1982).

## C. Previous Studies

Defant (1951) summarized the basic features of the diurnal wind field evolution for an idealized mountain valley (Fig. 1). 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. 2), enclosed by the Cheyenne Ridge to the north, the Palmer Lake Divide to the south, and the continental Divide to the west. Further details regarding the stations in this area are provided in the next chapter and in Appendix A.

Two interrelated systems of wind flow are shown in Fig. 1. The first system (the slope winds) is on a scale considerably smaller than the along-valley dimension. Horizontal temperature gradients develop due to heating (cooling) in a relatively thin layer of air parallel to the sloping valley walls. This layer thickens with daytime heating (to a lesser extent with nighttime cooling). The resulting horizontal pressure gradients within the sloping layer generate upslope (downslope) winds (Fig. 1b,f). These winds develop close to and follow the slope of the walls. (Downslope winds are also termed "drainage winds" or "katabatic winds".)




Schematic illustration of the normal diurnal variations of the air currents in a valley. (After F. Defant) [17].)

(a) Sunrise; onset of upslope winds (white arrows), continuation of mountain wind (black arrows). Valley cold, plains warm.

(b) Forenoon (about 1900); strong slope winds, transition from mountain wind to valley wind. Valley temperature same as plains.

(c) Noon and early afternoon; diminishing slope winds, fully developed valley wind. Valley warmer than plains.

(d) Late afternoon; slope winds have ceased, valley wind continues. Valley continues warmer than plains.

(e) Evening; onset of downslope winds, diminishing valley wind. Valley only slightly warmer than plains.

(f) Early night; well-developed downslope winds, transition from valley wind to mountain wind. Valley and plains at same temperature.

(g) Middle of night; downslope winds continue, mountain wind fully developed. Valley colder than plains.

(h) Late night to morning; downslope winds have ceased, mountain wind fills valley. Valley colder than plains.

Fig. 1 Schematic of the interactions between valley winds and slope winds for a complete 24 hour diurnal cycle (from Defant, 1951).

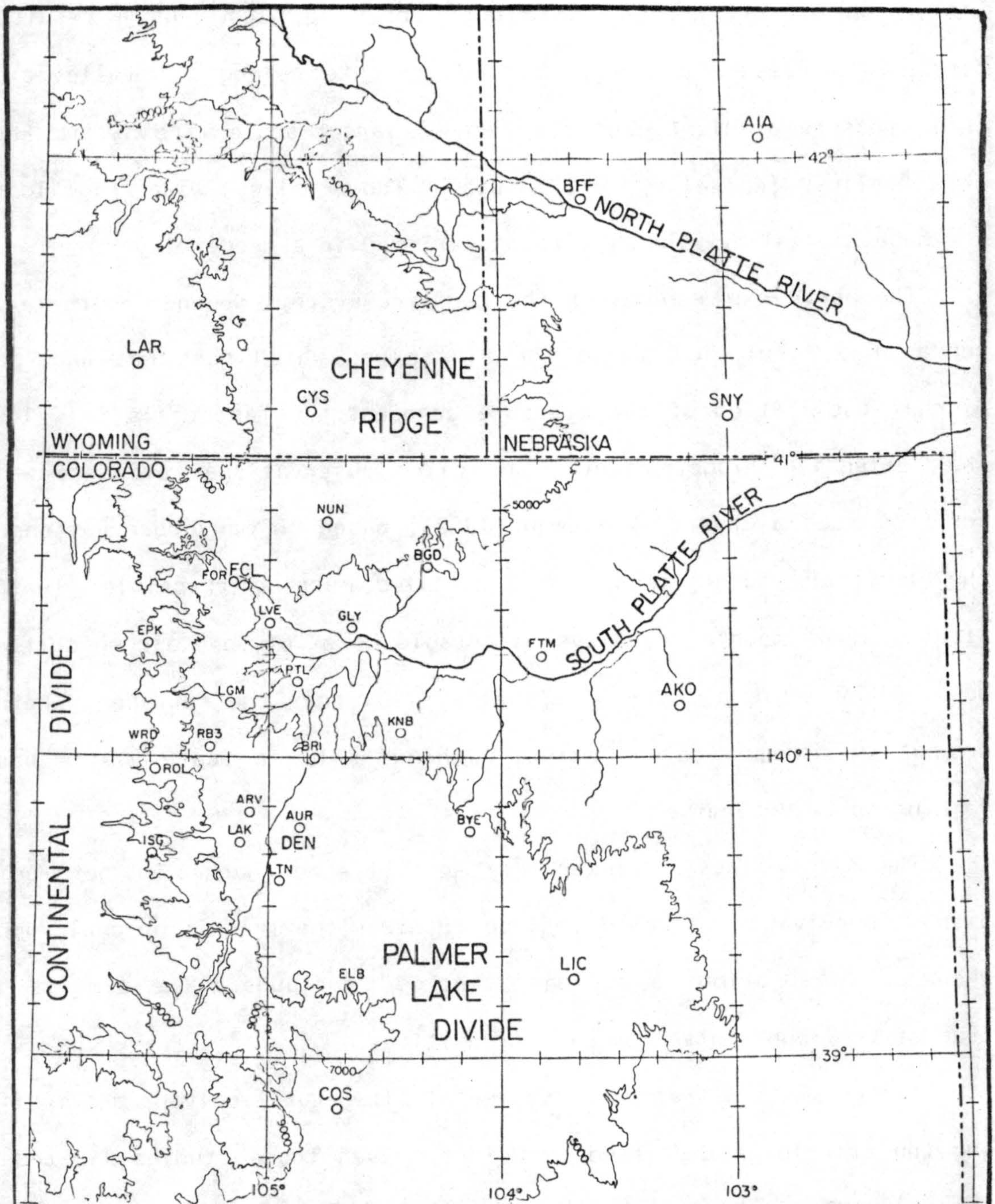



Fig. 2 PROFS Mesonetwork stations (small letters) and surrounding National Weather Service stations (large letters). Major topographic features are identified. Elevation contours are in feet.

The slope wind circulations redistribute mass both towards the valley center and across the ridge tops (Fig. 1c). As a result, a horizontal pressure gradient develops oriented along the valley axis. This pressure gradient causes a second, larger-scale wind system known as a "valley" (up-valley) or "mountain" (down-valley) wind (Fig. 1d,h). The mountain/valley wind develops later, and in a deeper layer.

The above explanation of the two wind systems depends on the existence of a level just above the ridge tops which does not undergo a diurnal oscillation of the pressure gradient. Defant calls this level the "effective ridge height". He cites observational evidence which confirms such a layer. Whiteman (1982), based on many observations in the vertical, identifies a more detailed morning transition feature within narrow mountain valleys--a "stable core" of cold air which flows down-valley above a layer of up-valley flow near the surface. Whether or not a similar feature exists within the broad South Platte basin remains to be determined.

The slope winds are extremely sensitive to changes in net radiation. Conceivably, a rapid upslope to downslope transition could occur when solar radiation is suddenly blocked by clouds. The same is not true of the mountain/valley wind transitions.

There exists a tremendous volume of literature applying and modifying the principles discussed by Defant. Even those studies limited to the Colorado area are numerous. No attempt will be made here to duplicate the thorough reviews of the literature by Dirks (1969), George (1979), Banta (1982), and others. Some of the previous studies that are on a scale which fits closely to the PROFS area will be discussed near the end of this section. Most studies, though, are on scales larger or smaller than the area covered by the PROFS mesonet. The physical mechanisms important on these other scales may be important in the PROFS area as well. In addition, circulations within the mesonet have often been found to depend on interactions with larger and smaller scale phenomena nearby.

On the larger scale, Bleeker and Andre (1951) found that an increase in nocturnal convergence over the Central Plains (Fig. 3) corresponds well with the nocturnal maximum of thunderstorms and precipitation in that area. The nocturnal maximum of thunderstorms over the Central Plains is obvious in Fig. 4. Equally obvious is the late afternoon maximum along a zone just east of the Continental Divide, including the PROFS area. The PROFS area is just above 4000 ft (~ 1.5 km) and is at the extreme western boundary of Bleeker and Andre's analysis in Fig. 3. While the details of their analysis within Colorado should be viewed with caution, the general pattern indicates a diurnal oscillation of horizontal divergence, occurring near the mountains, nearly opposite in phase to that over the Central Plains. Although the PROFS area must be affected to some extent by this oscillation, the terrain features within 100 km of the Continental Divide contribute far more to the diurnal evolution of the wind field.

Maddox (1981), in his study of mesoscale convective complexes (MCCs), states that MCCs are likely responsible, in large part, for the nocturnal maximum in Central Plains convective weather. Unlike other studies, similar to Bleeker and Andre (1951), which would suggest that the increased convergence <u>causes</u> the MCCs, Maddox found that the MCCs ultimately begin with <u>afternoon</u> convection, with the MCCs often having <u>propagated</u> eastward from the higher terrain. The nocturnal maximum in Central Plains convective weather has also been related to the nocturnal

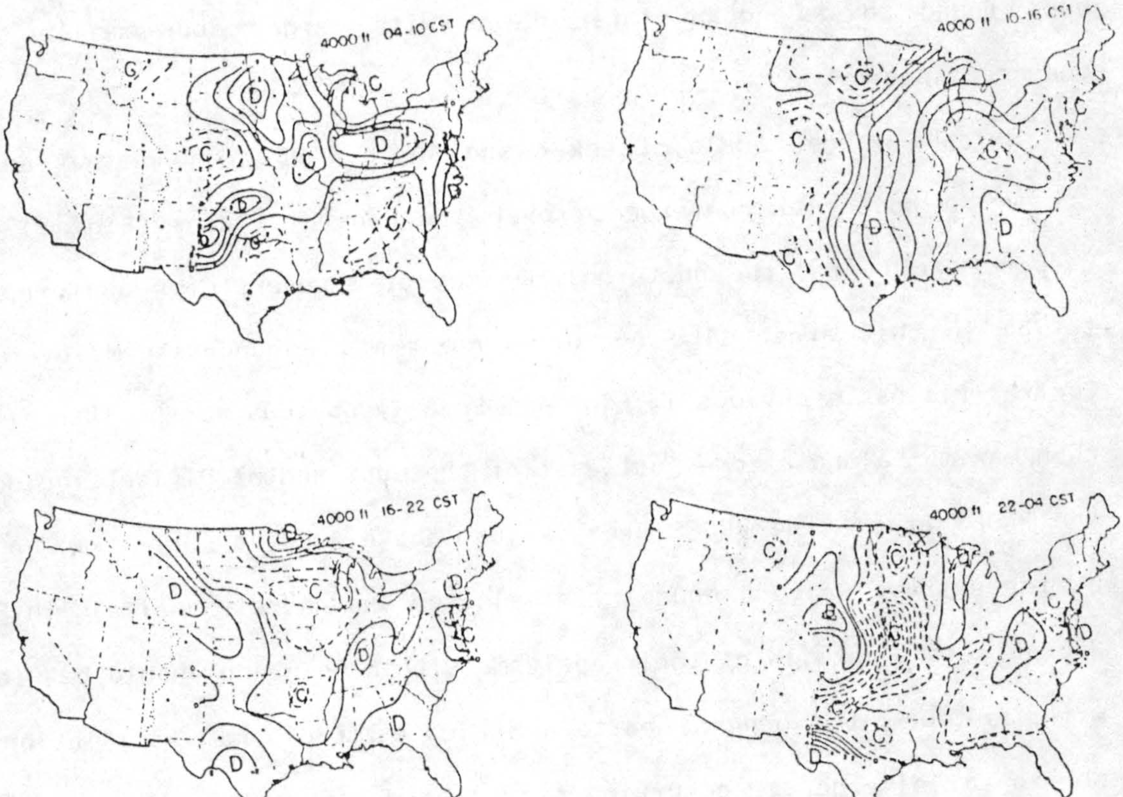



Fig. 3 Average change in divergence for August 1947 and August 1948 during the 6 hour period indicated (Central Standard Time). Isopleth interval is $1\times10^{-2}$ $hr^{-1}$ per 6 hr. Dashed isopleths are negative values, i.e. more convergent (from Bleeker and Andre, 1951).

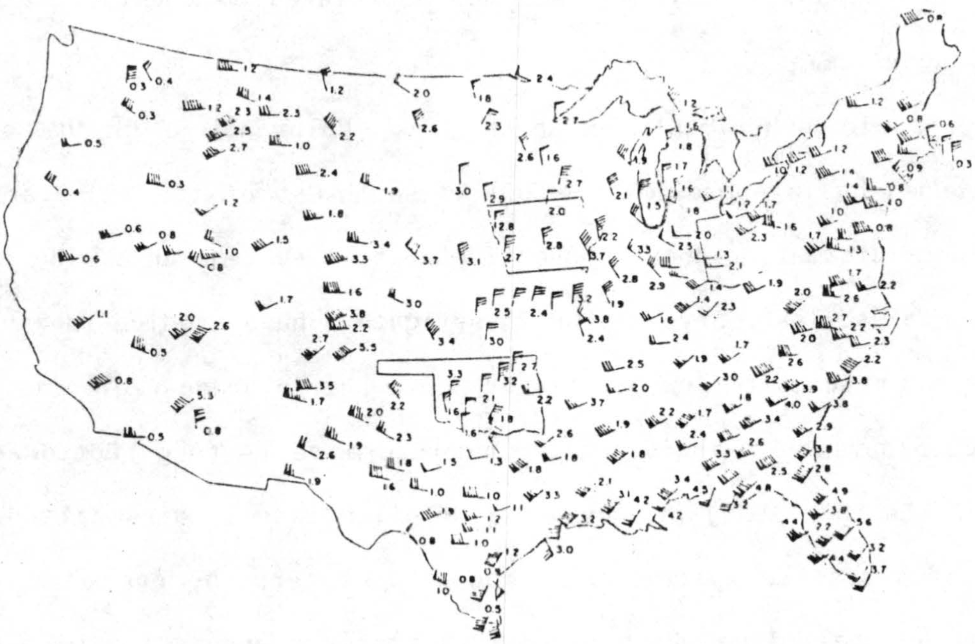


Fig. 4 Normalized amplitude and phase of the diurnal cycle in the total frequency of thunderstorms for the summer season (June-August). Normalized amplitude is indicated by the configuration of barbs on the tails of the arrows, where each half barb represents 5%, each full barb 10%, and each triangular flag 50%. Phase is indicated by the orientation of the arrows. An arrow pointing from the north indicates a midnight maximum (local time); one pointing from the east indicates a 0600 maximum, etc. The numbers plotted next to the stations represent the 24-hour mean frequencies in terms of percent of hours with thunderstorms (from Wallace, 1975).

low-level jet. The jet is a complex response to the thermal effects of the sloping terrain and to the variation of momentum mixing within the planetary boundary layer (McNider and Pielke, 1981).

The preceding discussion of the larger scale is incomplete; however, it will be left at this point. The purpose has been to indicate that the PROFS wind circulations may be related to the circulations on the larger scale.

A field experiment in South Park, Colorado, a broad mountain-surrounded basin approximately 100 km southwest of the PROFS area, has provided information about convective weather systems on a wide range of horizontal scales. Several CSU investigators have studied the synoptic-scale and mesoscale flow of moisture into the Colorado region as well as the development of individual thunderstorm cells (e.g. Cotton *et al*., 1982). George (1979) presents two detailed case studies of the evolution of mesoscale systems over mountainous terrain, one of which involves a squall line which propagates eastward across the High Plains. Wetzel *et al*. (1983) have looked at the early stages of developing MCCs as they move from the High Plains to the Great Plains.

Two other South Park studies, one by Banta (1982) and the other by Erbes (1978), offer conceptual models of dynamical processes which may be important in the PROFS area.

Banta (1982) determined that, even on a dry day, no clear distinction could be made in South Park between the slope wind system and the mountain/valley wind system. Therefore, he defined three wind *regimes*: the upslope regime (including upslope and valley winds), the downslope regime (including downslope and mountain winds), and the convective mixing regime (ridge-top winds mixed down to the surface). The development of each of these three regimes is indicated schematically in Fig. 5. In addition to surface observations, Fig. 5 is based on detailed vertical observations and also on numerical simulations. Before sunrise (5a), a downslope regime is well established. Upslope develops in a shallow layer during the early morning (5b). Shortly after, the convective regime begins near ridgetop. Note in Fig. 5c the development of a convergence zone between the convective mixing regime and the upslope regime. The convergence zone moves eastward and eventually the upslope regime is eliminated. In Banta's numerical simulation of this flow, an intense horizontal vortex developed just east of the convergence zone. 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 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 elevation difference is ~ 2 km over the PROFS mesonet vs. ~ 1 km over South Park. Nevertheless, a convergence zone similar to the one in Fig. 5 usually develops within the PROFS area, although at a later time (Johnson and Toth, 1982). A few relatively undisturbed (synoptically) days have been examined (Chapter IV) in an attempt to determine the applicability of Banta's mechanism to the PROFS area.

Erbes (1978) describes the typical sequence of thunderstorm development in eastern Colorado over the mountains and the plains. Around noon, thunderstorm cells first form over the mountains. The cold, moist downdraft outflows from these cells gain westerly momentum as the

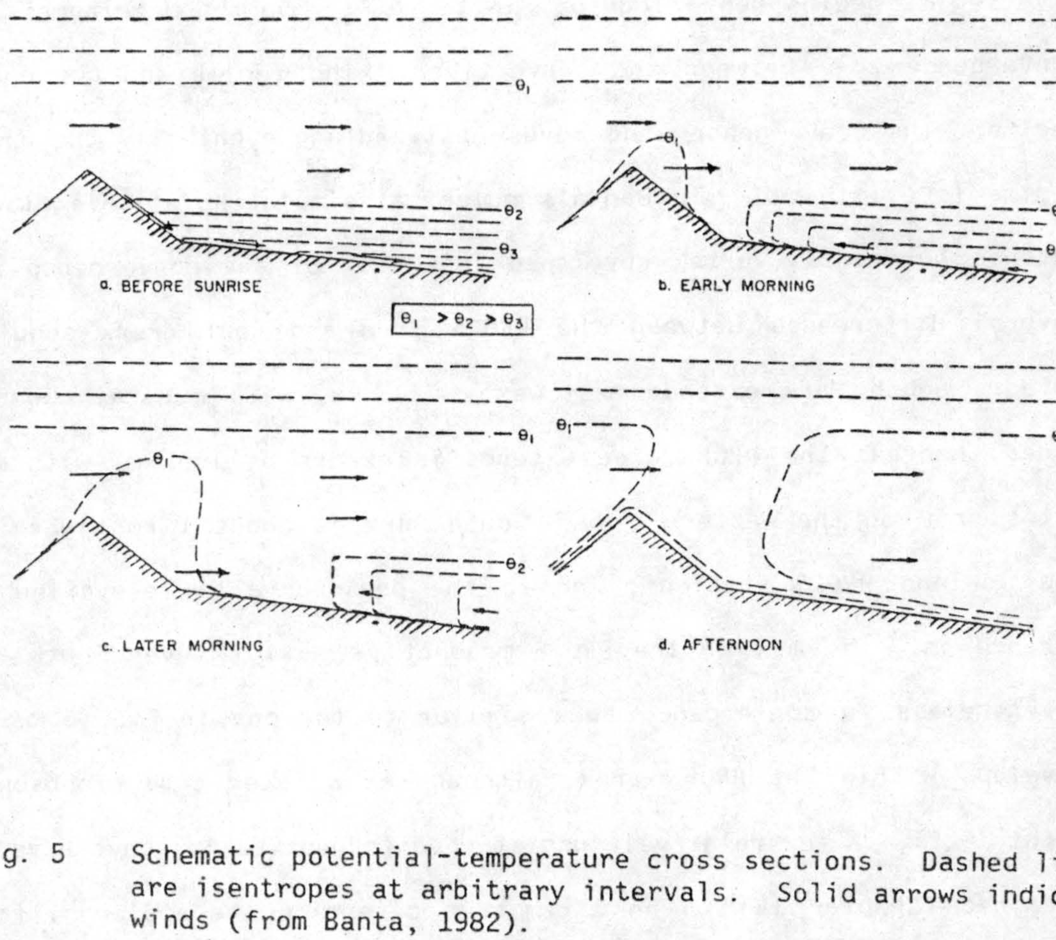



Fig. 5 Schematic potential-temperature cross sections. Dashed lines are isentropes at arbitrary intervals. Solid arrows indicate winds (from Banta, 1982).

outflows travel down the mountain slopes. New cells form in the convergence zone between the downdrafts and the environmental upslope flow. The new cells continuously access new moisture and create new downdrafts. With sufficient moisture supply and sufficiently strong westerly environmental winds, the entire system can propagate over 100 km across the Plains. Erbes argues that two factors tend to dissipate the system. First, the cirrus canopy generated by the system reduces surface heating and, hence, the thermal bouyancy. Secondly, the decreasing slope of the plains (compared to the mountain slopes) causes a reduction of the outflow speeds. However, the propagation of this system modifies the dry diurnal circulation over the plains and probably allows the formation of new storm systems in the late afternoon over eastern Colorado when the subsiding return flow over the plains disappears (Fig. 6).

There have been several numerical studies of the diurnal flow over the PROFS area. Dirks (1969) used a two-dimensional, hydrostatic, incompressible, model employing a vorticity equation in the x-z plane to study the dry slope flow circulations. His model developed a two-celled daytime circulation (Fig. 6). The flow reverses at about the mountain top level. The subsidence to the right of the steep-mountain/slightly-sloping-plain interface agrees well with the observation that, at the time of maximum heating, convection is suppressed over that portion of the plains. This subsidence area is approximately 100 km east of the Continental Divide. In Fig. 7 is shown the observed circulation at Denver, obtained by averaging six-hourly pibals. The observed vertical section is similar to the modeled circulation. Daytime upslope extends to near the ridgetop level, and a return flow is present above. In

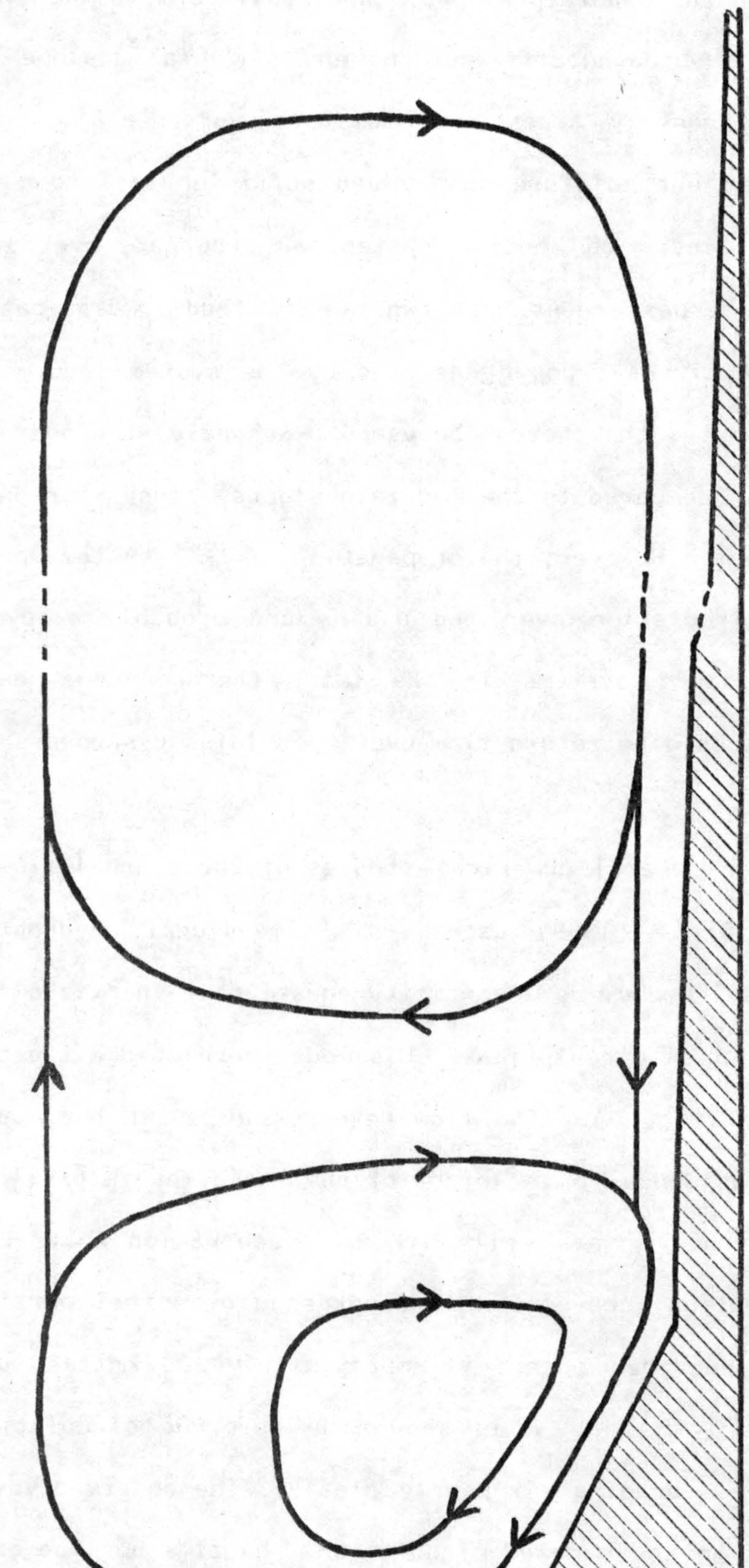


Fig. 6 Schematic illustration of the idealized mountain/plain daytime circulation (from Dirks, 1969).

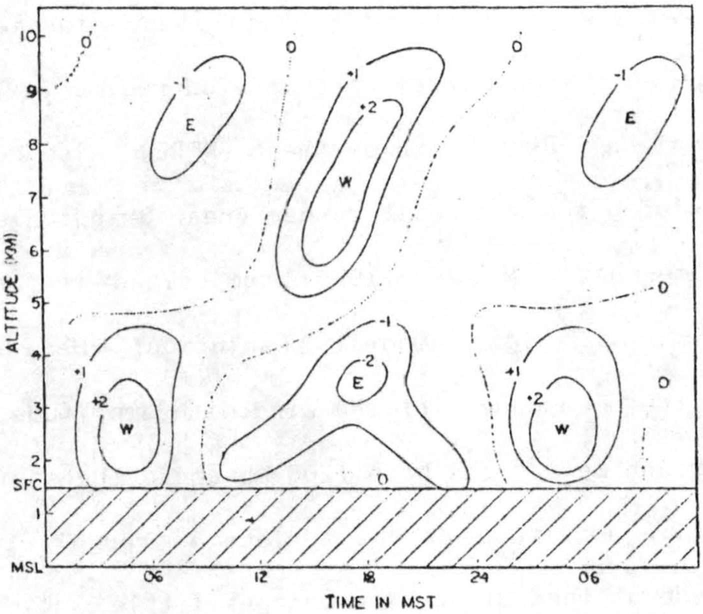



Fig. 7 Westerly component of the mean departure vector as a function of altitude and time for 28 days selected during summer, 1966, at Denver, Colorado. Values are in m $s^{-1}$ (from Dirks, 1969).

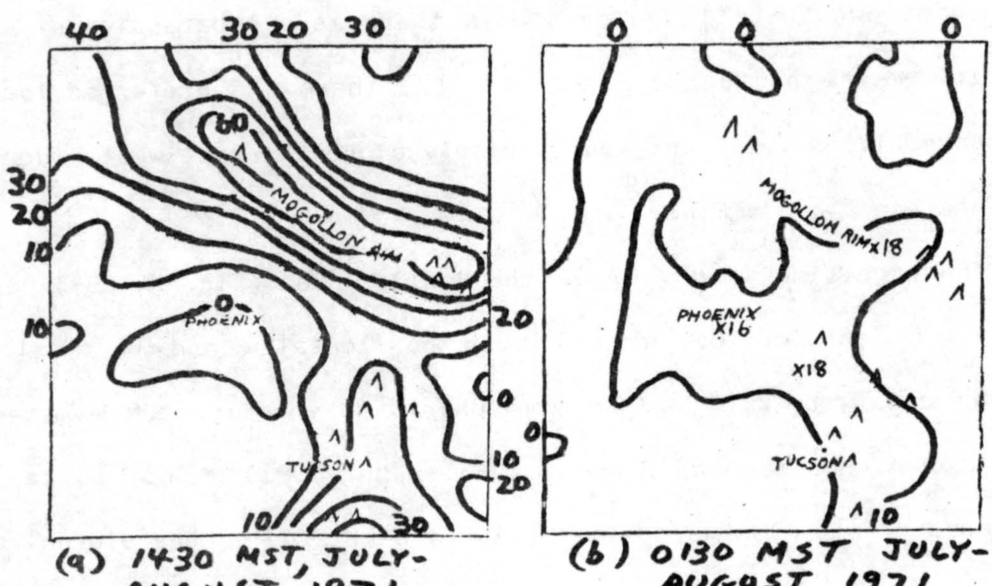



Fig. 8 Percent frequency of radar echo detection over Arizona at the indicated times (from Hales, 1972).

another numerical study, the three-dimensional boundary layer model of Pielke (1974) was used by Hughes (1978) to study diurnal wind effects, but in the simulations an actual upslope wind regime failed to develop.

The National Hail Research Experiment (NHRE), also conducted during the 1970's, included the northeast corner (near Briggsdale, BGD, Fig. 2) of the PROFS mesonet. Modahl (1979) composited the NHRE upper air soundings, which had high temporal resolution. He shows a diurnal oscillation of the u-component of the wind with amplitude $\sim 1\ \mathrm{m\ s^{-1}}$ 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 changes little.

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 (Weaver and Kelly, 1982; Weaver et al., 1983). All of 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. 2).

The nighttime wind flow in the Boulder area (Fig. 2, RB3) has been studied in considerable detail both horizontally and vertically including data from the Boulder Atmospheric Observatory 300 m meteorological tower (Hootman and Blumen, 1983; Hahn, 1981). But, so far, only Johnson and Toth (1982) and Smith (1982) have studied the diurnal evolution of the surface meteorological variables over the entire PROFS mesonet. The Johnson and Toth report is preliminary to this one and elements of it appear in later chapters. Smith selected three, clear, fall days that were relatively undisturbed synoptically. He found that the downslope wind speeds were generally stronger than the upslope speeds. Transitions began in the foothills and spread eastward, consistent with Johnson and Toth's previous findings for summer and for undisturbed fall days. But, for his fall cases, the transitions did not reach the eastern fringe of the PROFS area, where synoptic-scale southerly winds blew both day and night. The diurnal temperature variation in this fall period ranged from 22°C along the South Platte River to 11°C in the high mountains.

The diurnal wind flow in northeastern Colorado should have an important bearing on the progression of thunderstorms from the mountains to the plains. The more general results of this study may have applicability to other mountain/plain areas which show a similar progression of thunderstorms. There have been studies of diurnal effects in other areas (e.g., Mass, 1982); only two of them which involve thunderstorm activity will be mentioned here.

In New Mexico, Bowen et al. (1981) describe a local wind which forms as a result of weak thunderstorms with very little precipitation. Because clouds form over the mountains and block the solar insolation, while few clouds form over the valley, a temperature gradient develops which causes a strong downslope wind ($\sim 9$ m $s^{-1}$) to blow. The result is similar to that described by Erbes, but the solar radiation gradient, rather than the cloud dynamics, is viewed as the cause of the transition from upslope to downslope.

In eastern Colorado, the prevailing westerly winds favor a progression of thunderstorms from the mountains to the plains; however, other factors may be involved. In Arizona, Hales (1972) determined the frequency of radar echo detection for each hour of the day. At the time of maximum heating, there is a minimum of thunderstorm activity over the deserts (Fig. 8a). Shortly after midnight, there is a maximum over the deserts (Fig. 8b). The thunderstorms propagate steadily from the mountains southwestward to the deserts, perpendicular to the prevailing winds. This suggests that, within Colorado as in Arizona, other mechanisms, in addition to the prevailing winds, may be important for the eastward propagation of thunderstorms.

## D. Goals of this Study

The goals of this study are to:

(1) document the mean diurnal surface flow in the PROFS mesonet area and the relationship of this flow to observed weather,

(2) examine the day-to-day variability of this flow, and

(3) examine the forcing mechanisms of this flow and verify the conceptual models previously developed.

The next chapter is a discussion of the data and analysis procedures. The averaged, climatological results are presented in Chapter III. Following that is an examination of a few individual days in Chapter IV. The remainder of the thesis involves a discussion of the results and conclusions.

# II. DATA AND ANALYSIS PROCEDURES

In this chapter, the data source characteristics and the analysis procedures are described. Data for the summer of 1981 and for July 1982 and 1983 were analyzed.

## A. Surface Stations

At present, the PROFS surface mesonetwork consists of 22 automated stations at a variable density tending to correspond to the population density of northeast Colorado (Fig. 2). All stations are within a 100 km radius of station BRI (Brighton). Station ERI (Erie, not shown in Fig. 2) was added late in 1982, and will not appear in this study. A listing is provided in Appendix A of the location, full name, elevation, and siting characteristics of each of the first 21 stations. The mountain stations (EPK, WRD, ROL, ISG) and ELB (near the crest of the Palmer Lake Divide) range from 2135 m or 7000 ft to 3505 m or 11500 ft. The remaining 16 stations, which will be referred to as the "lowland" stations (a mixture of foothills and plains stations), are at 1615 ± 245 m (5300 ± 800 ft). The surrounding conventional stations range from 1206 m or 3957 ft (BFF, Scottsbluff, Nebraska) to 2217 m or 7275 ft (LAR, Laramie, Wyoming).

## B. Mesonet Data

Smith (1982) describes the mesonet data processing procedures. For each five-minute period, there is available the total amount of precipitation, as well as an average, maximum, and minimum value for each of the remaining measurements: temperature, dewpoint, wind speed, wind direction, pressure, insolation, and visual range. The wind direction and the wind speed are averaged independently from 30 samples taken during the 5-minute period and the wind direction is treated as a unit vector; hence, the 5-minute average wind is not a resultant wind (Panofsky and Brier, 1968), although in most instances it is probably very close to it. During the 1981 summer, this information was archived in hard copy format. From October 1981, until September 1982, the same information was archived on magnetic tape. Since then, only selected days have been saved, most of them by PROFS and a few by CSU.

In this study, the mesonet wind observations are used primarily. The temperature, pressure, and solar radiation observations are used as an aid in interpreting the wind observations. Table 2 (from Pratte, 1983) shows the characteristics, including root-mean-square error estimates, of each instrument. The error estimates are based on the instrument and processing specifications and on a subjective determination of the siting errors (e.g., trees may block the wind blowing from a particular direction). Note that for the wind measurements, the estimated siting errors are at least twice as large as either the instrument errors or the signal processing errors. At only a few of the stations (NUN, ELB, LTN) has a well-exposed wind instrument mounted on a 10 m tower been achieved. At some of the stations (LAK, LGM, GLY, KNB, FTM) the anemometers clear the roof of the one-story building on which they

Table 2. PROFS Mesonet; system error summary. (% R = Percent of reading)

| Variable (Instrument) | Nominal Measurement Height (AGL) and Instrument Range | Instrument Error | Signal Processing Error | Estimated Siting Error | Overall Observation Error |
|---|---|---|---|---|---|
| Temperature (aspirated, linearized themistor, 5 ft AGL) | 5 ft<br>-58 to 122° | 0.6°F | 0.2°F | 0.3°F | 0.7°F |
| Dew point (aspirated, cooled-mirror hygrometer, 5 ft AGL) | 5 ft<br>-40 to 140° | 1.1°F | 0.6°F | 0.3°F | 1.3°F |
| Wind Speed (propeller, 30 ft AGL) | 33 ft | 0.5kt+3%R | 1 kt | 20% R | 1kt+20%R |
| Wind Direction (vane, 30 ft AGL) | 33 ft<br>0-360°AZ | 4°AZ | 2°AZ | 8°AZ | 9°AZ |
| Pressure (capacitively-sensed aneroid, 5 ft AGL) | 5 ft<br>620 to 920 mb | 0.3 mb | 0.2 mb | 0.1 mb | 0.37 mb |
| Insolation (photovoltaic pyranometer, 25 ft AGL) | 28 ft<br>20-1500 W/M | 4% R | 1% R | 2% R | 5% R |
| Visual Range (forward scatter meter, 6 ft AGL) | 6 ft<br>1/32 to 3 N.M. | 15% R | 15% R | 5% R | 22% R |
| Accumulated Precipitation (rainfall only, wind shielded tipping-bucket gauge) (2 ft AGL) | 2 ft<br>0.01 to 4 in/hr | 0.01in+10%R | 0.01 in | 10% R | 0.01in+15%R |

are mounted by only a few meters. At others (BOU, FOR) the wind instrument is on a tall tower mounted on the roof of a multi-story building. Smith (1982) also noted this instrument siting problem. At the lowland stations, when interpreting gradients between the stations, the siting differences are probably just as important as the elevation differences.

The elevation and siting differences are less of a problem for certain types of analysis than they are for others. Time-series at individual stations can yield useful information despite the difficulties with instrument placements. On the other hand, calculations involving horizontal gradients, in particular the horizontal divergence, are subject to errors introduced by the factors described above. In spite of the errors, the results presented here in quantitative form are assumed to be qualitatively correct. This assumption is based on real-time, interactive calculations of surface convergence made on the department VAX 11/780 computer without regard to elevation and siting differences. The calculated areas of surface convergence correspond well with areas of upward motion and resulting clouds, just as they would be expected to correspond over flat, open terrain.

## C. Other Data

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 wind is a subjective, one-minute average vs. an objective, five-minute average from the mesonet.

For the case studies of individual days, satellite, radar and Profiler (Hogg et al., 1983) data have been included when available and appropriate. The satellite images are from high resolution digital data processed through the CSU Interactive Research Imaging System. The radar data are from the Limon (LIC) WSR-57 radar. The Profiler wind data are from the VHF Doppler radar located at PTL. Although the Profiler data are experimental and noisy, they do have nearly continuous temporal resolution. Representative readings, however, are given by one hour averages, available every 20 minutes. The Profiler data will be compared with the Denver rawinsonde data at nearly the same time, since, because of the JAWS (Joint Airport Weather Studies) field project (McCarthy et al., 1982), rawinsonde observations were made every three hours during the afternoon, rather the normal twice a day.

## D. Analysis Procedures

The persistence of the diurnal upslope/downslope pattern has motivated the composite, climatological approach to this study. For the summer months of 1981, 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. Effectively, this was the same as eliminating wind speeds greater than about 13 kt. The occurrence of the strong wind events in the data sample was rare and analyses with and without application of the removal procedure are virtually identical. Each month (June, July, August) was done separately, but the surrounding conventional stations were included only for July. The average speed and the persistence, defined as the resultant speed divided by the average speed (Panofsky and Brier, 1968), were also calculated.

For an 11-day period in July 1982, a nearly continuous set of mesonet observations was archived on tape. A similar averaging procedure was done for 6 of these days (1-4 and 7-8 July) that were relatively undisturbed synoptically. A cosine filter was applied to the data in an attempt to eliminate disturbances with periods less than an hour; every five-minute observation was used (i.e. 12 observations per hour each day). The filter weighted the observations near the hour most heavily and those near the half-hour very lightly. None of the data was eliminated for this period. Averages for the other parameters were also calculated using the cosine filter.

Usually, a subjective streamline analysis of the average winds has been the most effective way to present the data. Other presentations are used when more convenient. Divergence ($\partial u/\partial x + \partial v/\partial y$) and vorticity ($\partial v/\partial x - \partial u/\partial y$) were calculated from an evenly spaced (20 km) grid obtained using a bi-cubic splines subroutine fitted to the u-component and the v-component of the wind (each component independently) at each station. Real-time calculations (not shown) have been made using the simpler Bellamy (1949) triangle method. The two methods yield qualitatively similar results.

The climatological, averaged results are presented in the next chapter.

# III. SUMMER CLIMATOLOGY

As described in the last two chapters, a major focus of this study is on the average summertime resultant surface winds. The summer months in 1981 and the month of July 1982 were examined separately. For 1982, in addition to the winds, other surface variables were averaged. This was done to learn more about the mechanisms driving the evolution of the wind field. In Section A of this chapter, the averaged surface winds are presented, first for 1981 and then for 1982. In Section B, the July 1982 averaged temperature, pressure, and solar radiation data are presented.

## A. Surface Winds

Before looking at the winds themselves, the persistence of the winds will be considered. The persistence is defined as the speed of the resultant wind divided by the mean wind speed (Panofsky and Brier, 1968). In Fig. 9, the average persistence for all mountain stations and for all lowland stations has been plotted at each hour of the day. Fig. 9 is based on the July 1982 data; the 1981 months are very similar.

As shown in Fig. 9, the persistence is much higher during the night--over 0.9 at the mountain stations--than it is during the day. The resultant speed changes little at night, while the mean wind speed decreases. This decrease accounts for less than half of the increased persistence. There are at least three other reasons, which may in cases

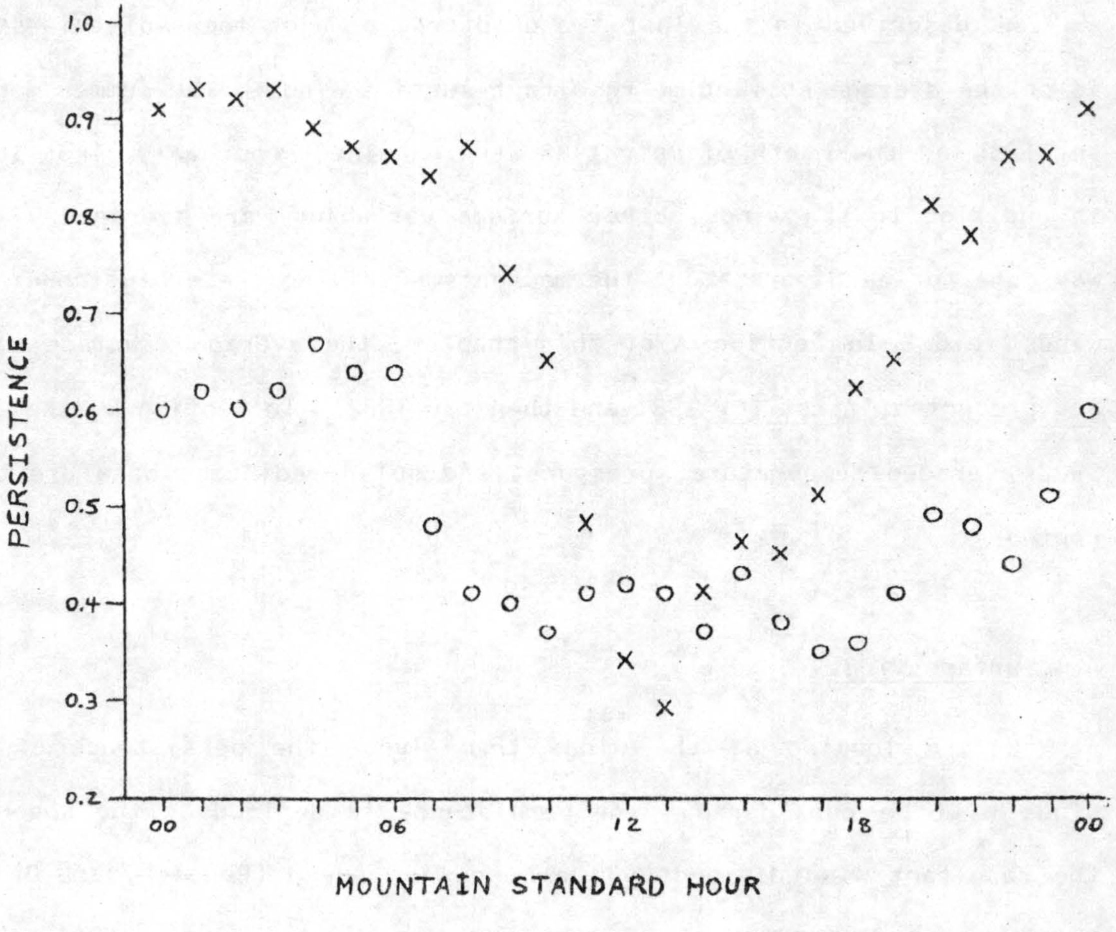



Fig. 9 Average persistence of the wind for each hour. The persistence is indicated for the mountain stations by an "X", and for the lowland stations by a circle.

be interrelated, for the increased persistence. First, the nighttime boundary layer is generally more stable. Therefore, the surface stations are not subjected to the large eddies which are present during the day. Second, the nocturnal flow is not complicated by a convective mixing regime, where the prevailing westerly winds reach the surface, as described by Banta (1982). At all of the mesonet stations, the downslope wind has a westerly component, so that, even if a similar mixing process were to somehow develop at night, the prevailing westerlies would tend to assist rather than oppose the downslope wind. Third, the much larger increase at the mountain stations at night can be explained by the development of localized nocturnal downslope flows at the two mountain stations located in high valleys. These nocturnal mountain flows are better shielded from synoptic-scale disturbances than are their lowland counterparts. At the same time, the other two mountain stations are near peaks which are well exposed to the mid-level (700 mb) winds. The early morning (0500 MST) Denver 700 mb wind is highly persistent (.73 for the July 1982 period).

Conversely, the persistence at mid-day is low. In addition, the upslope/downslope transitions near sunrise and sunset are characterized by a very low persistence. This combined daytime period of low persistence is fairly broad at the lowland stations. However, the mountain stations have a fairly short period of low persistence and a more rapid recovery to the higher values. The lower persistence in the day is a consequence of (1) boundary layer dry convection (e.g., thermals) and (2) daytime thunderstorm activity.

Averaged over the entire mesonet for all hours of the day, the persistence is fairly low compared to studies of diurnal flows in other areas (e.g., Skibin and Hod, 1979). The synoptic pattern in this area, even during the summer, is not highly persistent. Also, frequent afternoon and evening thunderstorm lower the persistence. In this area, the differences in persistence between the wind regimes and between the two distinct station areas are important and need to be kept in mind when interpreting the results.

Hourly streamline analyses of the mean July 1981 winds are presented in Johnson and Toth (1982). In Fig. 10 are shown selected analyses from that report, for comparison with later figures. Figs. 10a and 10c are the downslope and upslope regimes, respectively, at the times when these flows have become fully developed. Figs. 10b and 10d are the transition periods. The stations in and near the foothills have just recently had a shift in wind direction at the times of these two transition figures.

Fig. 11 shows the upslope regime for June and for August of 1981. Comparison of these two analyses with the July 1981 analysis (Fig. 10c) will show that the flow at this hour, 1600 MST, is indeed consistent, even though the persistence at this time (similar to Fig. 9) is quite low. The low persistence at this time indicates only that a number of random winds have been averaged in with the mean diurnal upslope flow, and therefore, reduced the resultant speed while not affecting the resultant direction. The July (Fig. 10c) and August (Fig. 11b) analyses both show upslope flow towards the Continental Divide, turning either north towards the Cheyenne Ridge or south towards the Palmer Lake Divide. The June flow (Fig. 11a) is slightly different. These subtle differences will be expanded upon later in this section.

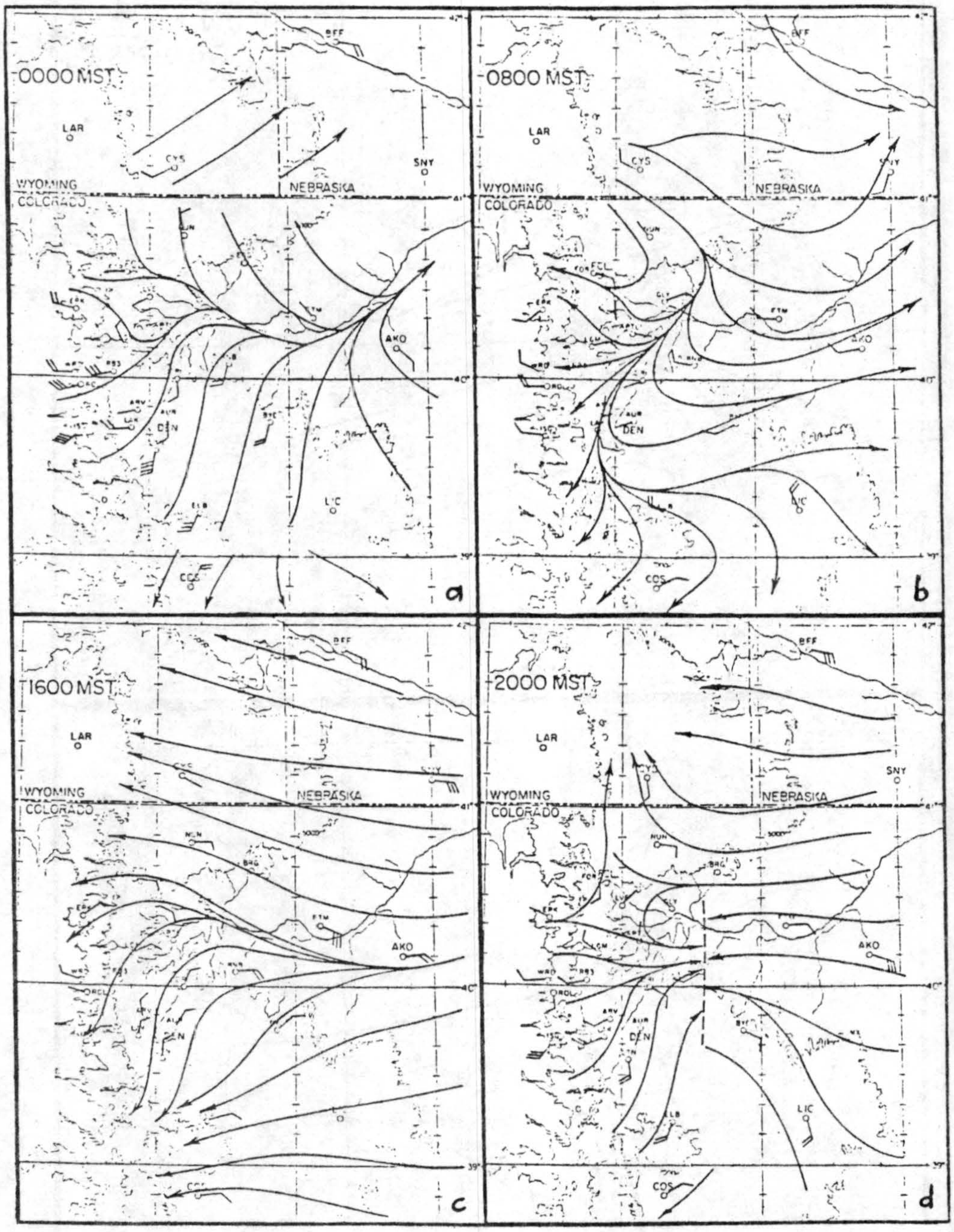



Fig. 10 Surface streamline analyses for July 1981 (a) 0000 Mountain Standard Time (MST) (b) 0800 MST (c) 1600 MST and (d) 2000 MST (from Johnson and Toth, 1982) (one full barb = 1 m $s^{-1}$).

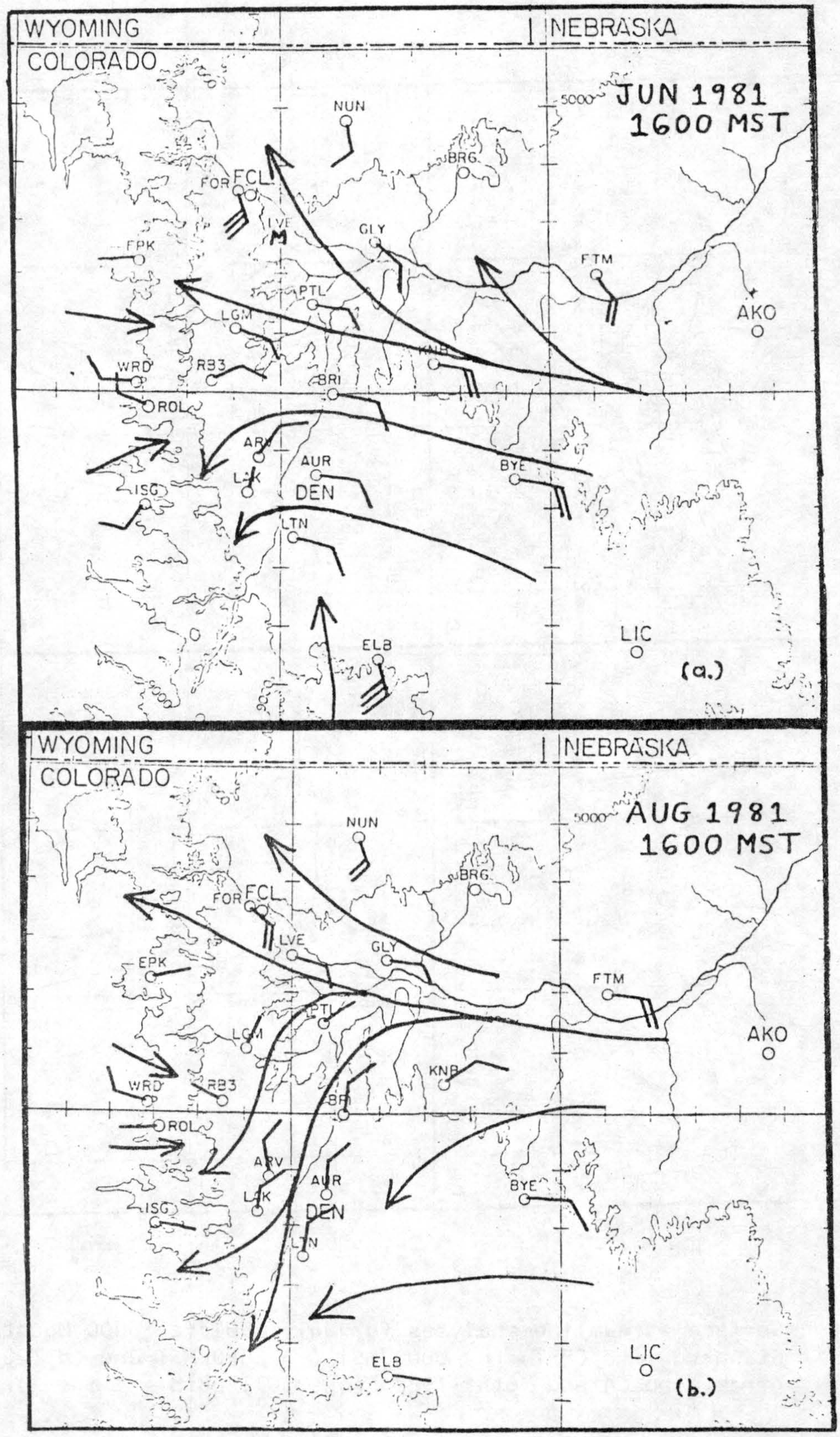



Fig. 11 Upslope regime for June and August 1981. Plotted as in Fig. 10.

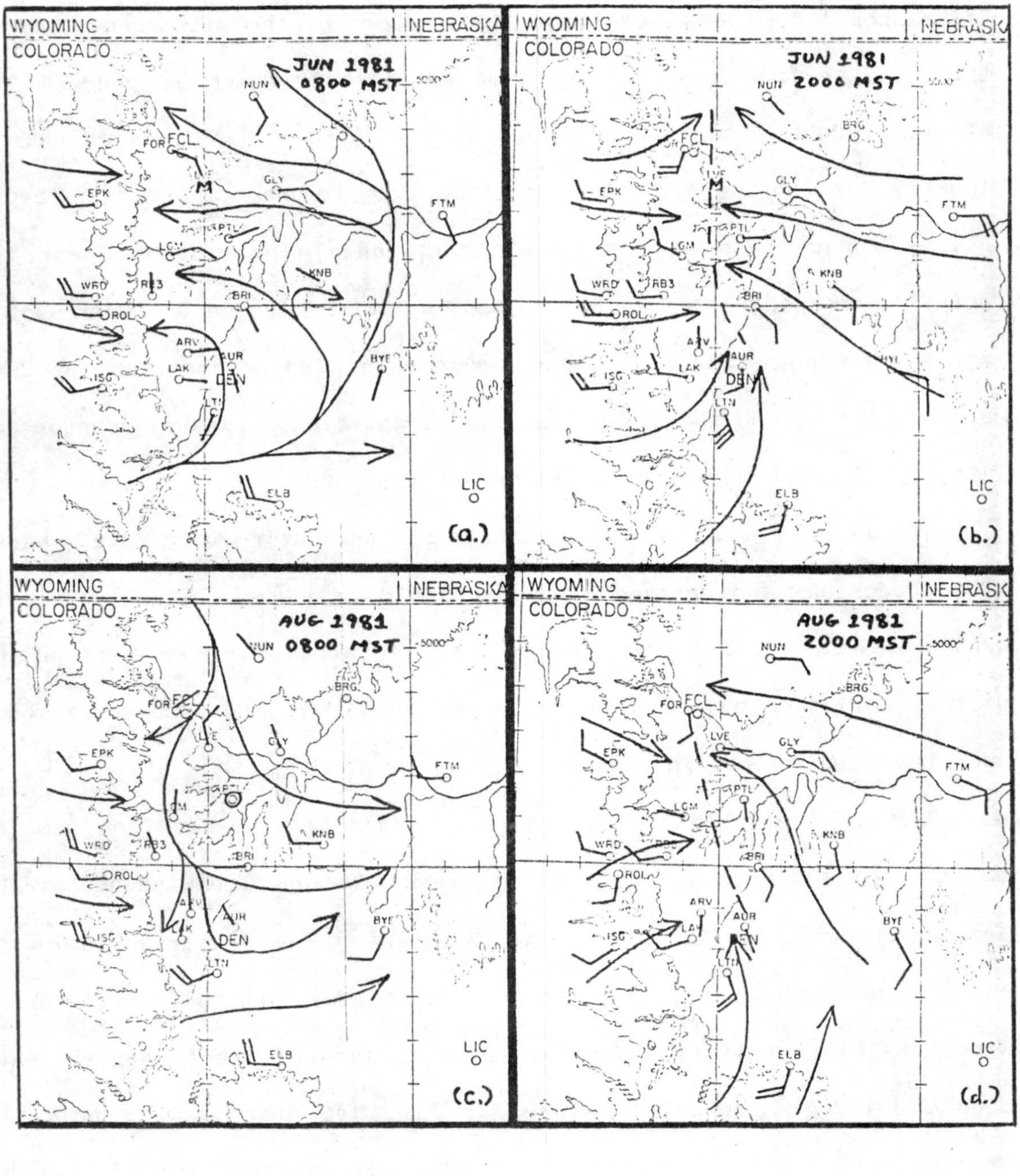



Fig. 12 Transition periods for June and August 1981. Plotted as in Fig. 10.

The flow at the transition times is shown in Fig. 12. Analyses for the June (Fig. 12a), July (Fig. 10b), and August (Fig. 12c) morning transitions are very different. It should be noted, however, that the differences are in areas of light winds. Some of the differences may be attributed to the change in the time of sunrise, which averages ~0.5 h later in August than in June and July. Also, the flow in June is slightly less northerly. The nighttime transitions compare more favorably. In each case, a north-south confluence line develops near the foothills and progresses eastward, passing out of the mesonetwork ~4-5 h later. The June (Fig. 12b) and August (Fig. 12d) transitions at 2000 MST are ~1 h behind the July (Fig. 10d) transitions found by Johnson and Toth (1982); otherwise, the patterns are similar.

Of course, there are other methods for presenting wind data. Here, wind hodographs and derived kinematic fields are used. Wind roses were experimented with, but were found to be too awkward for presenting the diurnal variation over the entire area. Moreover, the wind roses would add little additional information.

Because the amplitude of the wind oscillation varies from station to station, and because the station spacing varies, the wind hodographs are presented in two figures. Fig. 13 covers the entire area, including the surrounding conventional stations. In the western half of the area, where the mesonet station density is high, some of the hodographs have been omitted. These are restored in Fig. 14, which covers only the western half. The hodograph for LTN has been omitted from Fig. 14 due to its large nocturnal component. Several stations, particularly those on the northern slope of the Palmer Lake Divide (Fig. 13), have a prominent clockwise rotation of the wind vector with time. In the northern

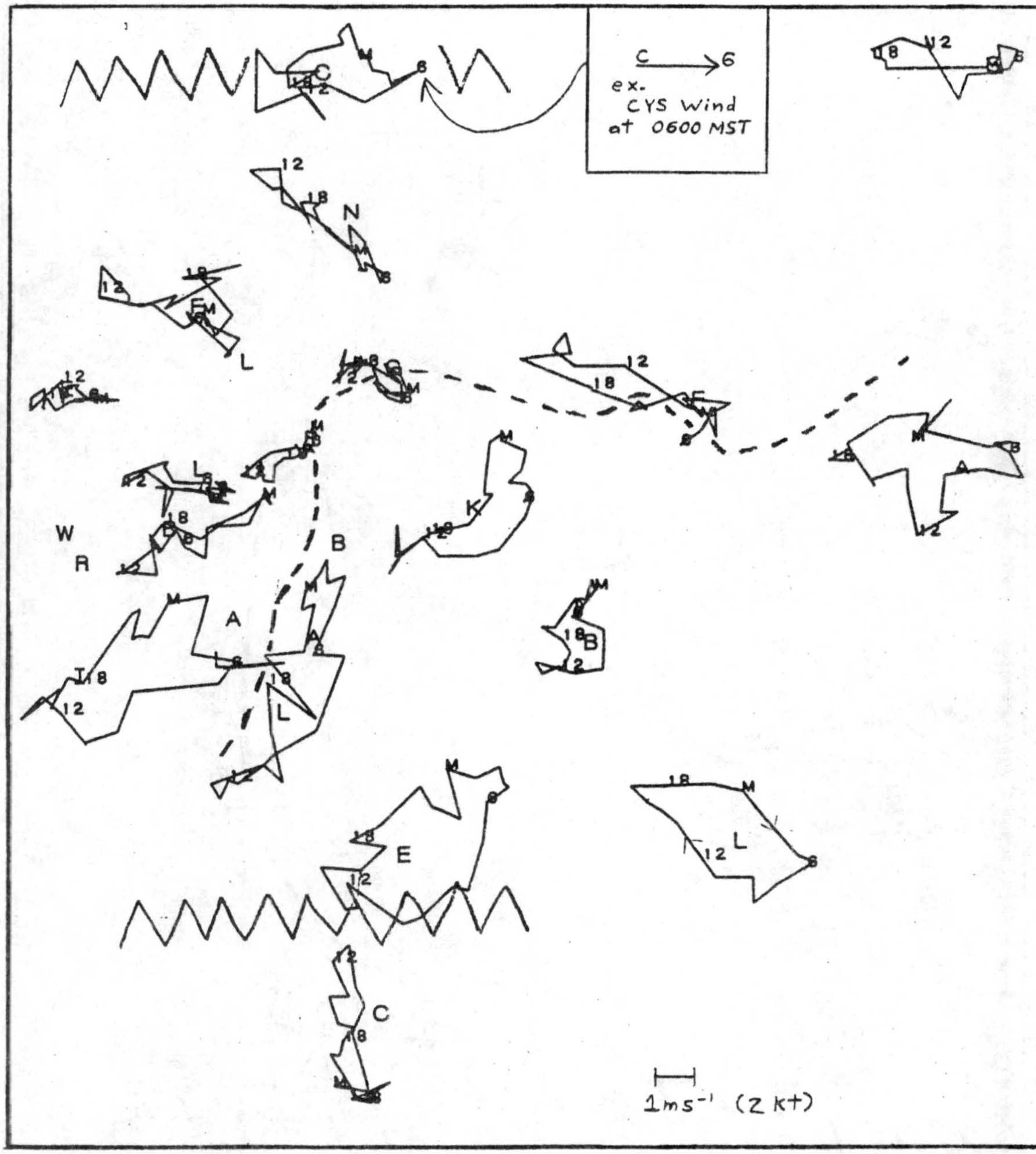



Fig. 13 Surface wind hodographs for the entire area, July 1981. The stations are labeled by their first letter. The wind vector end points are labeled at midnight (M), 0600 (6), 1200 (12), and 1800 (18) MST. The point indicated by each label is at the lower left corner of the label. The jagged lines indicate the Cheyenne Ridge and the Palmer Lake Divide. The dashed line indicates the South Platte River.

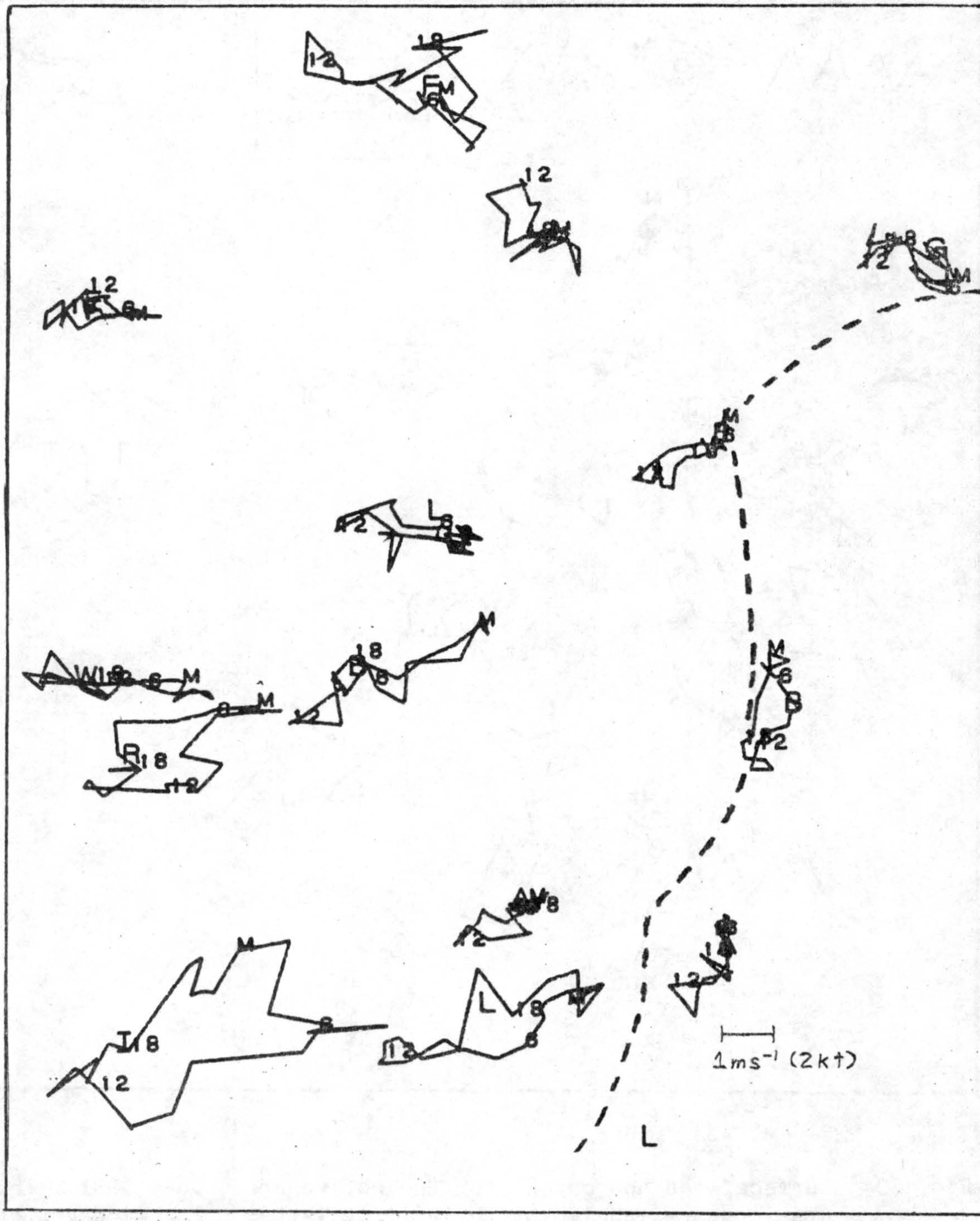



Fig. 14 Surface wind hodographs for only the west-central portion of the area, July 1981. Plotting conventions as in Fig. 13.

hemisphere, even if the horizontal forcing is limited to one dimension, clockwise turning is to be expected because of the Coriolis force. On the other hand, counter-clockwise rotation requires a horizontal forcing that turns counter-clockwise with time (Kusuda and Alpert, 1983; Mass, 1982). The only clear-cut counter-clockwise rotation is at FTM (Fig. 13), and even then for only part of the day. Other stations near the Cheyenne Ridge (e.g. NUN, Fig. 13) and to the north of the South Platte River (e.g. LGM, Fig. 14), although not actually counter-clockwise, do have a much reduced clockwise rotation. Based on the direction of turning of the hodographs, or on the lack of turning, some conclusions will be made in Chapter V about the change with time in the direction of the pressure gradient. Again, it is clear from the hodograph presentation that the amplitude of the diurnal wind oscillation changes considerably from station to station.

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 basic diurnal pattern presented in Johnson and Toth (1982) was found to be the dominant control on the local circulation for most summer situations. Stratification based only on the winds aloft revealed little difference in the average pattern. Only the timing of the transition from upslope to downslope was affected (1-2 h earlier with stronger westerly winds aloft). Although the timing changed, the nature of the transition (i.e. beginning near the foothills and propagating eastward) remained the same.

There are subtle differences between the severe weather synoptic situation as described by Doswell (1980) and the "normal" situation. Fig. 15 is a comparison of the average divergence and vorticity fields for all days in July 1981 (15a,c) and for 15 severe weather days selected from all 3 of the 1981 months (15b,d). (The differences are more apparent in the kinematic fields than they are in the streamline analyses.) The severe days were selected based on reported severe weather within the mesonet area meeting standard criteria (tornado, or hail $\geq$ 3/4 in, or wind $\geq$ 50 kt) when there was a synoptic situation fitting Doswell's general description. Positive centers of convergence and vorticity are present near KNB for the "normal" days. Similar centers are present for the severe days, but the centers are shifted southeast towards the Denver area. Apparently, this is a reflection of the Denver area convergence-vorticity zones examined by Szoke _et_ _al_. (1983) in connection with severe storm and tornado development. The averaging method used here obviously smooths out any strong areas of convergence and vorticity, and these average results are not as enlightening as individual case studies. However, the average patterns do suggest that the convergence-vorticity zone between the South Platte River and the Palmer Lake Divide is a normal diurnal development. For the severe days that were averaged, the zone became enhanced and shifted towards higher terrain. The calculated surface vertical component of the wind, $\underset{\sim}{v} \cdot \nabla z$ (Fig. 15e,f), indicates that the same zone is an area of upward vertical velocity (0.5-1.0 cm at the $s^{-1}$) surface.

It was noted earlier that there were subtle abnormalities in the June 1981 flow. June contributed more to the severe day analysis in Fig. 15 than did each of the other two months. Considering this, the

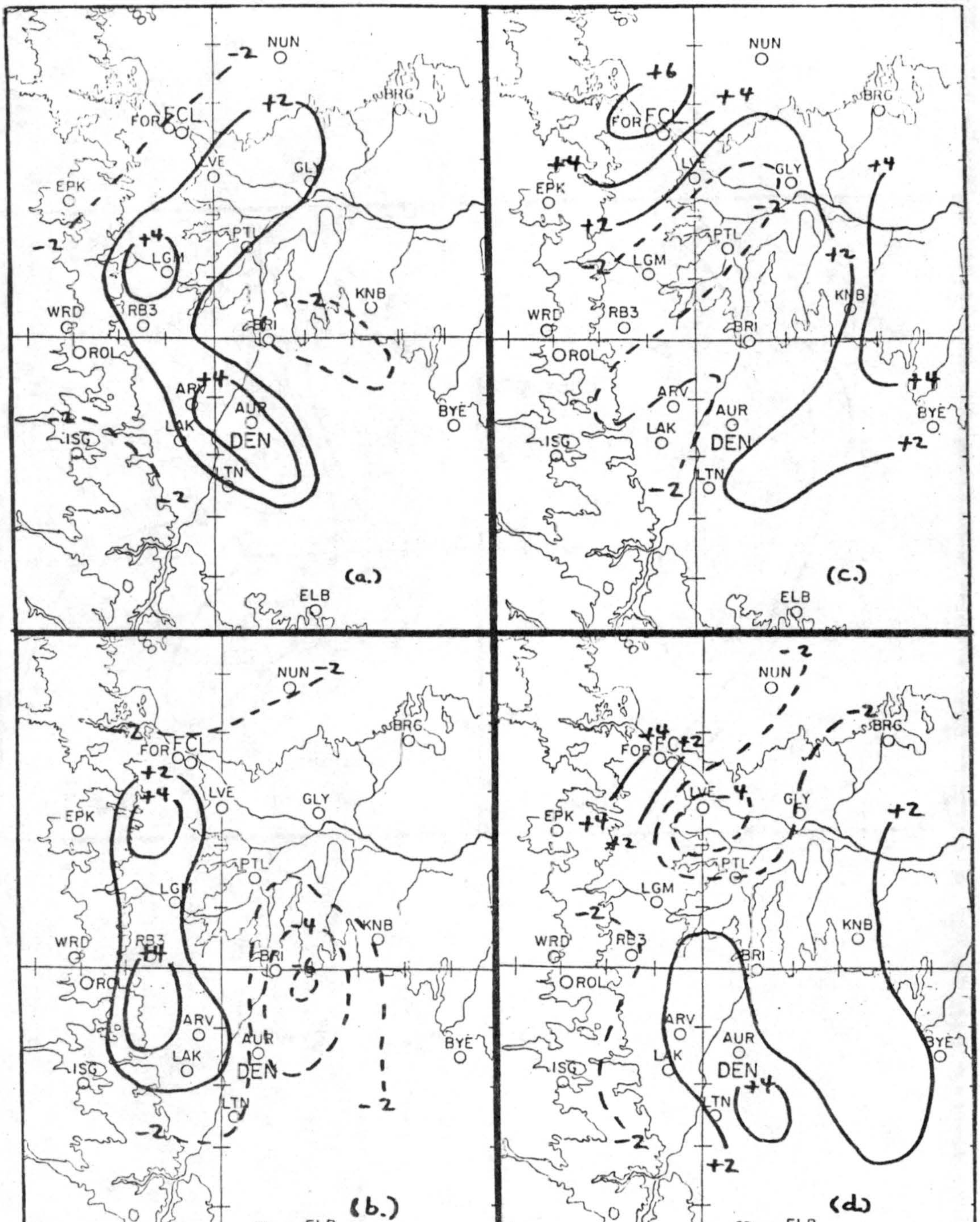



Fig. 15 Mean divergence and vorticity at 1300 MST for July 1981, compared with the same for severe weather days in 1981. Units are $\times 10^{-5}\ s^{-1}$. (a) divergence for July days (b) divergence for severe days (c) vorticity for July days (d) vorticity for severe days.

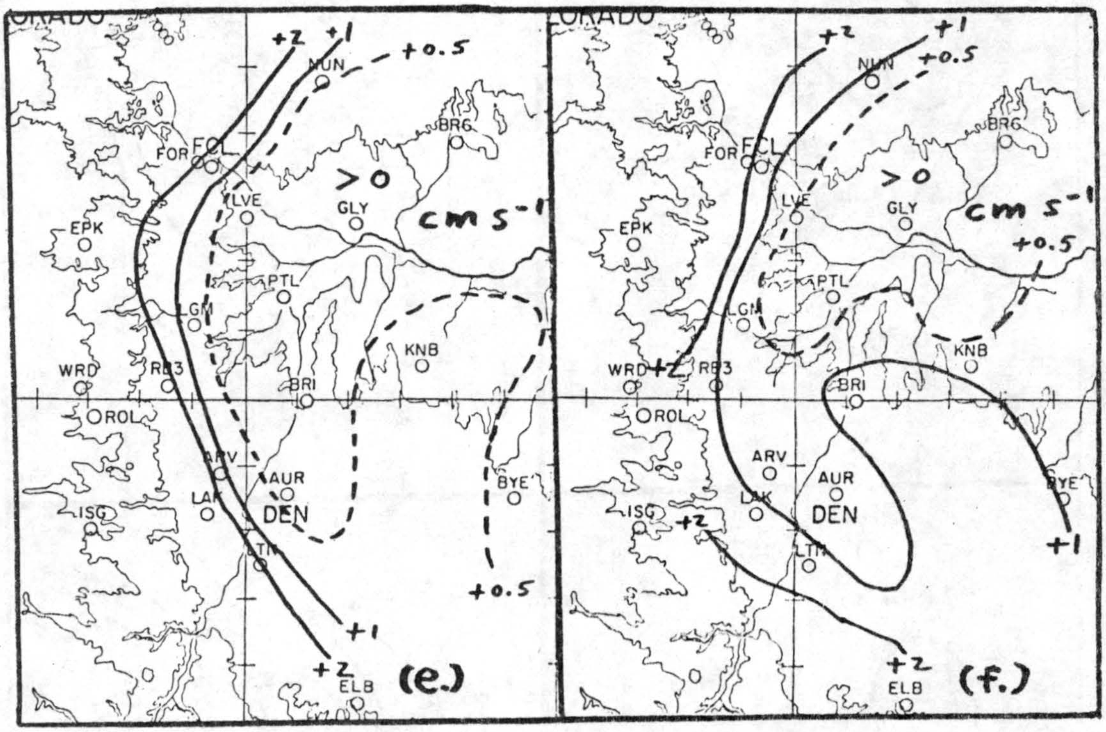



Fig. 15 (cont.) (e) $w_{sfc}$ - July (f) $w_{sfc}$ - severe.

differences between the June flow (Fig. 11a) and the August flow (Fig. 11b) may be seen as differences between a more severe month and a more "normal" month. Of course, several more years of data would be needed to determine if the difference in June is normal or merely a reflection of one or two severe episodes.

The remainder of this section deals with the mesonet wind fields derived from the early-July 1982 averaging procedure. The corresponding temperature, pressure, and solar radiation fields are presented in the next section. Days on which a strong surface front or upper-level trough was near the mesonet were not used. The remaining six days were characterized by a moderate southwesterly upper-level flow (500 mb wind speed 15-20 m $s^{-1}$), near normal upper-level temperatures (500 mb temperature ~ -8°C) and slightly below normal surface temperatures. Four of the days were relatively inactive in terms of strong thunderstorms, the other two were relatively active with severe weather reported. New details of the flow were found for these days, but the broad features of the wind field evolution were found to be the same.

Figs. 16 and 17 are the wind hodographs for the 1982 period (1-4 and 7-8 July). Even with the application of a cosine filter (Ch. II), and the use of five-minute data, the hodographs are not as smooth as their 1981 counterparts. Fewer days were averaged for 1982. Also, there was no attempt made to eliminate the effects of the 1982 convection. The FTM hodograph is peculiar. The wind vector there does not rotate smoothly counter-clockwise from southeasterly at 1200 MST to easterly at 1800 MST, as was the case for 1981. Instead, the wind nearly reverses to a weak downslope component before returning to the easterly upslope flow. The FTM wind has often been found to participate

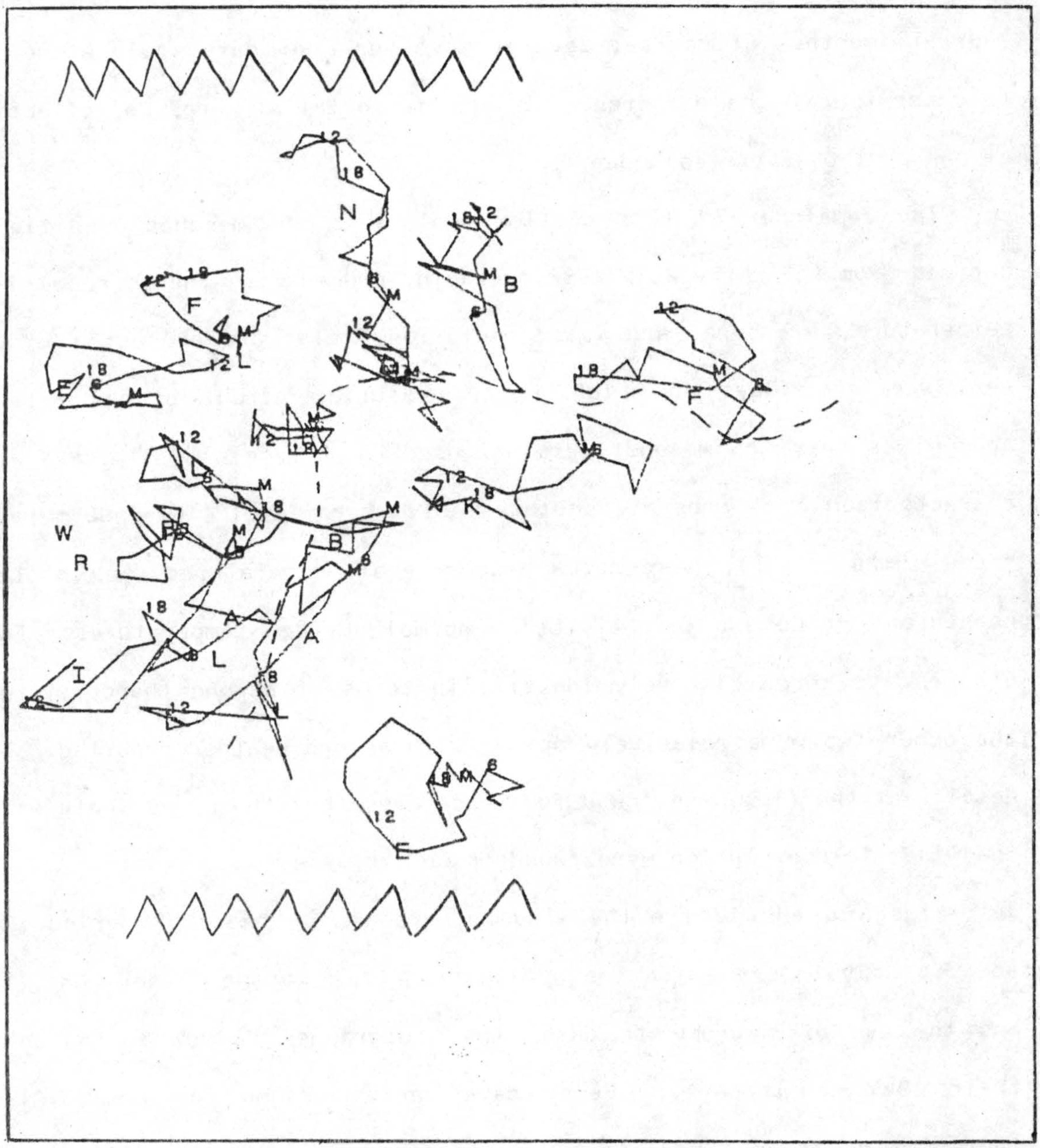



Fig. 16 As in Fig. 13, except for July 1982, and for the mesonet stations only.

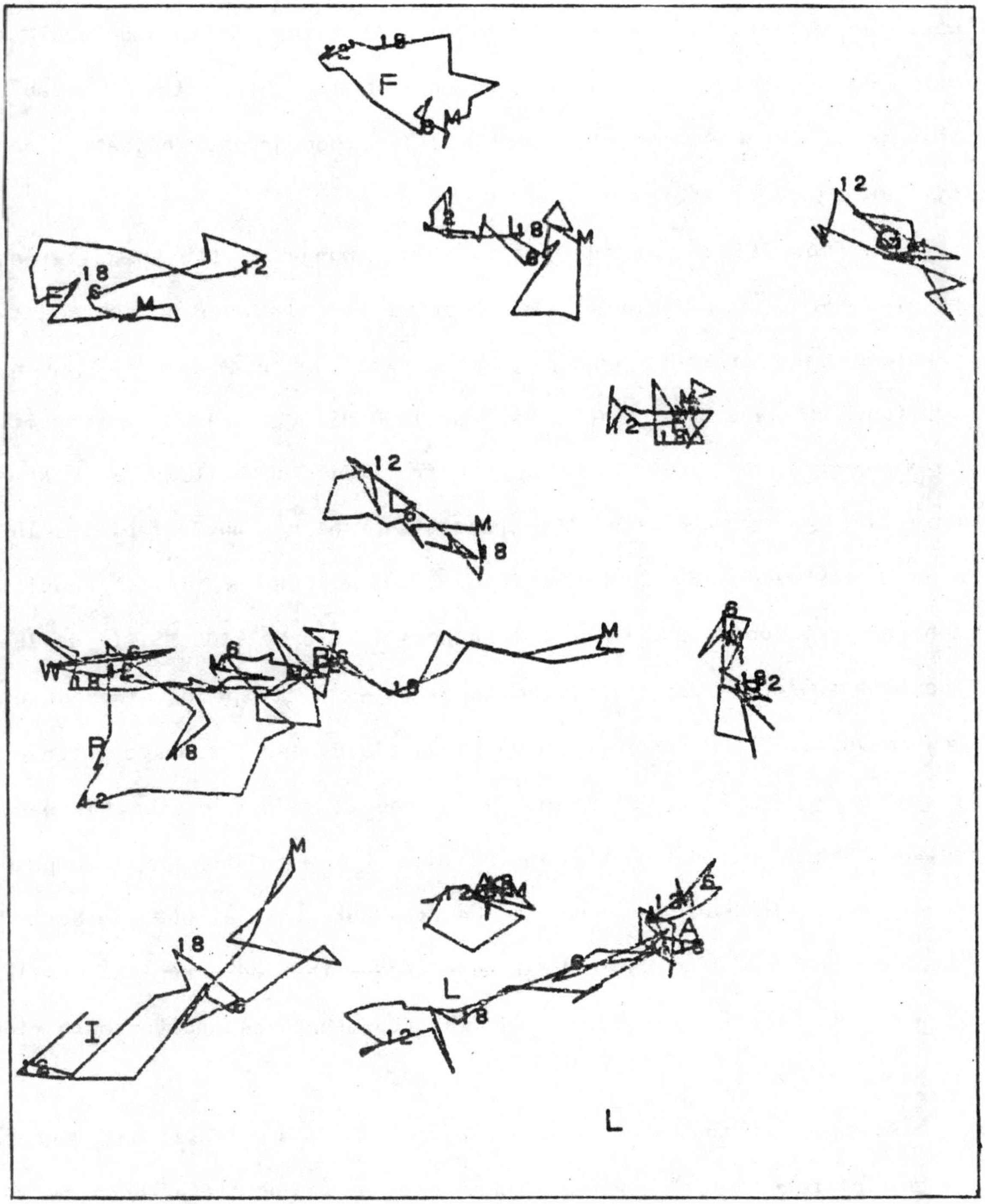


Fig. 17 As in Fig. 14, except for July 1982.

in the diurnal upslope flow only late in the afternoon, and this was the case for two of the six days averaged. At times (Smith, 1982) FTM may not participate at all in the diurnal flow. Other than the abrupt changes in the FTM wind, the 1981 and 1982 hodographs indicate broadly similar diurnal patterns.

In Fig. 18, streamline analyses are presented for the afternoon/evening transition period. Also plotted are the average surface temperatures and pressure changes, which will be examined in the next section. Between 1700 (Fig. 18a) and 1800 MST (Fig. 18b), a transition to westerly flow begins moving out from the foothills. By 1900 MST (Fig. 18c), for this case, the transition zone has moved rapidly (15-20 m $s^{-1}$) eastward. By 2000 MST (Fig. 18d), a complex, broad transition zone has developed, and this zone changes little by 2100 MST (Fig. 18e). The broadening of the transition zone may reflect the development of a new convective line as proposed by Erbes (1978) and discussed in Chapter I. Finally, by 2200 MST (Fig. 18f), the downslope regime has become established over nearly the entire area. A weak downslope component develops at FTM over the next few hours. Note that at BGD, an easterly component of the wind could be interpreted either as a regional upslope flow or as a small-scale downslope flow from the small north-south ridge located just east of BGD.

Aside from the more uneven nature of this transition, and the slight differences in timing, there are no major differences between this afternoon/evening transition period and the ones presented previously. In the following section, other, related fields are presented for this same period.

## B. Related Fields

Although only 6 days were averaged for 1982, the wind fields were found to be broadly similar to the 1981 analyses, and this was not surprising. In this section, the related temperature, solar radiation, and pressure data for the same 6 days are presented. Each period of days began and ended at sunrise, and so at that time the curves are discontinuous. The periods began after a stronger weather disturbance had moved east (higher pressure over the PROFS area) and ended as a new disturbance was approaching from the west (lower pressure). Rather than hourly analyses of the fields, time series were plotted for selected stations along a line through the mesonet. The line extends from the west, near the middle of the mesonet, east to the South Platte River, and then downstream along the South Platte to FTM.

Figure 19 is a plot of the potential temperature at each hour for the five stations along the line. The three lowest stations (PTL, GLY, FTM), which are on the plains, begin the day with a stronger temperature inversion than BOU, which is a foothills station, which itself is colder (potentially) than the mountain station of ROL. The potential temperature difference decreases throughout the morning, but is still present at noon. Excluding PTL, the remaining four stations have a double maximum in temperature. This effect becomes less pronounced further east (lower elevations) and might be better considered as a leveling-off of the temperature, since the dip between the temperature peaks is small. The dip itself may, to some extent, reflect the averaging of several days, each with a different amount of convective activity and, as a result, a different time of maximum temperature. ROL reaches the leveling-off temperature just before noon; this time is consistent with

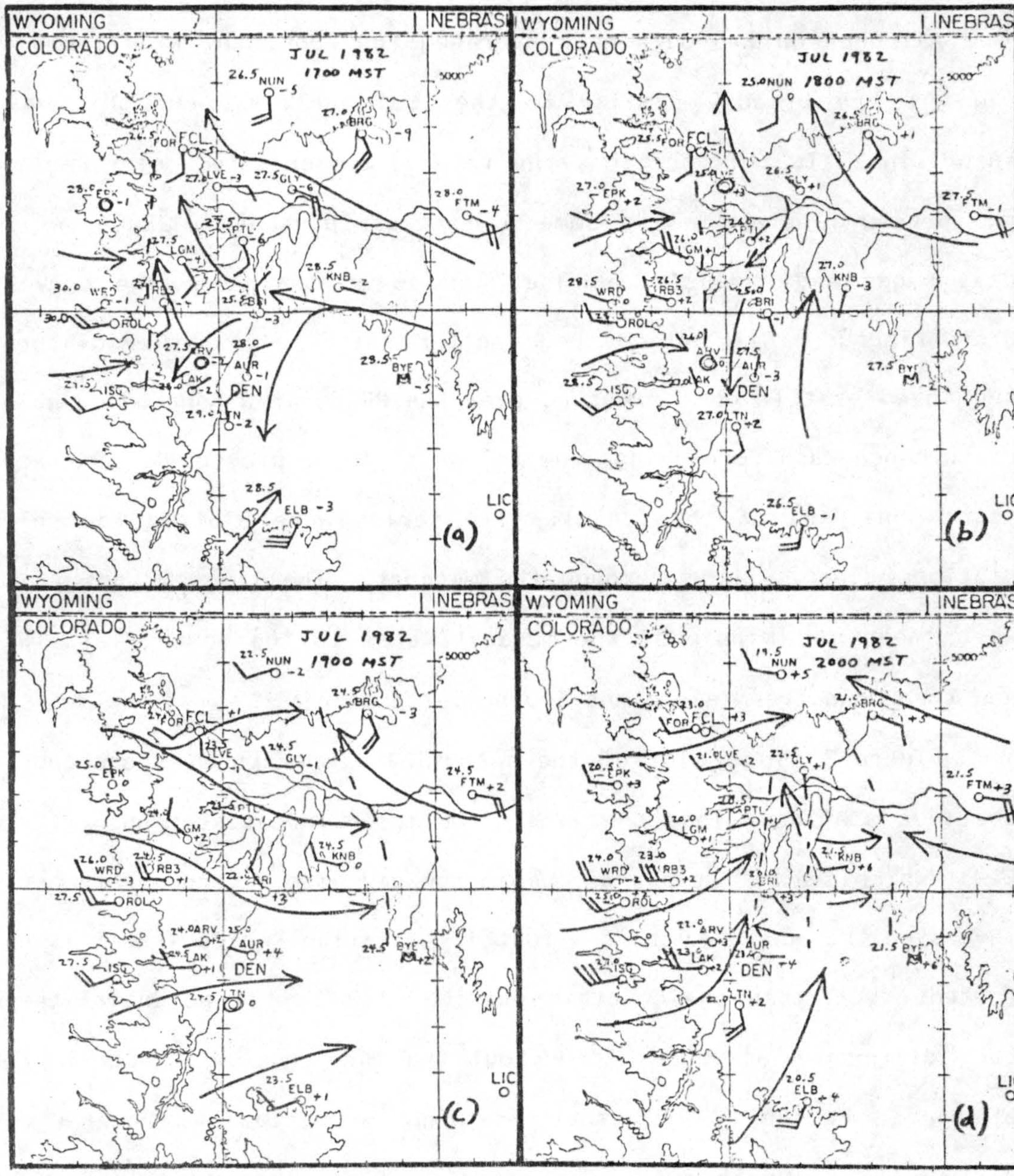



Fig. 18 Surface plot and streamline analyses for early July 1982. Wind plots and streamline analysis as before. Average potential temperature (°C, reduced to reference level of 1615 m, often referred to as "$\theta_B$") is plotted at the upper left corner of the station. Average one-hour pressure change (0.1 mb) is plotted to the right of the station. (a) 1700 MST (b) 1800 MST (c) 1900 MST (d) 2000 MST.

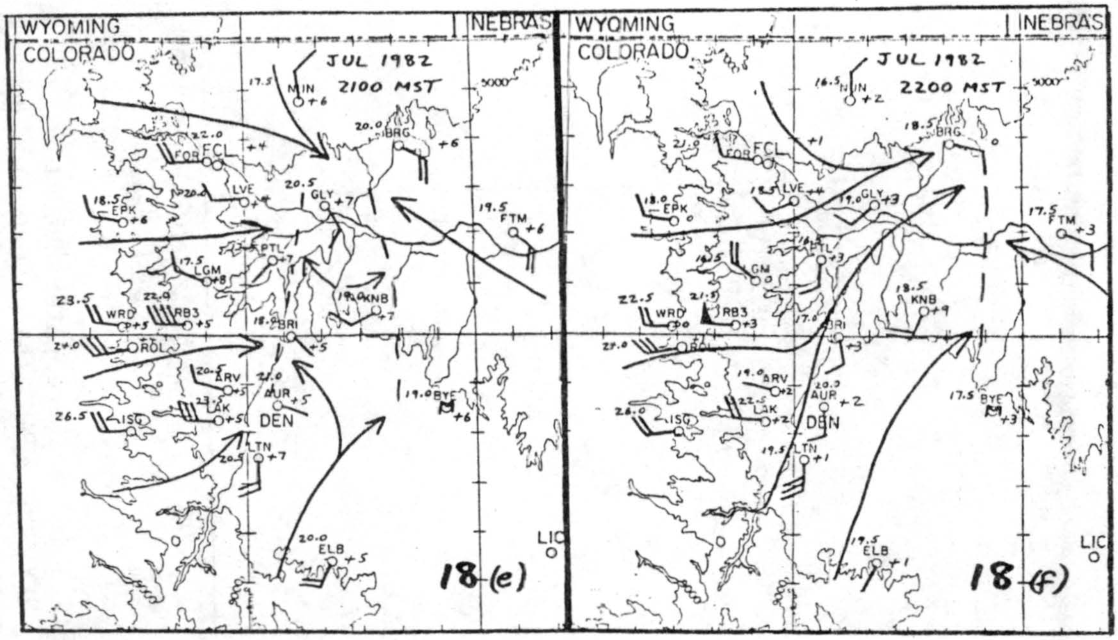



Fig. 18 (cont.) (e) 2100 MST (f) 2200 MST.

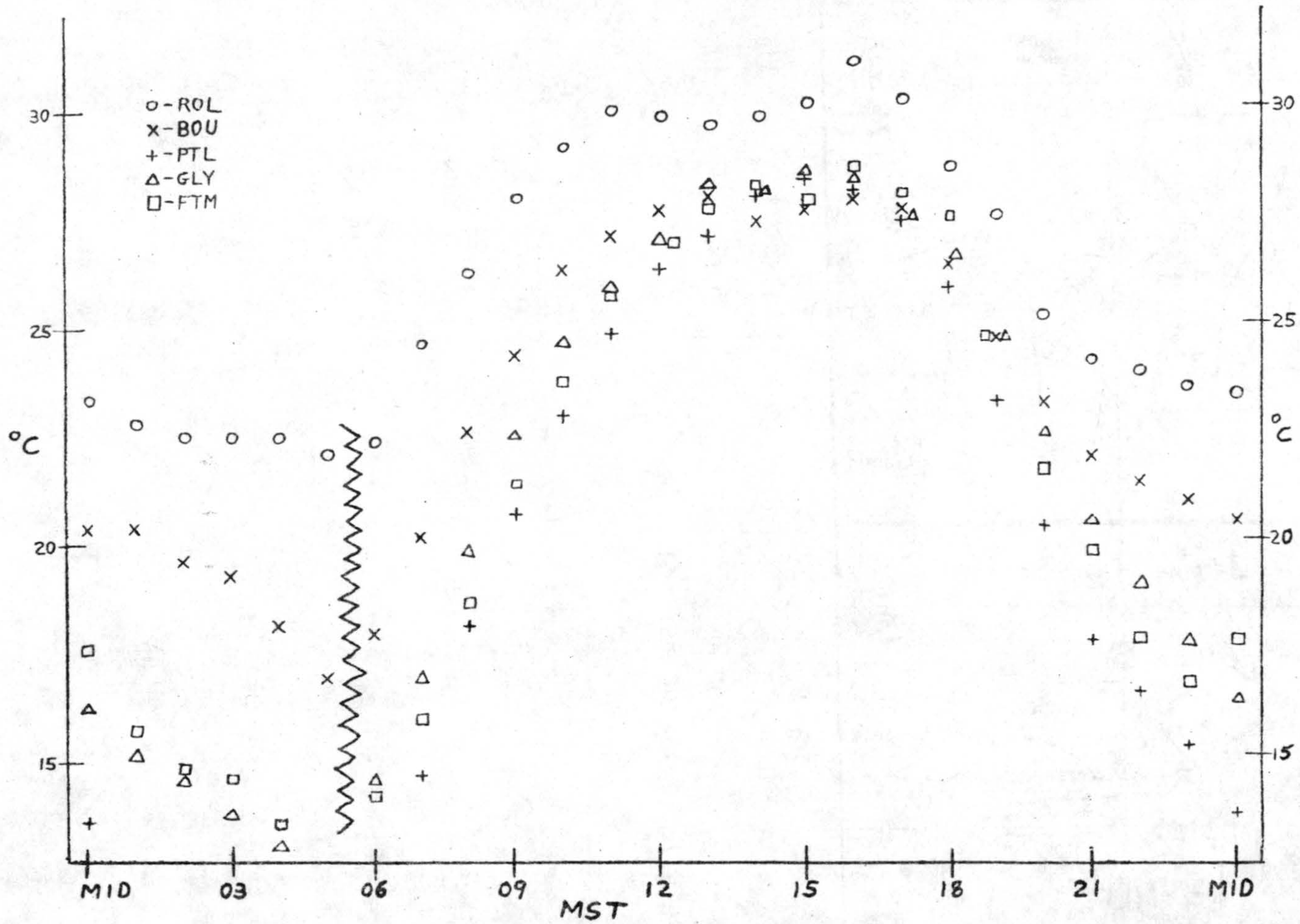



Fig. 19 Time series of the average temperature (°C, potential temperature referenced to Boulder's elevation of 1615 m) for ROL, BOU, PTL, GLY, and FTM. The jagged line at 0500 MST indicates the (arbitrary) start and end point for the data.

Smith (1982) where it was reported that the mountain-peak stations were the first to reach their maximum temperature--at noon. BOU achieves this same leveling-off point shortly after noon, and the other stations about an hour later. The temperature behavior at PTL is not consistent with GLY and FTM, and this may be caused by PTL's location closer to the bottom of the river valley, whereas the other two stations are at airports and on ground slightly elevated above the valley. (The behavior of the time of maximum temperature as a function of elevation is opposite the heating function specified by Hughes (1978, his Fig. 13). His numerical simulation of the flow over this area had the earliest maximum temperatures at the <u>lowest</u> elevations.) For the remainder of the afternoon, the lowland stations maintain nearly equal potential temperatures. Often, the lowland potential temperature will approach the mountain potential temperature as showers develop over the mountains. By 1800 MST, all the temperatures are dropping, although not as fast at FTM as at the other stations. But by 2000 MST, FTM has joined PTL and GLY in a rapid cooling, while BOU has leveled off.

Interpretation of the interaction between the surface winds, discussed in the last section, and these surface temperatures suffers from the lack of information about the time behavior of the temperatures <u>above</u> the surface. However, some speculations can be made about the vertical temperature structure, especially during the afternoon when the boundary layer is deep and well mixed. This speculation will be done in Chapter V.

Figure 20 is similar to Fig. 19, except that the variable plotted is the total solar radiation. Of interest is the relative difference between stations. Through 1000 MST, all stations receive nearly the

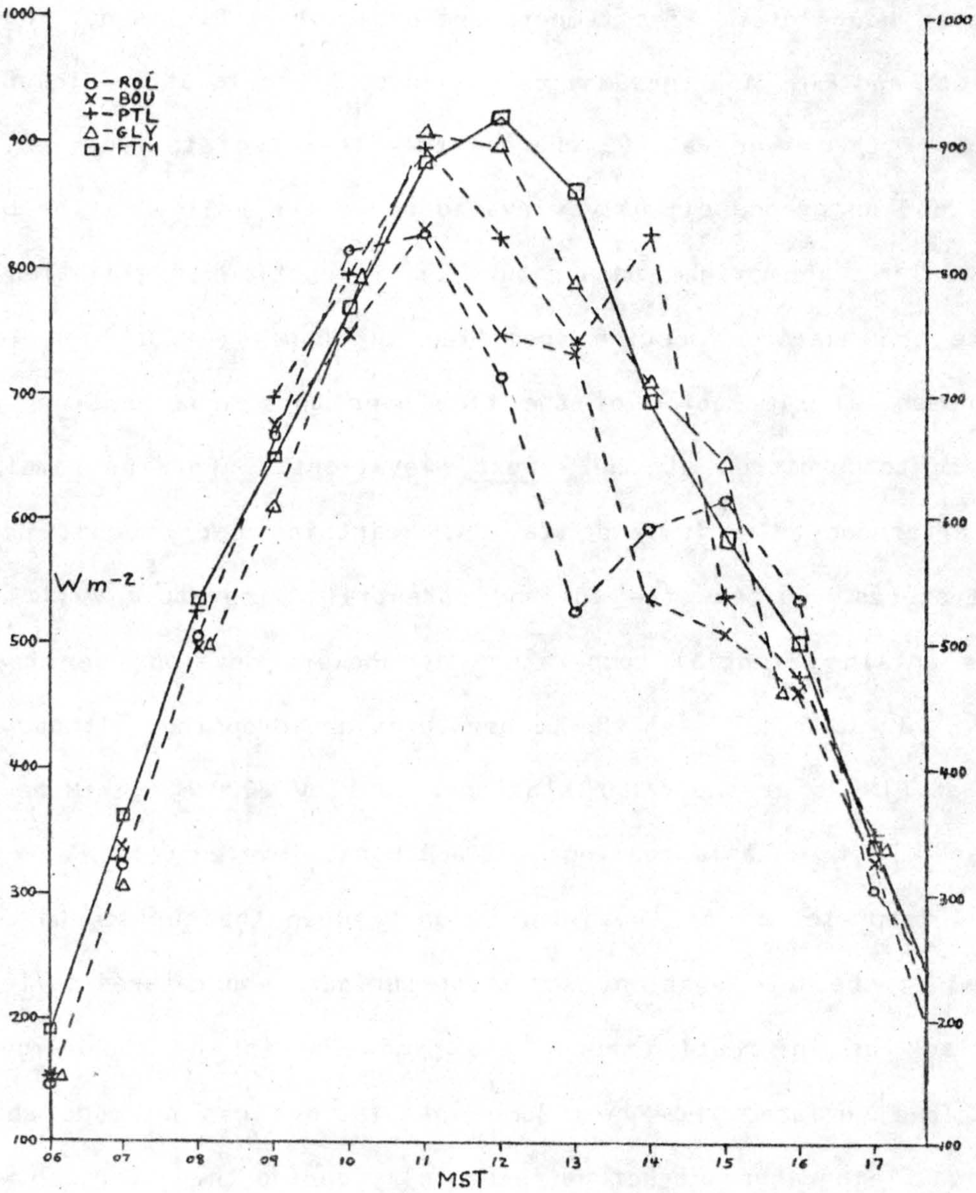



Fig. 20 Time series of the average total solar radiation (W $m^{-2}$) for ROL, BOU, PTL, GLY, and FTM.

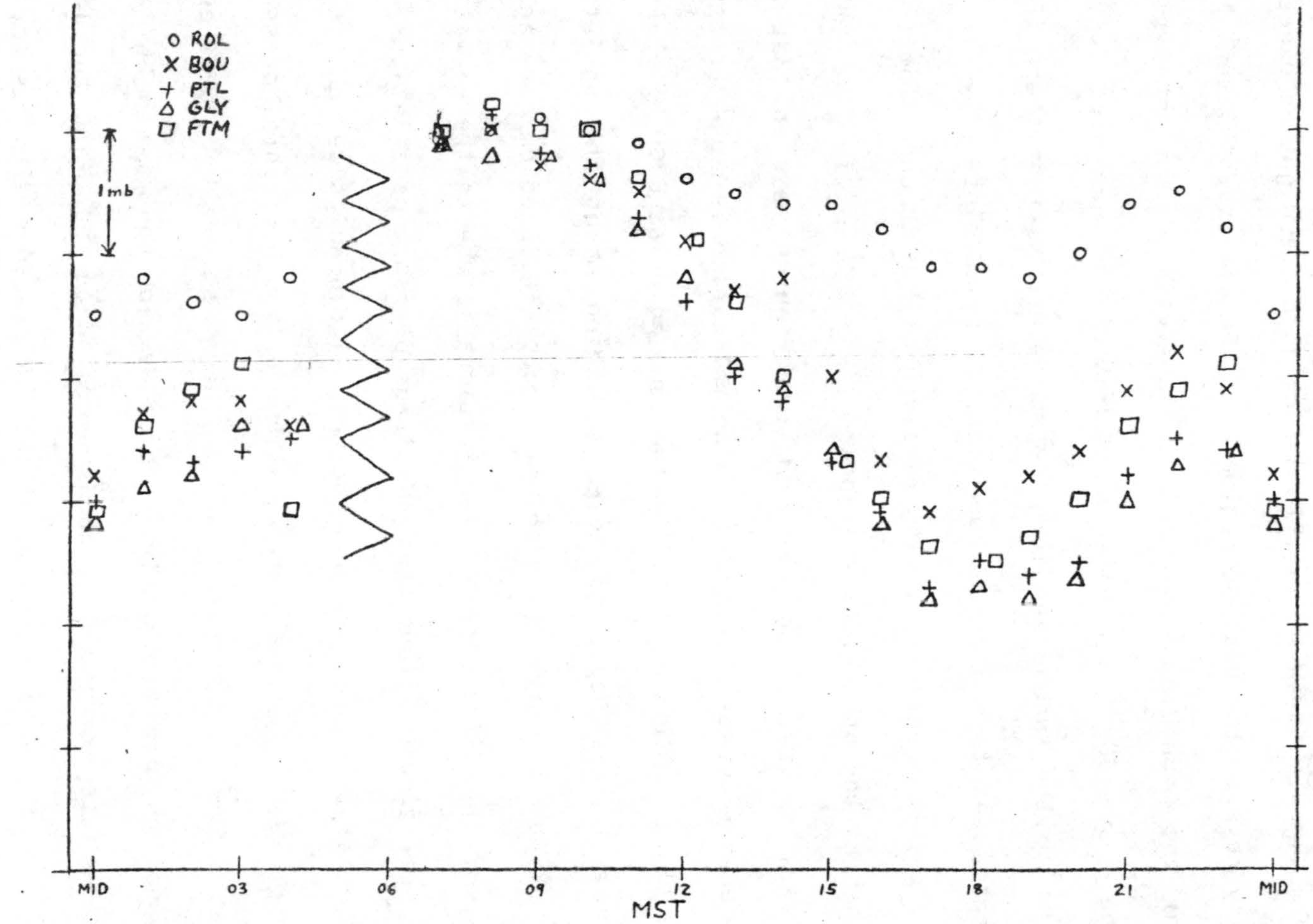



Fig. 21 Time series of the average pressure (1 mb scale shown) for ROL, BOU, PTL, GLY, and FTM. The plots have been shifted so that all five stations start from the same point at 0700 MST. The jagged line at 0500 MST indicates the (arbitrary) start and end point for the data.

same amount of radiation, although this amount is reduced slightly from its maximum possible value. At noon, increased cloud cover over the mountains has established a downslope solar radiation gradient from 700 W $m^{-2}$ at ROL to over 900 W $m^{-2}$ at FTM. Such a change might be expected to eventually reverse the upslope regime, but the effects of latent heat release near the mountains complicate the analysis of the total slope flow forcing. By 1500 MST, the solar radiation has increased at ROL, corresponding to the second and larger temperature maximum there (Fig. 19). BOU has moved to the bottom position, followed closely by PTL and FTM. Still, the integrated radiation received at FTM through this point is larger than at the other four stations.

Figure 21 is similar to the last two figures, except that the variable plotted is station pressure. A normalization is made such that each of the station plots starts from the same point at 0700 MST. From such a figure it was hoped to learn something about the variation through the day of the pressure gradient force. The problem here again is that most of the difference between stations is due to the elevation difference. The figure illustrates the large pressure oscillations due to a semi-diurnal pressure tide and the thermal diurnal tide, but it is difficult to estimate the small oscillations of the horizontal pressure gradient that drive the horizontal wind. There is some very weak evidence of an upslope pressure gradient force developing between GLY and PTL during the late morning, and then reversing again during the late afternoon. Also, the erratic change of the FTM pressure with respect to the GLY and PTL pressures at least agrees with the behavior of the FTM wind (Fig. 16). But, unfortunately, it is difficult, without corrections based on knowledge of the detailed vertical temperature structure throughout the day, to calculate the evolution of the horizontal pressure gradient.

This discussion completes the presentation of the climatological results. In the next chapter is a brief presentation of the behavior of the winds on some individual days. Following that is a discussion of the results from the two chapters.

# IV. INDIVIDUAL DAYS

The main focus of this study has been to develop an improved understanding of the diurnal variation of the surface flow over northeast Colorado and to determine the factors controlling its evolution. The purpose of this chapter is to present two individual days which illustrate the complex interaction of the afternoon wind flow with moist-convective systems. It is felt that these aspects are not obvious in the climatological portion of this study, or in other (i.e. radar and satellite) climatological studies (Chapter I).

That the afternoon diurnal wind flow affects the development of convection was shown in Johnson and Toth (1982). Confluence develops along the major east-west ridges (in Colorado the Cheyenne Ridge, Palmer Lake Divide and Raton Mesa), and, as a result, these ridges are preferred regions for thunderstorm development. Climatological radar and satellite studies have established the higher frequency of thunderstorm development along the ridges. In the first section of this chapter, a day is presented on which satellite imagery clearly reveals the development of thunderstorm cells in a preferred location--along the Cheyenne Ridge.

The second section is an example of the opposite effect. Afternoon thunderstorm development on an otherwise undisturbed day was responsible for large deviations from the diurnal flow that would normally have been expected.

A. 7 July 1983

After several dry days in eastern Colorado, a dominant, warm, upper-air high pressure cell responsible for a lack of thunderstorms over the area shifted slowly southeastward (Fig. 22, 1700 MST). A slightly cooler and slightly more moist south-southwesterly flow of air entered the PROFS area near ridgetop level (Fig. 22c) and above (Fig. 22a). The surface air was already sufficiently moist for thunderstorm development. By late afternoon, below ridgetop level, a diurnal upslope flow prevailed, although combined with a large-scale southerly component of the wind (Fig. 22b,d). Even though the flow at all levels had become more favorable for thunderstorms, the mid-afternoon thunderstorms were generally confined to the mountains, as can be seen in the satellite image for 1400 MST (Fig. 23a). East-west bands of towering cumulus can be faintly seen just north of the Cheyenne Ridge (north of the Colorado-Wyoming border near the middle of the picture), just south of the Palmer Lake Divide (slightly above the label for the city of Pueblo), and near the Raton Mesa (in the lower right corner). Fig. 23b is identical to Fig. 23a except that the image has higher contrast, and so the three areas of towering cumulus are more apparent. It is proposed that the development of these clouds is a consequence of low-level convergence and lifting caused by the normal, diurnal upslope flow towards the east-west ridges in a conditionally unstable environment. This cloud development is consistent with the composite radar studies by Henz (1973), and Wetzel (1974) which documented the preference for initial radar echo development along the ridges. Fig. 24a is a plot of the surface stations for approximately the same time as Fig. 23a/b. With the exception of CYS, where the wind was westerly, possibly due to the

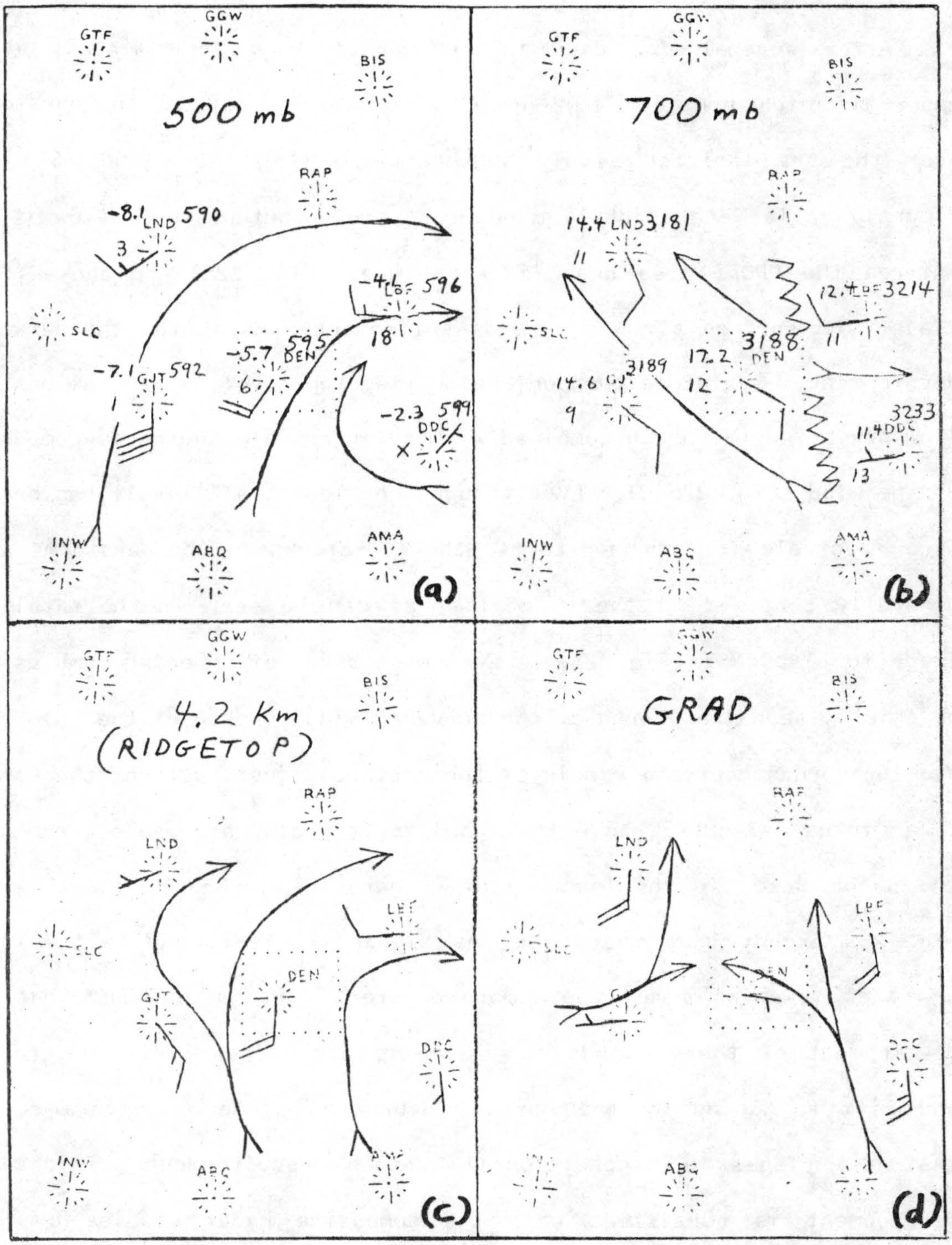



Fig. 22 Local upper-air pattern for 1700 MST, 7 July 1983. (a) 500 mb with temperature and dewpoint depression (°C), height (dm), wind (1 full barb = 5 m $s^{-1}$), and streamline analysis. (b) 700 mb, same as 500 mb except that height is in meters, (c) wind at 4.2 km above sea level (d) wind at the second standard level (~ 0.5 km above ground).

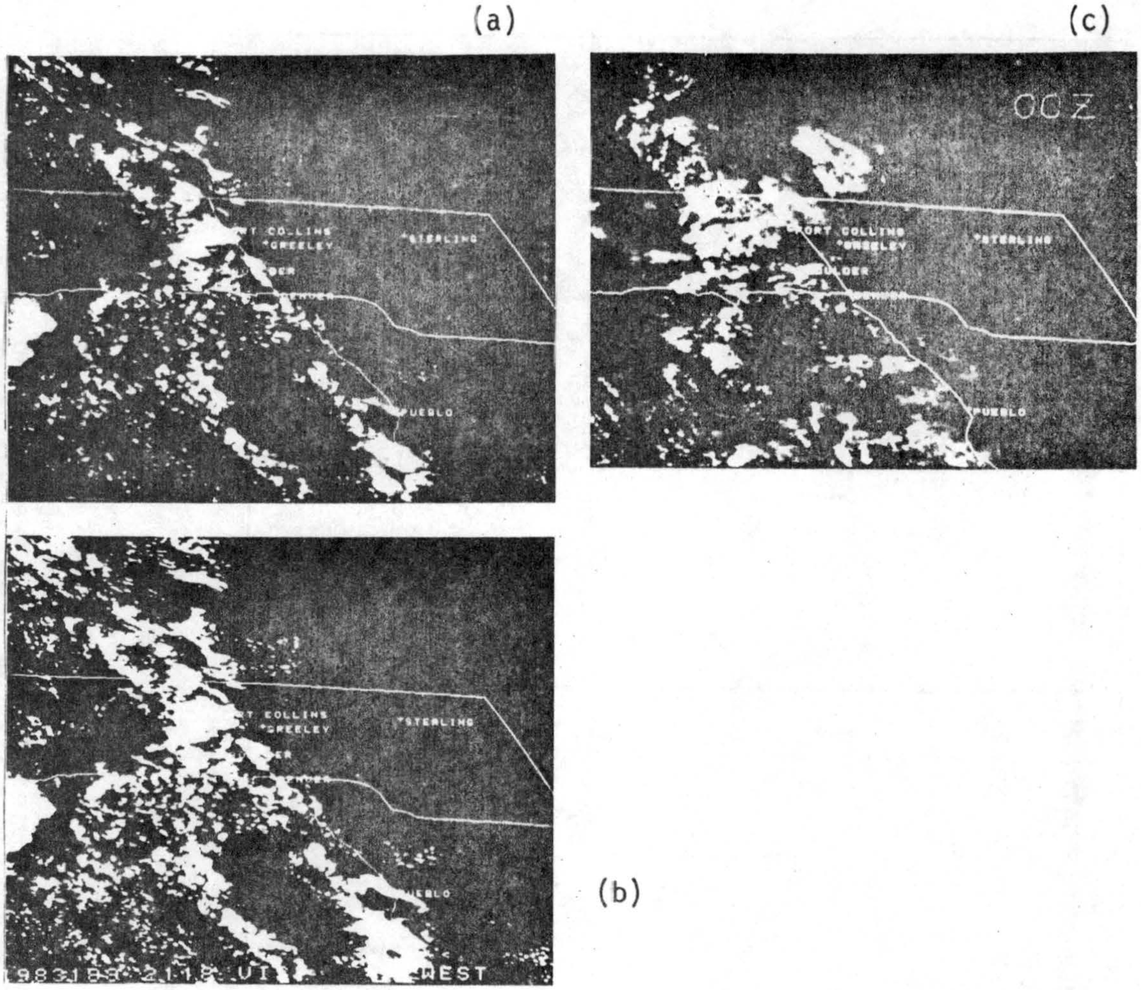



Fig. 23 Visible satellite imagery for 7 July 1983. (a) 1400 MST. (b) same as (a), but with higher contrast. (c) 1700 MST. The locations of a few eastern Colorado cities are labeled. Highway I-25, extending from near Fort Collins southward, marks the intersection of the plains (to the east) with the mountains (to the west). Also highlighted are highway I-70 and the Colorado State border.

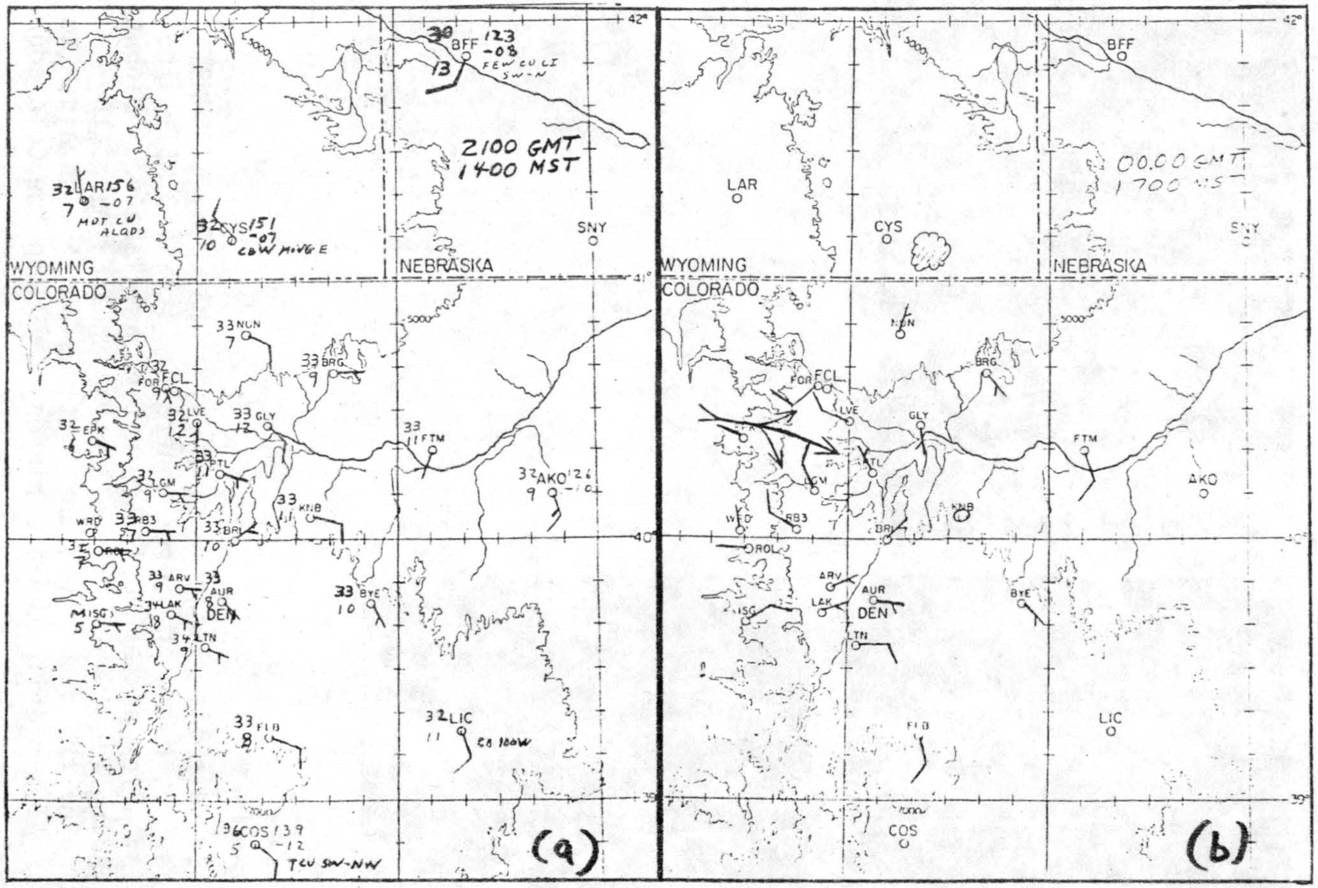



Fig. 24 Surface station plots for 7 July 1983. (a) 1400 MST with wind (1 full barb = 5 m $s^{-1}$), temperature (°C, potential temperature corrected to the 1615 m reference level), and dewpoint (°C). (b) 1700 MST with only winds. The cross-hatched scalloped area just east of CYS is the approximate location of the newly developed thunderstorms. Also indicated is the thunderstorm downdraft between FOR and LGM.

outflow from a thunderstorm to the west (the CYS observation includes the remark: cumulonimbus west moving east), a normal diurnal upslope flow had developed, again with an added, large-scale southerly component.

Turning again to the satellite imagery in Fig. 23a, and concentrating on the northern portion of the picture, we can see that a north-south line of clouds near CYS (just northeast of the intersection of I-25 with the Colorado border) had developed more than the towering cumulus further east along the Cheyenne ridge. Just west of this more highly developed line is a relatively clear area. By 1700 MST (Fig. 23c), the line had propagated eastward, and a large area of new thunderstorms had developed east of Cheyenne. One possible interpretation is that the line intersected with the area of enhanced clouds, and, as a result, the new thunderstorms developed (Purdom, 1976). Meanwhile, closer to Fort Collins, an earlier mountain thunderstorm left a large anvil over the foothills and slightly over the plains. A moderately strong, cold outflow from this cell had entered the foothills and plains between FOR and RB3 (Fig. 24b). Temperatures within this outflow were ~ 5°C colder than at 1400 MST; temperatures over the remaining area changed little. New storms might have been expected to develop along this outflow as it entered the plains, but new development suffered from the lack of a favorable environment. Unlike the Cheyenne Ridge area, the diurnal circulation had contributed to surface divergence, sinking, and a lack of clouds in this lowland area between the ridges.

This apparent role of the diurnal circulation over the plains, i.e. converging moisture onto the ridges and away from the river valleys, even if not acting as the thunderstorm trigger mechanism itself, is felt to be important on most other days. However, on many days the interactions are even more complicated than this case.

B. 20 July 1982

This day is an example of the normal diurnal flow leading to convective development, which then modifies the diurnal flow. The morning of 20 July 1982 began with the normal downslope to upslope transition. The large scale surface pressure gradient was very weak (DEN - LBF, NB; DEN - GLD, KS; both less than 2 mb). By 1300 MST (Fig. 25), upslope flow had become established, although a few stations (NUN, ELB, FTM) were not participating. In addition to the normal formation of clouds over the Palmer Lake Divide and Cheyenne Ridge, a band of clouds had developed along a line extending from ELB to the northeast corner of Colorado. This band (indicated by the dashed line in Fig. 25) was the remnant of an old, weak cold front. The cloud coverage along this band changed little during the afternoon. Included in Fig. 25 are the solar radiation data, which are circled at each station. The top number in each circle is the average of the solar radiation readings (rounded to the nearest $10^2$ W $m^{-2}$) over the previous hour. The bottom numbers are the range of the readings. From this plotted solar radiation information, it can be seen that mostly sunny skies prevailed over the lower portion of the South Platte River (FTM, GLY, PTL), while partly to mostly cloudy skies prevailed away from the valley. The east-west variation of solar radiation is similar to the averaged solar radiation data presented in the last chapter. The winds above Denver were light at all levels, throughout the day, including the late afternoon (Fig. 26).

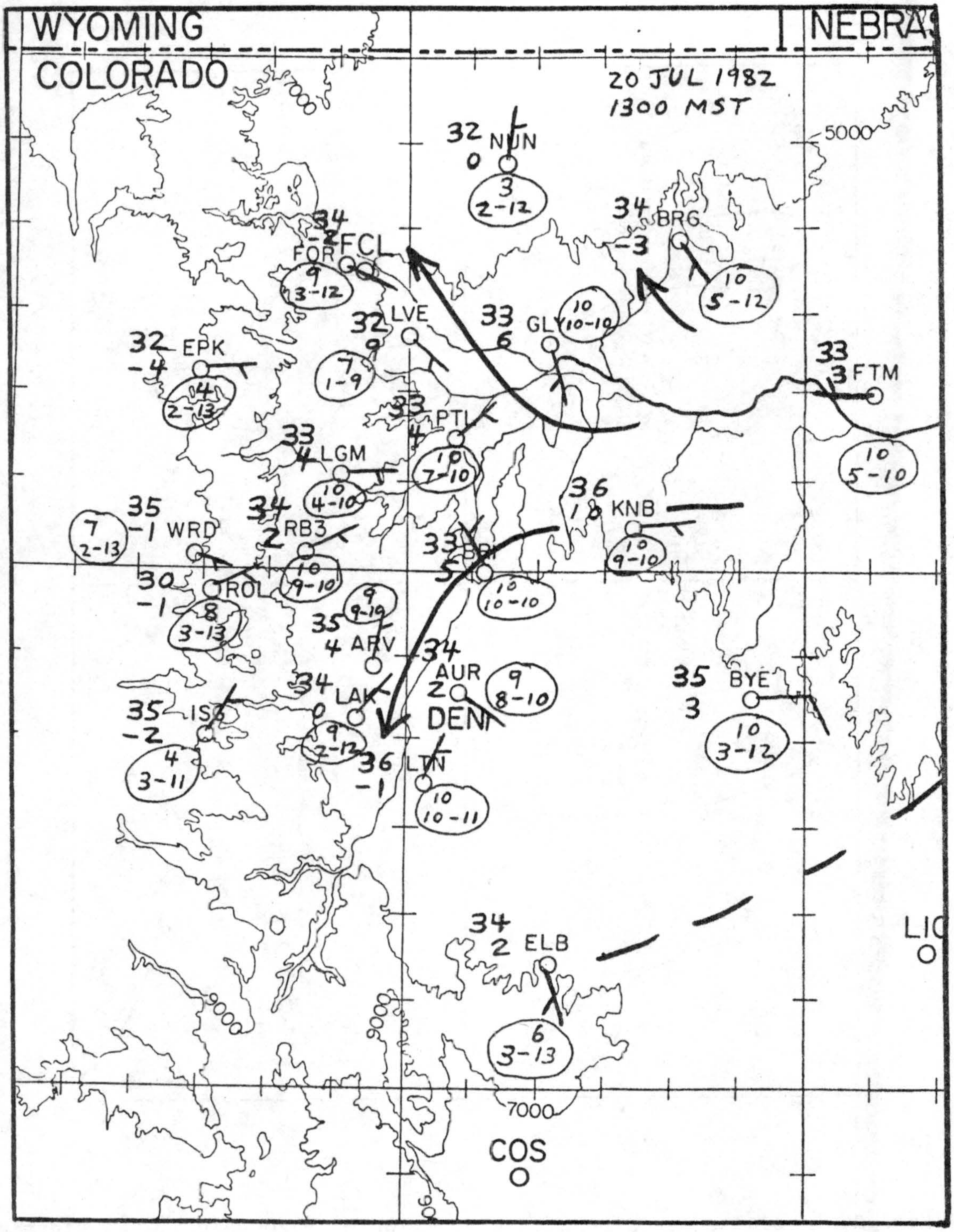



Fig. 25 Surface station plots for 1300 MST (1 hour average), 20 July 1982. Plotting as in Fig. 24a, except that solar radiation data (circled) have been added. The top value in the circle is the average solar radiation (100 W m$^{-2}$) over the past hour. The bottom values are the range over the past hour.

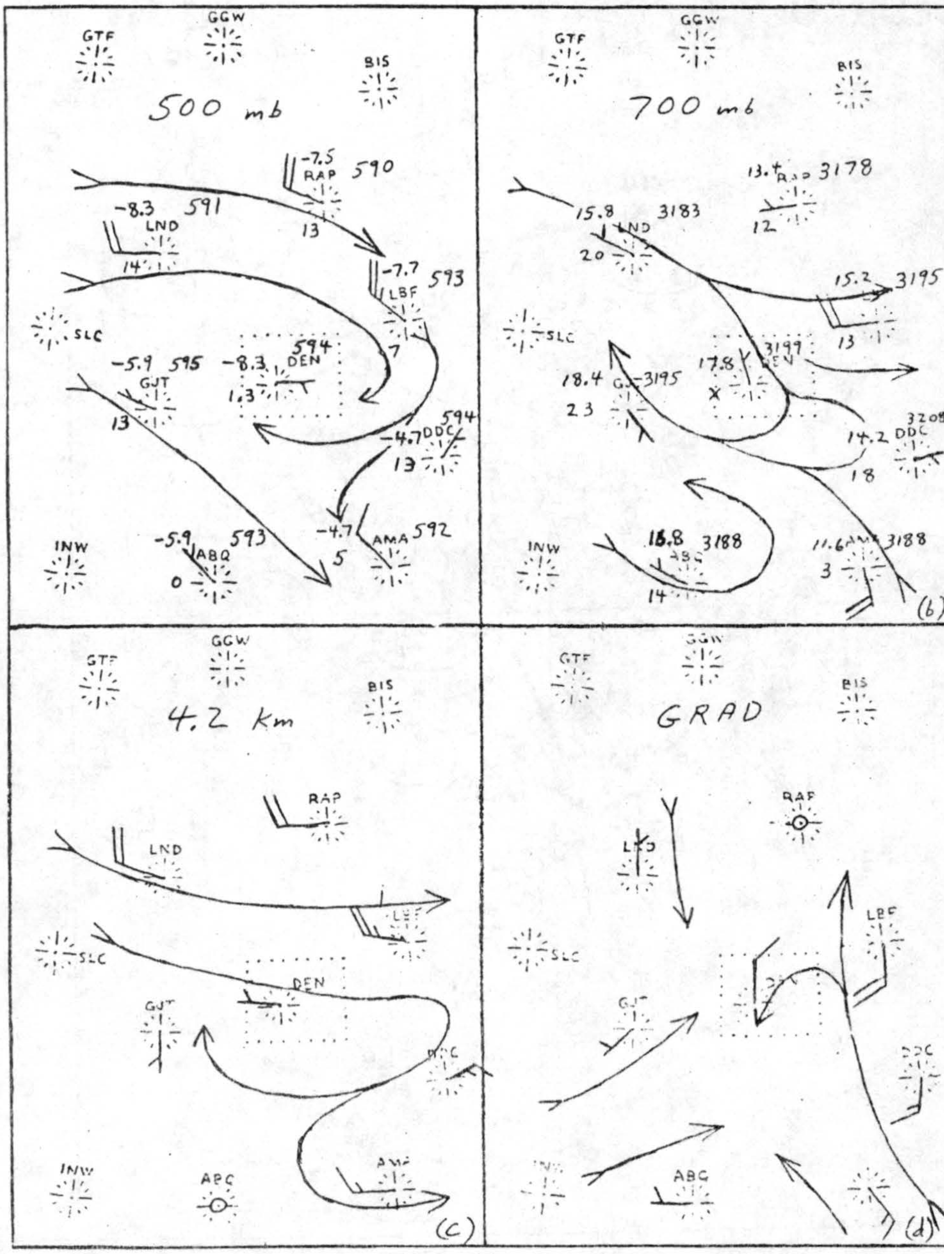



Fig. 26 Local upper air pattern for 1700 MST, 20 July 1982. Plotting as in Fig. 22.

Fig. 27 is a time series of the winds aloft measured by the VHF Profiler located at PTL. Only the winds from the lowest two levels (~ 600 mb and ~ 500 mb) are shown. The wind was fairly steady and light westerly throughout the morning. Shortly before noon, the wind at both levels became more northerly, and then later, at 500 mb, more westerly. Possibly, this is evidence of a return flow (refer to Figs. 6 and 7), coming from the Cheyenne Ridge and then from the Continental Divide just above the boundary layer. By mid-afternoon, based on the radiosonde data from Denver, the boundary layer had grown very deep, to between the 500 mb and 600 mb levels. The Profiler winds became more erratic by mid-afternoon, probably due to boundary layer mixing.

At 1500 MST (Fig. 28) the basic upslope pattern still prevailed. Even though the surface dewpoints were low, high based thunderstorms were forming. There was some tendency for convergence along the north slope of the Palmer Lake Divide near KNB. Interestingly, this is the same area for which increased convergence developed in the July 1981 averaged winds (Fig. 14). Two hours later (Fig. 29), a strong (50 dBz core) thunderstorm had formed south of KNB. Light northerly surface winds had developed to the north of this cell, and a light <u>southerly</u>, flow was beginning to develop at the mid-levels, as indicated by the Profiler data. There was no evidence of southerly flow in the Denver rawinsonde observations. The surface winds show some characteristics of a transition to downslope flow, but this transition has taken place much earlier than would normally have been expected (Fig. 12). It appears that, on this particular day, the high-based thunderstorms have helped to initiate the transition to downslope flow in a portion of the mesonetwork.

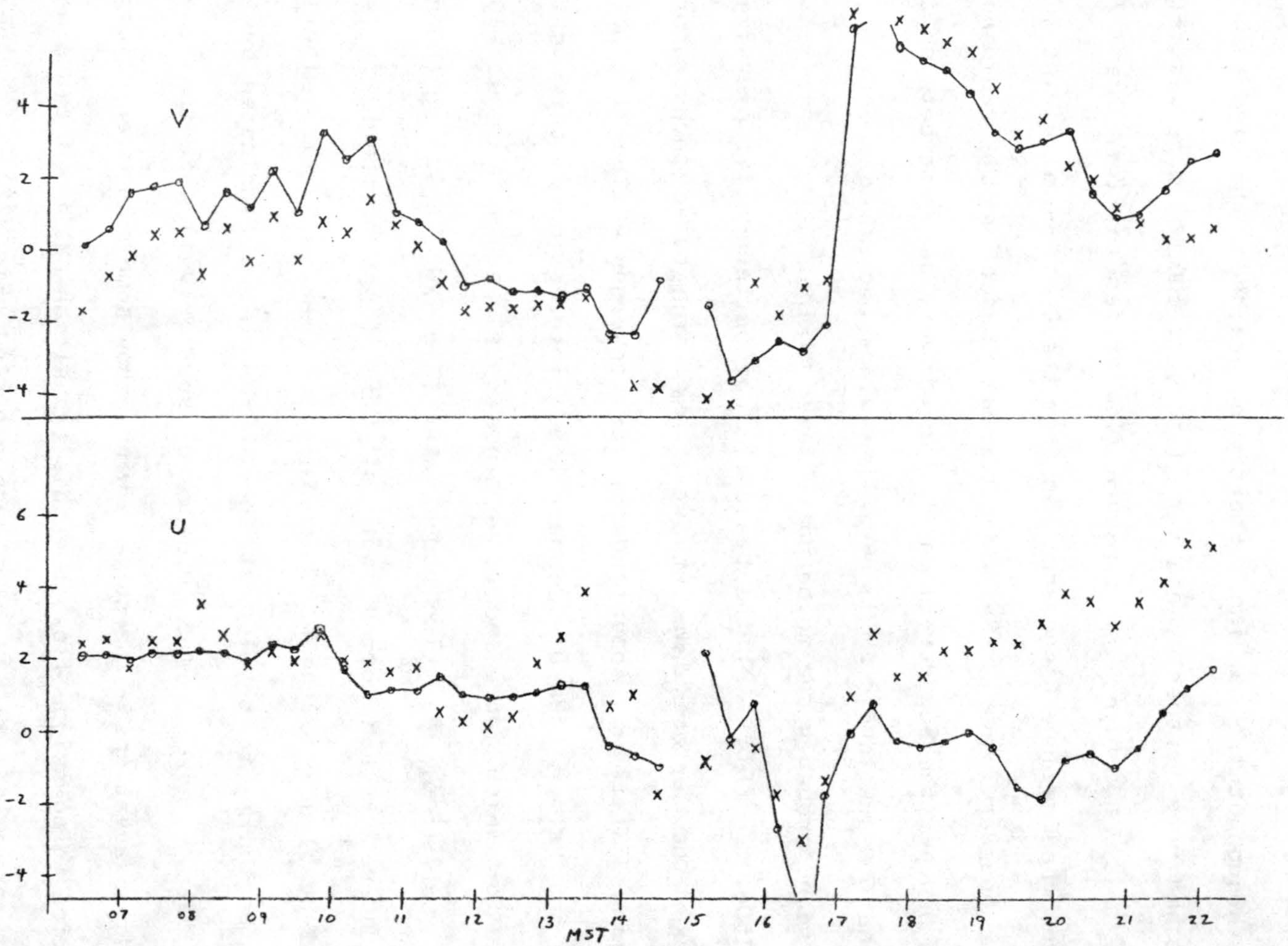



Fig. 27 Time series of the Profiler wind data for 20 July 1982. The circles indicate the lowest level measured (4.2 km or ~ 600 mb), and the x's the next higher level (5.6 km or ~ 500 mb). The v-component of the wind is at the top, and the u-component at the bottom.

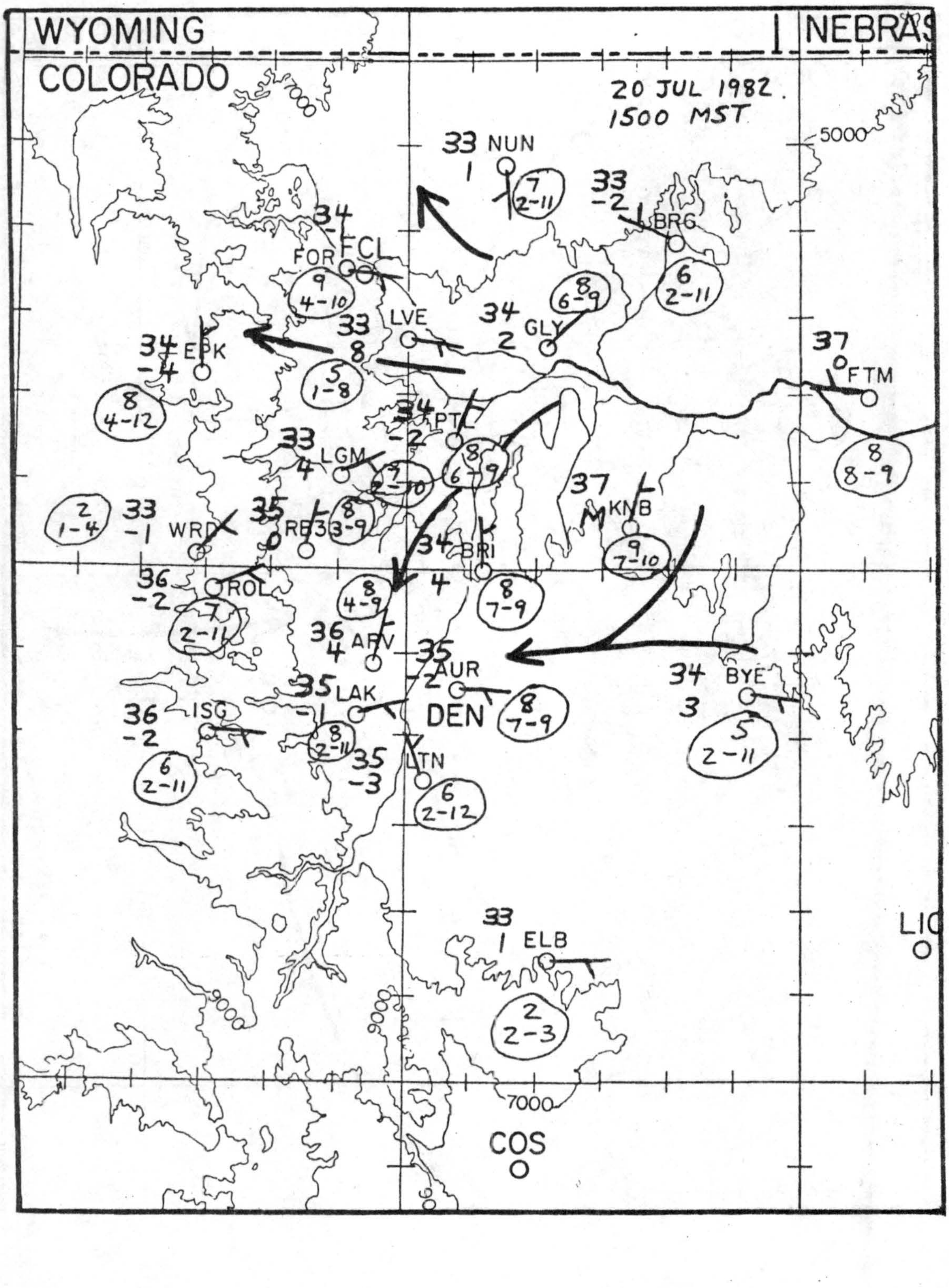



Fig. 28 As in Fig. 25, except for 1500 MST.

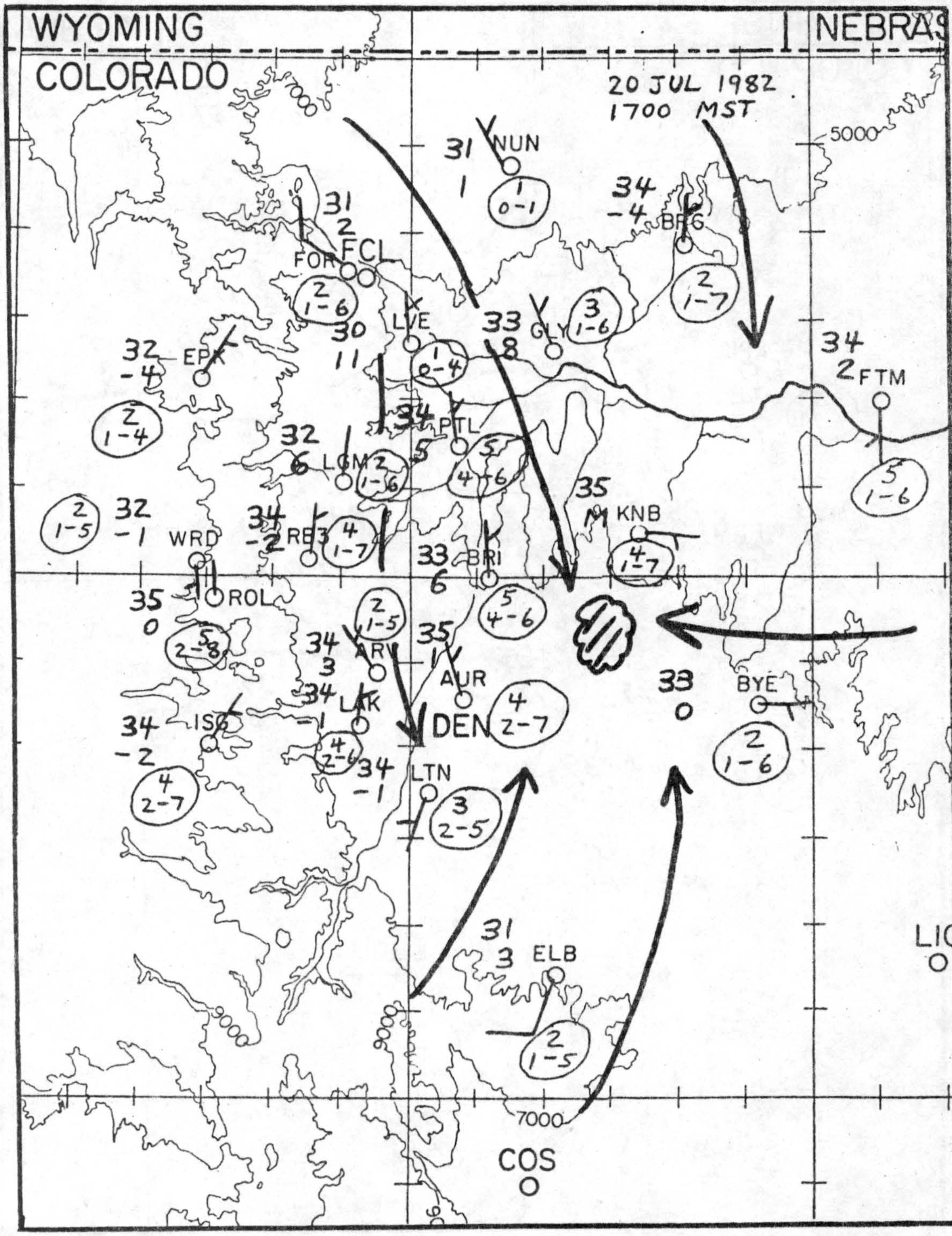



Fig. 29 As in Fig. 25, except for 1700 MST.

It was hoped to learn more about the upslope-to-downslope transition by obtaining Profiler data for two relatively undisturbed (light pressure gradient at all levels, low surface dewpoints) days. Results from 20 July 1983 have been shown. A second day, (not shown) was similarly complex, strongly affected by convective circulations. As a result, it has not been possible to make any generalizations about the transition for relatively undisturbed days. Each day was strongly affected by unique circulations which developed in response to the diurnal upslope flow, but then became independent from it. The sparsity of days with no cumulonimbus development along the Colorado front range highlights the difficulty in obtaining data which might be used to identify the role of dry <u>vs</u> moist processes in the development and propagation of the evening downslope transition.

The two cases presented here illustrate differences in the evolution of the diurnal flow on individual days. Prior to, and in the initial stages of, the development of convection, the diurnal flow can be used to understand initial convective development. Once the convection develops, a better understanding of thunderstorm interactions is necessary to completely understand the complex transition from upslope to downslope flow.

# V. DISCUSSION AND INTERPRETATION

It is convenient to separate this discussion into two parts. The first part deals with the evolution of the afternoon upslope flow, up through the initial development of moist convection. The second part deals with the beginnings of the transition to downslope flow and the associated eastward propagation of convective systems.

## A. Evolution of the Upslope Flow

Johnson and Toth (1982) and Smith (1982) both note the eastward propagation of the downslope-to-upslope transition zone. Based on the additional data presented here, some minor modifications are made to Smith's schematic diagrams of the transition.

The hodographs presented in Chapter III suggest that the wind flow in and around the South Platte River basin evolves similar to the classic description of valley flows. That is, the upslope flows develop first, and then, perhaps a few hours later, the valley wind begins. The dashed arrows in Fig. 30 suggest the local upslope flows which might be present. These slope flows would initially develop in a shallow layer under the nighttime inversion. While information about the depth of the inversion along the lower portions of the South Platte (e.g., FTM) is lacking, it seems reasonable to assume that the cold air is deeper there. This assumption would mean that the top of the inversion slopes down less rapidly than the underlying terrain as one moves from the

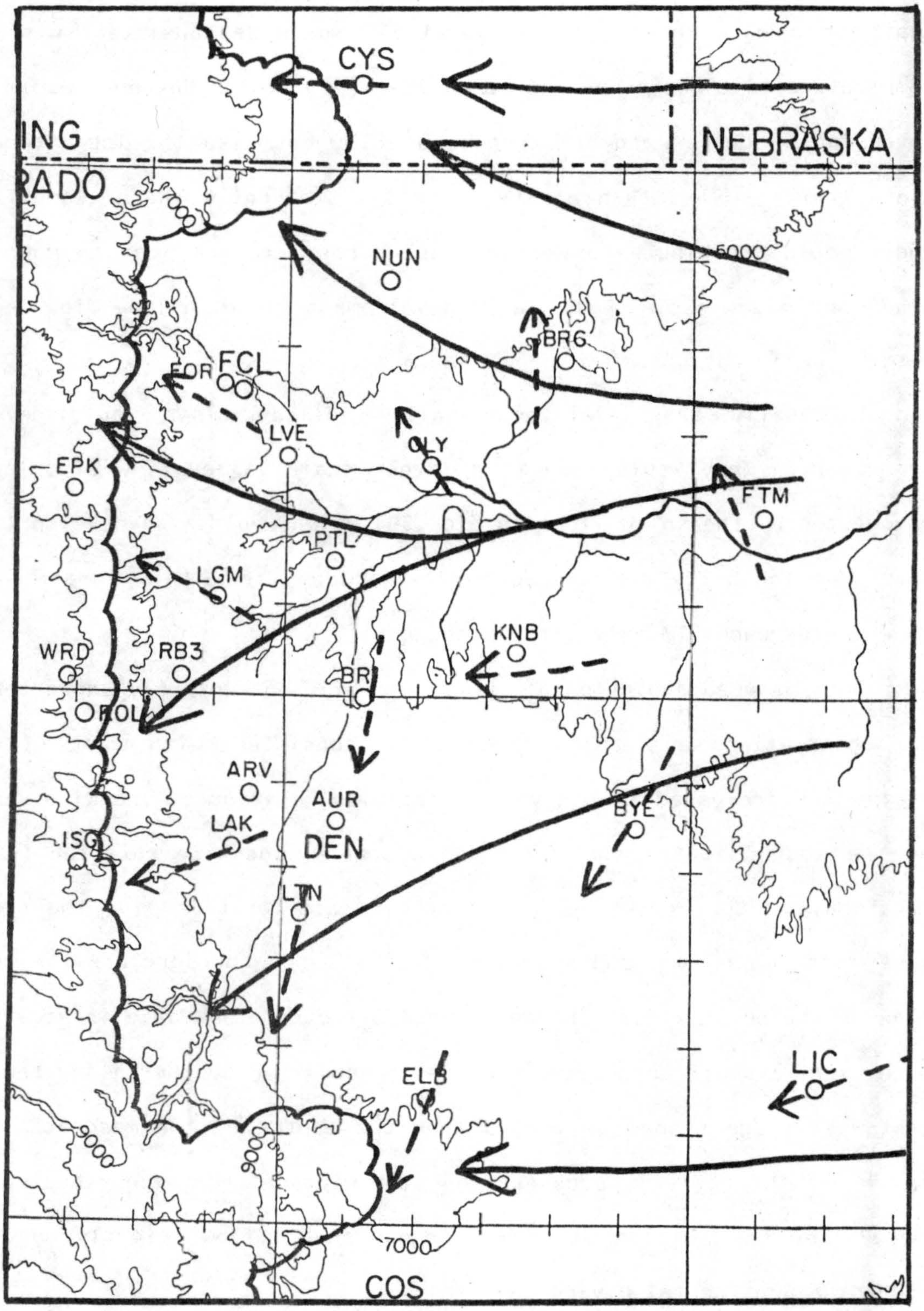



Fig. 30 Schematic of the early, local, upslope flow (dashed arrows) and the later, larger-scale, upslope flow (solid arrows). Scalloped areas indicate enhanced cloud development due to surface convergence.

foothills and ridges to the river valley. Either an increased inversion depth or a more intense inversion at FTM would be consistent with the temperature time series presented earlier (Fig. 20). Not only would the inversion be deeper and/or stronger at FTM, but also the local terrain slope there is less than at the foothills stations. These two differences would contribute to weaker slope winds, compared to the mountain wind, and might explain the later development of an upslope flow regime at the lower stations.

Eventually the relatively shallow upslope flows would develop everywhere. They would lead to a larger scale valley flow circulation (suggested by the solid lines in Fig. 30) which would also develop first near the foothills and propagate eastward. Often, this larger scale flow would reach FTM only late in the day.

This assumed evolution of the flow, while not entirely supported by the observations available, is at least consistent with them. It explains the increased tendency for clockwise rotation of the wind vector on the south side of the river and a counterclockwise rotation (or no rotation) on the northside. The Coriolis acceleration aids the clockwise rotation on the south-side and opposes the counterclockwise rotation on the north-side. The additional effect of the Coriolis acceleration might explain any asymmetries in the observed weather along the two east-west ridge slopes as viewed from the center of the mesonet. As a result of the Coriolis acceleration, the winds along the north slope of the Palmer Lake Divide at mid-afternoon should flow slightly more towards the Continental Divide.

Whether considered as a large scale valley flow or as individual upslope flows, the diurnal pattern by early afternoon is converging moisture towards the east-west ridges and towards the Continental Divide. Convection over the higher terrain, by releasing latent heat (condensation exceeds evaporation as the cloud field grows and precipitates), would, at least initially, assist the diurnal upslope circulation. The developing convective systems will themselves produce new circulations which complicate the diurnal flow.

## B. Transition Mechanisms

Profiler data were obtained for two relatively undisturbed days in order to investigate the importance over this area of the mixing down of westerly momentum, found by Banta (1982) to be important over South Park, Colorado. There was no evidence of this transition mechanism for the day presented in the last chapter. Instead, convective cells developing along the Cheyenne Ridge and along the north slope of the Palmer Lake Divide appear to have been responsible for developing a circulation in which the ridgetop winds (south-southeasterly) were opposite to the surface winds (north-northeasterly). The surface winds gradually made the transition to downslope. The transition occurred earlier than would normally have been expected. The results for the second day were not presented, but they too suggested the development of a circulation around a horizontal axis. Banta found in his numerical simulation that a strong horizontal vortex developed in association with the surface upslope winds. There may be some similarities with the development, for these two cases, of a horizontal vortex in association with the onset of downslope winds (Fig. 31). The proposed circulation in Fig. 31 is simply a reversal of the mountain circulation cell illustrated by Dirks (Fig. 6). Data with better horizontal resolution are

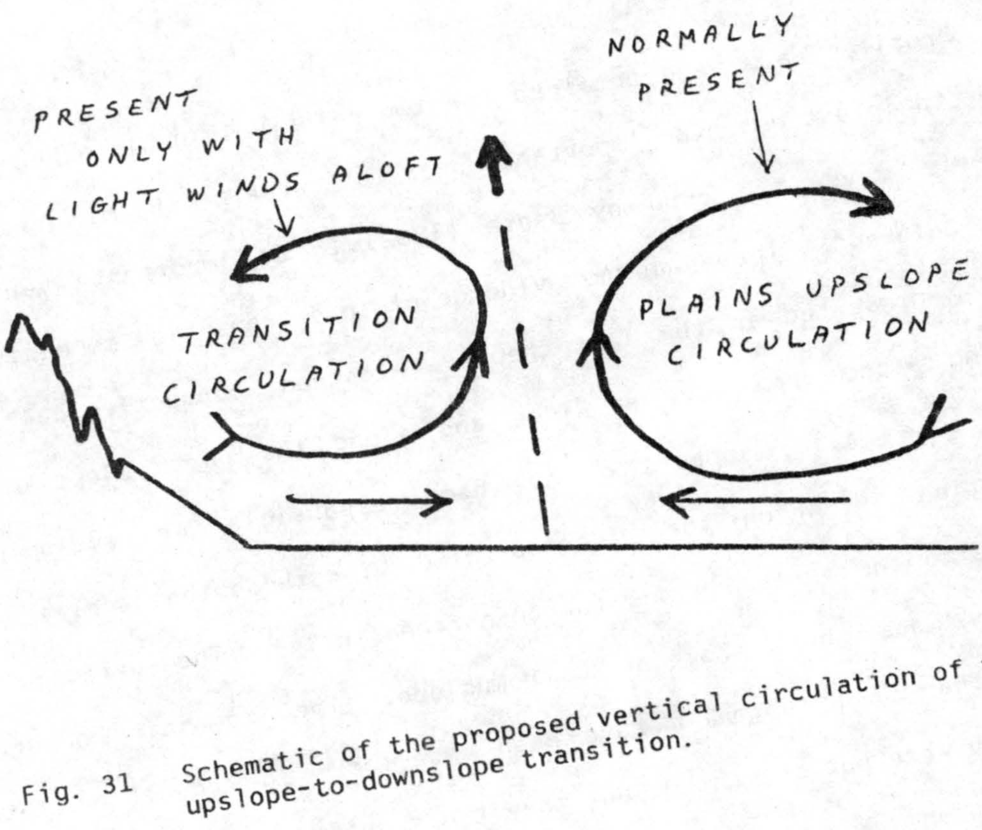



Fig. 31 Schematic of the proposed vertical circulation of the upslope-to-downslope transition.

needed to further investigate the extent of any circulations near the transition zone.

The mixing down of westerly momentum is likely important on days which have moderate westerly winds at ridgetop. For the 6 days averaged in 1982, which had moderate southwesterly winds aloft, this mechanism was probably involved with the late afternoon transition in the foothills. However, PROFS and other data presently available, are insufficient to convincingly verify the operation of this mechanism. Again, the transition over the PROFS mesonet generally occurs several hours later, well after the time of maximum temperature, than it does over South Park, Colorado.

The solar radiation data were plotted to determine what effect cloud cover might have on the transition to downslope. The gradient of solar radiation from the mountains to the plains at mid-afternoon does appear to be significant (Fig. 20), and the slope winds might be expected to decrease or reverse. But, by this time, a larger scale valley wind has become established, at least near the foothills, and it would be relatively unaffected for an hour or more. Other mechanisms may become more important by then.

No matter how the transitions are intiated in the foothills, they generally result in new convective activity developing slightly eastward into the plains. This is in agreement with the observation by Erbes (1978) that this area of downslope winds converges with the previously established larger scale upslope circulation. The presence of convection within the transition zone is likely responsible for the uneveness of the transition zone, both in terms of speed and width, as it crosses the plains. In general, the wind observations tend to support previous conceptual models of the early evening thunderstorm propagation eastward across the plains.

# VI. SUMMARY AND CONCLUSIONS

Analysis of summer surface winds over northeast Colorado, using data from the Program for Regional Observing and Forecasting Services (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.

Monthly averages of the surface winds were calculated for each hour for the months of June, July and August 1981. Streamline, kinematic, and wind hodograph analyses of the resultant wind were prepared. Several days in July 1982 were analyzed. Some of the 1982 days were averaged and others were examined on an individual basis.

The late-night downslope flows and the late-morning through mid-afternoon upslope flows were consistent from month to month and were present on the individual days examined. The early-morning downslope-to-upslope transition zones began near the foothills and propagated eastward across the plains. Winds within the morning transition zones were light and, even after averaging, varied considerably from month to month. The upslope-to-downslope transition zones also began near the foothills and propagated eastward, but were often complicated by late-afternoon and early-evening convective systems.

The upslope flow through mid-afternoon developed according to classic descriptions of upslope and valley winds. At stations on the south side of the South Platte River, the wind vector rotated clockwise through the afternoon, while at stations on the north side the wind vector exhibited little turning or even slight counter-clockwise turning. Convergence associated with the mean diurnal wind flow caused initial development of cumulus clouds over preferred areas. Time series for the mean solar radiation and mean temperature as well as satellite imagery for an individual day provided evidence of the preferred distribution of clouds. A mean convergence/vorticity zone was found along the north slope of the Palmer Lake Divide, and it was suggested that this zone shifts to the Denver area on severe weather days.

The upslope-to-downslope transitions were found to be complicated by and to interact with circulations generated by convective systems. Examination of two relatively undisturbed days for which nearly continuous upper-air information was available failed to establish the relative importance of the various mechanisms (momentum mixing, cloud shadowing, cloud dynamics) suggested for these transitions. Some conceptual models of the transition mechanisms as they might apply to this particular area were suggested. Further study of these mechanisms is required.

## Suggestions for Future Research

Further study should be done of the interaction of the surface winds with the ridgetop winds. UHF Profiler data, which has more resolution within and just above the boundary layer, could be averaged and the mean diurnal flow at the various levels determined. These calculations could be facilitated if the Profiler data were made available from PROFS in a more convenient form and for more than one location within the mesonet. A wind and temperature profiler along the lower portions of the South Platte, say between GLY and FTM, could yield additional information about the wind transitions in that area.

The climatological diurnal flow is useful for understanding the initial convective development in preferred locations. Once convection develops, detailed case studies of individual days might better illustrate the complex transitions from upslope to downslope. Doppler weather radar can provide a much more detailed analysis of the circulations associated with the convective systems.

It would be useful to have additional mesonet stations where there are presently large gaps in the coverage, both horizontally and vertically. Possible locations are: along the south slope of the Cheyenne Ridge between NUN and CYS, along the north slope of the Palmer Lake Divide between ELB and KNB, and, in the western portion of the network, along a line between the foothills stations and the mountain stations, extending from Wyoming southward to west of ELB.

And finally, numerical and/or analytical models might be used to better understand the complex transitions. The detailed surface and upper-air data available could be used to specify boundary conditions for these models.

## REFERENCES


Banta, R.M., 1982: An observational and numerical study of mountain boundary-layer flow. Atmos. Sci. Paper No. 350, Colorado State Univ., Fort Collins, 203 pp.

Banta, R.M., and W.R. Cotton, 1981: An analysis of the structure of local wind systems in a broad mountain basin. J. Appl. Meteor., 20, 1255-1266.

Bellamy, J.C., 1949: Objective calculations of divergence, vertical velocity and vorticity. Bull. Amer. Meteor. Soc., 30, 45-49.

Beran, D.W., and C.G. Little, 1979: Prototype Regional Observing and Forecasting Service: From concept to implementation. Nat. Wea. Digest, 2-5.

Bleeker, W., and M.J. Andre, 1951: On the diurnal variation of precipitation, particularly over central USA, and its relation to large-scale orographic circulation systems. Quart. J. R. Meteor. Soc., 77, 260-271.

Bowen, B.M., J.M. Dewart, and F.G. Fernald, 1981: A study of the nocturnal drainage flow over a sloping plateau in north-central New Mexico. Preprint Volume: Second Conference on Mountain Meteorology, November 9-12, 1981; Steamboat Springs, CO, 224-232.

Cotton, W.R., R.L. George, and K.R. Knupp, 1982: An intense, quasi-steady thunderstorm over mountainous terrain. Part I: Evolution of the storm-initiating mesoscale circulation. J. Atmos. Sci., 39, 328-342.

Cotton, W.R., 1983: Up-scale development of moist convective systems. Lecture Notes; Course on Mesoscale Meteorology, May 30 - June 10, 1983; Pinnarpsbaden, Sweden.

Defant, F., 1951: Local winds. Compendium of Meteorology, Amer. Meteor. Soc., 655-672.

Dirks, R.A., 1969: A theoretical investigation of convective patterns in the lee of the Colorado Rockies. Atmos. Sci. Paper No. 154, Colorado State Univ., Fort Collins, 122 pp.

Doswell, C.A., 1980: Synoptic-scale environments associated with High Plains severe thunderstorms. Bull. Amer. Meteor. Soc., 61, 1388-1400.

Erbes, R.E., 1978: A kinematic description of Colorado thunderstorms. M.S. Thesis, Dept. of Atmospheric Science, Colorado State Univ., Fort Collins, 103 pp.

George, R.L., 1979: Evolution of mesoscale convective systems over mountainous terrain. Atmos. Sci. Paper No. 318, Colorado State Univ., Fort Collins, 160 pp.

Hahn, C.J., 1981: A study of the diurnal behavior of boundary-layer winds at the Boulder Atmospheric Observatory. Bound.-Layer Meteor., 21, 231-245.

Hales, J.E., 1972: A study of radar echo distribution in Arizona during July and August. NOAA Technical Memorandum, NWS-WR-77, Dept. of Commerce, Salt Lake City, Utah, 21 pp.

Haugen, D.A., and R.C. Lipschutz, 1982: A verification program for severe convective storm forecasts. Preprint Volume. Ninth Conference on Weather Forecasting and Analysis, June 28 - July 1, 1981; Seattle, WA, 102-110.

Henz, J.F., 1974: Colorado High Plains thunderstorm systems - A descriptive radar-synoptic climatology. M.S. Thesis, Dept. of Atmospheric Science, Colorado State Univ., Fort Collins, 82 pp.

Hogg, D.C., M.T. Decker, F.O. Guirard, K.B. Earnshaw, D.A. Merritt, K.P. Moran, W.B. Sweezy, R.G. Strauch, E.R. Westwater, and C.G. Little, 1983: An automatic profiler of the temperature, wind, and humidity in the troposphere. J. Climate Appl. Meteor., 22, 807-831.

Hootman, B.W., and W. Blumen, 1983: Analysis of nighttime drainage winds in Boulder, Colorado during 1980. Mon. Wea. Rev., 111, 1052-1061.

Hughes, R.L., 1978: A numerical simulation of mesoscale flow over mountainous terrain. Atmos. Sci. Paper No. 303, Colorado State Univ., Fort Collins, 123 pp.

Johnson, R.H. and J.J. Toth, 1982: A climatology of the July 1981 surface flow over northeast Colorado. Atmos. Sci. Paper No. 342, Colorado State Univ., Fort Collins, 52 pp.

Johnson, R.H., G.S. Young, J.J. Toth, and R.M. Zehr, 1983: A study of mesoscale weather effects of variable snow cover over northeast Colorado. Submitted to Mon. Wea. Rev.

Karr, T.W., and R.L. Wooten, 1976: Summer radar echo distribution around Limon, Colorado. Mon. Wea. Rev., 104, 728-734.

Kusuda, M., and P. Alpert, 1983: Anti-clockwise rotation of the wind hodograph: Part I: Theoretical study. J. Atmos. Sci., 40, 487-499.

Lilly, D.K., 1981: Doppler radar observations of upslope snowstorms. Preprint Volume: Second Conference on Mountain Meteorology, November 9-12, 1981; Steamboat Springs, CO, 346-353.

Maddox, R.A., 1981: The structure and life-cycle of mid-latitude mesoscale convective complexes. Ph.D. Thesis, Dept. of Atmospheric Science, Colorado State Univ., Fort Collins, 311 pp.

Maddox, R.A., 1980: Mesoscale convective complexes. Bull. Amer. Meteor. Soc., 61, 1374-1387.

Mass, C., 1982: The topographically forced diurnal circulations of western Washington State and their influence on precipitation. Mon. Wea. Rev., 110, 170-183.

McCarthy, J., J.W. Wilson, and T.T. Fujita, 1982: The joint airport weather studies project. Bull. Amer. Meteor. Soc., 63, 15-22.

McNider, R.T., and R.A. Pielke, 1981: Diurnal boundary-layer development over sloping terrain. J. Atmos. Sci., 38, 2198-2212.

Modahl, A.C., 1979: Low-level wind and moisture variations preceding and following hailstorms in northeast Colorado. Mon. Wea. Rev., 107, 442-450.

Panofsky, H.A. and G.W. Brier, 1968: Some Applications of Statistics to Meteorology, The Pennsylvania State University, 224 pp.

Pielke, R.A., 1974: A three-dimensional model of the sea breezes over south Florida. Mon. Wea. Rev., 102, 115-139.

Pratte, F., 1983: An informal discussion of PROFS mesonet data errors. Meteorological Workshop for 1983 Forecaster Exercise, May 25-27, 1983; Boulder, CO, 7 pp.

Purdom, J.F.W., 1976: Some uses of high-resolution GOES imagery in the mesoscale forecasting of convection and its behavior. Mon. Wea. Rev., 104, 1474-1483.

Reynolds, D.W., 1983: Prototype workstation for mesoscale forecasting. Bull. Amer. Meteor. Soc., 64, 264-273.

Riehl, H., and D. Herkhof, 1972: Some aspects of Denver air pollution meteorology. J. Appl. Meteor., 11, 1040-1047.

Schlatter, T.W., D.V. Baker, and J.F. Henz, 1983: Profiling Colorado's Christmas Eve blizzard. Weatherwise, 36, 60-66.

Skibin, D., and A. Hod, 1979: Subjective analysis of mesoscale flow patterns in northern Israel. J. Appl. Meteor., 18, 329-338.

Smith, J.K., 1982: Undisturbed clear day diurnal wind and temperature in northeastern Colorado. M.S. Thesis, Dept. of Atmospheric Science, Colorado State Univ., Fort Collins, 90 pp.

Szoke, E.J., M.L. Weissman, T.W. Schlatter, F. Caracena, and J.M. Brown, 1983: A sub-synoptic analysis of the Denver tornado outbreak of 3 June 1981. Submitted to Mon. Wea. Rev.

Wallace, J.M., 1975: Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States. Mon. Wea. Rev., 103, 406-419.

Weaver, J.F., and F.P. Kelly, 1982: A mesoscale, climatologically-based forecast technique for Colorado. Preprint Volume: Ninth Conference on Weather Forecasting and Analysis, June 28-July 1, 1982; Seattle, WA, 277-280.

Weaver, J.F., M. Klitch, F.P. Kelly, and T.H. Vonder Haar, 1983: Convective cloud climatologies constructed from satellite imagery. Submitted to J. Climate Appl. Meteor.

Wetzel, P.H., 1973: Moisture sources and flow patterns during the northeast Colorado hail season. M.S. Thesis, Dept. of Atmospheric Science, Colorado State Univ., Fort Collins, 90 pp.

Wetzel, P.J., W.R. Cotton, and R.L. McAnelly, 1983: A long-lived mesoscale convective complex. Part II: Evolution and structure of the mature complex. Accepted for publication in Mon. Wea. Rev.

Whiteman, C.D., 1982: Breakup of temperature inversions in deep mountain valleys: Part I. Observations. J. Appl. Meteor., 21, 270-289.

Whiteman, C.D., and T.B. McKee, 1982: Breakup of temperature inversions in deep mountain valleys: Part II. Thermodynamic model. J. Appl. Meteor., 21, 290-302.

## APPENDIX A

## LOCATION AND DESCRIPTION OF PROFS MESONET STATIONS

These descriptions are based in large part on site surveys by Smith (1982).

Arvada (ARV):

Lat. - 39°48' Long. - 105°05' Elev. - 1641 m/ 5385 ft

Located in a small park near the intersection of 57th Avenue and Garrison Road in the city of Arvada on a low hill with a very gentle slope. The anemometer and pyranometer are mounted on a 30-foot tower. A line of 25-foot trees is on the west of the station, about 10 feet from the tower. Surrounded by residential area.

Aurora (AUR):

Lat. - 39°45' Long. - 104°52' Elev. - 1625 m/ 5332 ft

At Stapleton International Airport, National Weather Service. The surrounding terrain is smooth.

Boulder (BOU/RB3):

Lat. - 40°01' Long. - 105°15' Elev. - 1629 m/ 5344 ft

Located on the roof of the six-story NOAA/ERL building at 30th and Arapahoe in downtown Boulder. The anemometer and pyranometer are mounted on a 20-foot tower and the shelter is mounted 4 feet above the roof. There are numerous obstructions to airflow on the roof.

Briggsdale (BGD/BRG):

Lat. - 40°38' Long. - 104°20' Elev. - 1483 m/ 4865 ft

Located along the Briggsdale-Hereford Road, about one mile north of Highway 14 at a U.S. Forest Service station. The anemometer and pyranometer are mounted on a 30-foot tower. The terrain is smooth, but slopes up to the north and east. There is a line of 20-foot trees to the east, and the soil is dry with short grass.

Brighton (BRI):

Lat. - 40°00' Long. - 104°48' Elev. - 1518 m/ 4980 ft

Co-located with the Brighton Cooperative Observer station. It is about two miles east of the South Platte River. The surrounding terrain is smooth in all directions. The anemometer and pyranometer are on a 43-foot tower to avoid interference from trees in the area. Surrounded by irrigated farmland.

Byers (BYE):

Lat. - 39°45'  Long. - 104°08'  Elev. - 1554 m/ 5100 ft

Co-located with the Byers Cooperative Observer station, about five miles northeast of Byers on Highway 36. The 30-foot tower is located on the southside of a clump of 40-foot trees. The shelter is located in short grass. The surrounding terrain is smooth.

Elbert (ELB):

Lat. - 39°14'  Long. - 104°38'  Elev. - 2131 m/ 6992 ft

Located in a grass field at the Running Creek Field Station, about five miles north of the Palmer Divide. The anemometer and pyranometer are mounted on a 30-foot tower with no obstructions. The surface slopes gently up toward the Divide.

Estes Park (EPK):

Lat. - 40°23'  Long. - 105°34'  Elev. - 2368 m/ 7770 ft

Located in a grassy field 200 yards west of the Rocky Mountain National Park Visitor's Center. The station is placed in a low spot in a poorly drained valley. The anemometer and pyranometer are on a 45-foot tower. There is moderate pine cover in the area.

Fort Collins (FOR):

Lat. - 40°35'  Long. - 105°08'  Elev. - 1609 m/ 5279 ft

Located at the CSU Department of Atmospheric Science building west of Fort Collins. The building is on a hill about a half mile east of the first ridge of the foothills. The 20-foot tower is located on the roof of the three-story building. The shelter is to the east of the building, next to the large satellite dish.

Fort Morgan (FTM):

Lat. - 40°20'  Long. - 103°49'  Elev. - 1387 m/ 4550 ft

Located at the Fort Morgan Airport. The airport is located near the top of the south slope of a ridge that parallels the South Platte River on the north side. The 30-foot tower is mounted on top of a one and half story building, while the shelter is just north of the building. There are no trees or tall buildings around to affect the wind flow, and the airport is surrounded by dry rolling grassland.

Greeley (GLY):

Lat. - 40°26'  Long. - 104°38'  Elev. - 1415 m/ 4642 ft

Located at the Weld County Airport. The anemometer and pyranometer are on the roof of the one-story airport headquarters building. The shelter is about 5 feet from the brick building on the east side on an irrigated lawn. The surrounding terrain is smooth with no obstructions around the anemometer.

Idaho Springs (ISG):

Lat. - 39°40'  Long. - 105°30'  Elev. - 3503 m/ 11500 ft

Located on the top of Squaw Mountain. The anemometer and pyranometer are on a 20-foot tower, but a rock outcrop to the northwest of the tower interferes with the wind flow from that direction.

Keenesburg (KNB):

Lat. - 40°04' Long. - 104°26' Elev. - 1482 m/ 4862 ft

Located at the Weld Central High School. The anemometer and pyranometer are on a 10-foot tower on the roof of a shed. The shelter is about 15 feet to the southwest of the shed. The surrounding terrain is smooth irrigated farmland sloping gently eastward.

Lakewood (LAK):

Lat. - 39°42' Long. - 105°08' Elev. - 1832 m/ 6009 ft

Located at Lakewood Fire Station No. 4, which is about halfway up the eastern slope of Green Mountain. The anemometer and pyranometer are on a 10-foot tower that is mounted on the roof of the one-story firehouse. The shelter is next to an asphalt parking lot. No tall buildings or trees are located near the site.

Littleton (LTN):

Lat. - 39°34' Long. - 104°57' Elev. - 1750 m/ 5740 ft

Located at the northeast corner of the intersection of Highways 177 and 470 at a Colorado Department of Health trailer in a grassy field. The terrain slopes up to the south toward the Palmer Divide, and also to the east away from the South Platte River, which is three miles west of the station. The anemometer and pyranometer are on a 30-foot tower. There are no obstructions.

Longmont (LGM):

Lat. - 40°10' Long. - 105°10' Elev. - 1532 m/ 5027 ft

Located at the Longmont Airport. The anemometer and pyranometer are on a 10-foot tower on the roof of the one-story Judson Flying Service building. The shelter is on the ground on the north side of the building. The surrounding terrain is smooth irrigated farmland with no obstructions to the wind flow.

Loveland (LVE):

Lat. - 40°25' Long. - 105°02' Elev. - 1512 m/ 4960 ft

Located about halfway between Loveland and Interstate Highway 25 along U.S. Highway 34 at the Greeley Water Treatment Plant. The anemometer and pyranometer are on a 30-foot tower mounted on the roof of the one-story building. The shelter is on the north side of the building, well removed from the ponds on an irrigated lawn. There are no tall trees or tall buildings close by and the surrounding terrain is slightly rolling. Boyd Lake extends three miles to the north.

Nunn (NUN):

Lat. - 40°48' Long. - 104°42' Elev. - 1634 m/ 5360 ft

Located approximately three-fourths of a mile southeast of the Central Plains Experiment Station Headquarters, about eight miles north of Nunn in dry grassland. The anemometer and pyranometer are on a 20-foot tower. The area is treeless and consists of low rolling hills. The surface slopes upward toward the Cheyenne Ridge to the north.

Platteville (PTL):

Lat. - 40°15'  Long. - 104°53'  Elev. - 1460 m/ 4790 ft

Located one mile north of the Fort St. Vrain Power Plant in the middle of the "Y" near the confluence of the St. Vrain and South Platte Rivers. The 30-foot tower and shelter are located just south of the floodplain in very sandy soil. Bluffs line the northwest bank of the St. Vrain River about a quarter mile to the north and west of the station.

Rollinsville (ROL):

Lat. - 39°54'  Long. - 105°29'  Elev. - 2749 m/ 9020 ft

Located on a 200-foot high rock outcrop near the Fritz Peak Observatory. The anemometer and pyranometer are on a 13-foot tower.

Ward (WRD):

Lat. - 40°02'  Long. - 105°32'  Elev. - 3048 m/ 10,000 ft

University of Colorado Mountain Research Station located on the southeast side of Niwot Ridge. The anemometer and pyranometer are mounted on a 20-foot tower.