A Climatology of the July 1981 Surface Flow over Northeast Colorado

by
Richard H. Johnson and James J. Toth

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Colorado State University

Department of Atmospheric Science

Paper No. 342

A CLIMATOLOGY OF THE JULY 1981 SURFACE FLOW OVER NORTHEAST COLORADO

by

Richard H. Johnson
and
James J. Toth

Research supported by the
Environmental Research Laboratories of the
National Oceanic and Atmospheric Administration
under Grant No. NA81RA-H-00001,
Amendment 2, Item 4, and the
Cooperative Institute for Research in the
Atmosphere at Colorado State University

Department of Atmospheric Science

Colorado State University

Fort Collins, Colorado

September 1982

Atmospheric Science Paper No. 342

ABSTRACT

Surface wind data from 20 Prototype Regional Observing and Forecasting Service (PROFS) surface mesonetwork stations have been analyzed for the month of July 1981 to determine characteristic flow patterns over northeast Colorado. Streamline analyses of the surface flow over this region have been prepared on an hourly basis and are presented in this paper. It has been found that diurnal forcing by radiative heating exerts a dominant control on the flow fields with a basic pattern of drainage flow at night and upslope flow in the daytime. It is observed along the front range of eastern Colorado that rather than occurring simultaneously at all elevations, the downslope-to-upslope and upslope-to-downslope transitions begin at the foothills of the Rocky Mountains and propagate eastward toward the plains. The period of time for the transition from downslope to upslope during July mornings is ~ 3 h and from upslope to downslope ~ 4-5 h.

During July local confluence is found at midday along major east-west ridges in the region (e.g., Cheyenne Ridge and Palmer Lake Divide) and, consequently, these ridges are preferred regions for afternoon thunderstorm activity. The late afternoon onset of downslope flow appears to be often associated with a preferred development of thunderstorms at this time just west of the upper reaches of the South Platte River basin followed by propagation toward eastern Colorado later in the evening. The occurrence of the downslope onset well before sunset may be a consequence of downward mixing of westerly momentum by the growth of the convective boundary layer or may somehow be caused by the early afternoon development of cumulonimbus along the Continental Divide. Further study of this flow feature is in progress.

A comparison of the mean July surface flow is made with a single fall case (11 November 1981) and it is found that the flow patterns, both day and night, are quite similar. The only significant difference occurs in the late afternoon and is associated with the lack of thunderstorm activity in the November case.

TABLE OF CONTENTS

1. Introduction

Early in 1981 a mesometeorological network of surface stations was established along the northern Colorado front range as part of the National Oceanic and Atmospheric Administration's Prototype Regional Observing and Forecasting Service (PROFS) experiment (Beran and Little, 1979). A primary objective of this continuing experiment is to improve short term (0-3 h) forecasting on the mesoscale ($\lesssim$ 100 km) by providing through technological advances a more rapid delivery as well as a more thorough processing and display capability of real-time weather data to the local weather forecaster. The mesometeorological network represents one additional data resource that, when available to the forecaster in near-real-time, should, in principle, lead to improved short term forecasts.

The establishment of the PROFS mesonetwork and its continued operation since early 1981 has provided a unique opportunity for the determination of a regional climatology of surface meteorological conditions over northeast Colorado. A host of climatological analyses are possible, and as a first step, Johnson and Toth (1982) undertook a study of the resultant surface winds in the region for July 1981. The period includes days having various degrees of convective activity, as expected during July in northeast Colorado. Most of the major findings of the study were reported in Johnson and Toth (1982); however, space limitations prevented the presentation of analyses of the surface flow at all time periods for which it was determined. In this report we present resultant wind analyses on an hourly basis for a full 24-hour day using the data for July 1981. This work represents part of a continuing investigation and should be considered preliminary as more refined analyses are in progress.

2. Discussion of Previous Studies

The study of mountain valley and slope circulations has received the attention of numerous meteorologists for many years. A thorough review of all of the literature on this subject would probably include well over a thousand references. A concise depiction of the basic surface flow patterns that are to be expected in a mountain-plain region (such as northeast Colorado) is given by Defant (1951). A review of progress in understanding mountain-valley circulations up to the mid-1960's was assembled by Reiter and Rasmussen (1967). Considerable effort has been expended in recent years to better understand the United States Rocky Mountain and Great Plains low-level circulations on a wide range of horizontal scales. Several observational programs have contributed to important advances in our understanding of regional-scale flows in the vicinity of the Colorado Rocky Mountains. Not all can be mentioned, but several are worthy of note. We exclude from our discussions the subjects of mountain waves and circulations associated with downslope windstorms.

In recent years a field program under the direction of Prof. William Cotton of Colorado State University has been carried out in a high mountain valley region in Colorado (South Park) just to the east of the Rocky Mountain Continental Divide. South Park is a relatively flat valley having a horizontal dimension ~ 50 km and at an elevation ~ 1 km below the adjacent ridgetops. Certain characteristics of the diurnal variation of the flow during undisturbed conditions have been documented by Banta and Cotton (1981). These authors point out that while one typically expects in a traditional model of ridge-valley winds two wind regimes on a dry day (downslope, drainage wind at night and upslope wind during the day), yet a third regime was observed in South Park: a late morning or afternoon wind which corresponded in direction to the winds above the ridgetops (referred to as the "afternoon westerlies"). The onset of the westerlies is attributed to the development of the convective boundary layer and subsequent downward mixing of westerly momentum from aloft. The geographical setting in South Park is somewhat analogous to that defined along the Colorado front range (east slopes of the Rockies) with the Great Plains stretching to the east; however, the horizontal scale and vertical separation between mountains and valley or plains are significantly larger in the latter case. Because of the differences in scales, it is not obvious that the Banta and Cotton mechanism for the generation of westerlies at the surface in the afternoon should be expected along the front range, despite the fact that the convective boundary layer along the front range often reaches to a height approaching the summit of the Continental Divide (Holzworth, 1964). An analysis of PROFS data relative to this mechanism will be given later.

A second important field experiment bearing on mountain valley circulations has been reported by Whiteman (1982) and Whiteman and McKee (1982). These authors examined the vertical structure of mountain valley circulations in Colorado's western valleys and applied simple models in an effort to understand the primary physical mechanisms controlling the flows. Relative to the valleys in the plains along the front range, the mountain valleys studied by Whiteman and McKee are narrow and steep; nevertheless, their work may provide some insight into the possible vertical structure of the flows in the PROFS region, although definitive comparisons will require augmented observational programs.

While at present PROFS mesonetwork data give only surface information, the vertical structure of the boundary layer in the PROFS region is now being continuously sampled by the Boulder Atmospheric Observatory (BAO) 300-m meteorological tower near Erie, Colorado (Kaimal, 1978). Valuable information, say, the depth and characteristics of natural drainage flows (Hahn, 1981) has been obtained from the BAO tower that can be coupled with observations of mesoscale circulations in the PROFS area.

Some regional surface flow studies in the Denver, Colorado, area have been carried out in recent years, many for the purpose of examining air pollution problems in that urban area (e.g., Riehl and Herkhof, 1972; Haagenson, 1979). The PROFS data provide information on a considerably larger scale that are potentially of great value in assessing pollution impacts in the South Platte River drainage basin of northeast Colorado (Johnson and Toth, 1982).

Because July is a time of frequent thunderstorm activity in Colorado, the diurnal variation of surface flow along the front range might be expected on any day to be significantly modified by thunderstorm effects, e.g., downdraft outflows, cloud shadowing, etc. The initiation of thunderstorms in this region has been found to be closely linked with topographic features (Dirks, 1969; Wetzel, 1973; Henz, 1974; George, 1979; Doswell, 1980; Maddox, 1981) which combine with the diurnal solar heating cycle to create areas of localized and concentrated low-level convergence (Johnson and Toth, 1982). The results reported in this study will highlight the important relationship between boundary layer flows and convective activity.

3. The PROFS Mesonetwork Data and Analysis Procedures

In early 1981 a mesonetwork of 20 automated surface stations (average separation ~ 40 km) was established as part of PROFS along the northern Colorado front range (Fig. 1). A 21st station was placed at Briggsdale (BGD) later in the year. A listing of station locations, elevations and siting characteristics is found in Appendix A.

The variation in elevation over the region is large, with stations ranging from 1,372 m or 4,500 ft (Fort Morgan, FTM) to 3,505 m or 11,500 ft (Squaw Mountain, ISG). From its inception until October 1981 the only archive of PROFS mesonetwork data was in a hard copy format at the Department of Atmospheric Science, Colorado State University Office of the Colorado State Climatologist. Because of the cumbersome nature of this data set, our initial attempts to develop a wind climatology that included the first spring and summer of operation were severely limited. As a first step, however, data for July 1981 were processed with 5-minute average winds at one-hour intervals being extracted from the data tabulations. Additionally, hourly surface observations for this month were obtained from the National Climatic Center, Asheville, NC for the following National Weather Service stations: in Colorado, Acron (AKO), Colorado Springs (COS) and Limon (LIC); in Wyoming, Cheyenne (CYS); and in Nebraska, Scottsbluff (BFF) and Sidney (SNY). These stations were selected to enable documentation of the flow field beyond the PROFS mesonetwork to include three major mesoscale (~ 100-300 km) topographic features: the Cheyenne Ridge along the Colorado-Wyoming border, the upper reaches of the South Platte River drainage basin and the Palmer Lake Divide to the south of Denver.

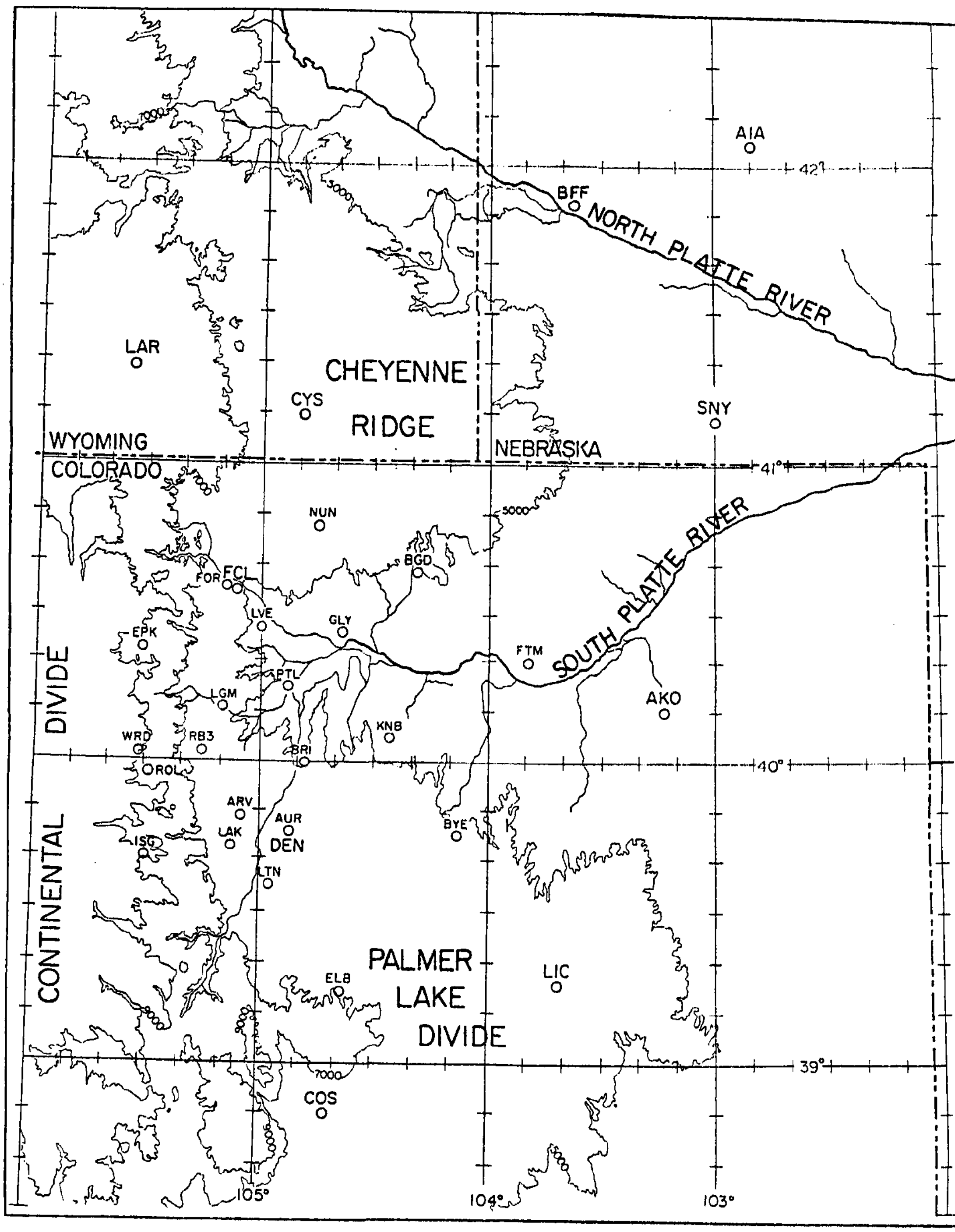

Fig. 1. PROFS Mesonetwork stations (small letters) and surrounding National Weather Service stations (large letters). Major topographic features are identified. Elevation contours are in feet.

A study of the accuracy and representativeness of PROFS surface mesonetwork data is presently being carried out under the direction of Prof. Tom McKee, Colorado State University (Smith, 1982). While problems have been identified with some of the reported variables, it appears as though the wind observations are generally reliable and the siting of the stations below 2000 m is such that the reported winds are generally representative of the immediate (~ 10 km) environment of each station. One exception for stations on the plains might be at Loveland (LVE), where streamline analyses (to be shown later) indicate that a flow field possibly nonrepresentative of the local environment of that station is being sampled.

For July 1981 we have prepared streamline analyses showing the hourly evolution of the surface flow field based on 31-day averages at each hour. The winds have been vector-averaged at each hour following the removal of observations with wind speeds greater than two standard deviations from the mean. The intent of this procedure was to exclude from the averages anomalous wind events such as thunderstorm wind gusts, etc. The occurrence of strong wind events in the data sample was rare and analyses with and without application of the removal procedure are virtually identical.

We are interested in a July composite view of the flow relative to sunrise and sunset, but since these times change only by 20 minutes over the month, an hour-by-hour composite should approximate the perspective we want. The daily examination of PROFS data on a real time basis has convincingly demonstrated to the authors the persistence of the diurnal pattern of slope flows and motivated the compositing approach that we have taken in this study.

4. Resultant Surface Winds for July 1981

A climatology of the full range of meteorological variables both at the surface and aloft in a mesoscale region such as the PROFS mesonetwork, with stratifications of the data for different weather event types, should be of great value to local forecasters. The results presented here represent only a preliminary effort toward this end.

In Figs. 2-25 the mean surface flow field at 1-hour intervals from 0000 MST to 2400 MST is shown. The average flow fields depicted in Figs. 2-25 are extremely coherent, indicating the dominance of diurnal forcing in this region and the effectiveness of the averaging procedure in removing longer - period synoptic effects. Maps on many individual days look like those shown in the figures. For reference, the reader should note that for July the average sunrise is at 0445 MST and sunset at 1930 MST.

During the late night and early morning hours (2300 - 0700 MST, Figs. 25, 2-9) there is drainage flow off the Cheyenne Ridge and Plamer Lake Divide into the river basins to their north and south. During this 8-hour period, a confluent flow exists along the South Platte River basin and maintains the same general character with only minor variations. PROFS data provide no information on the depth of the surface drainage flow over the region. However, some information on its vertical structure may be obtained from a study by Hahn (1981). Based on an analysis of BAO tower data for September 1978, Hahn determines that the nocturnal drainage flow near Erie, Colorado (approximately halfway between RB3 and BRI in Fig. 1) is generally confined to a depth of 100 m. A mapping of the vertical structure of the drainage flow over the entire PROFS region clearly requires further observational study.

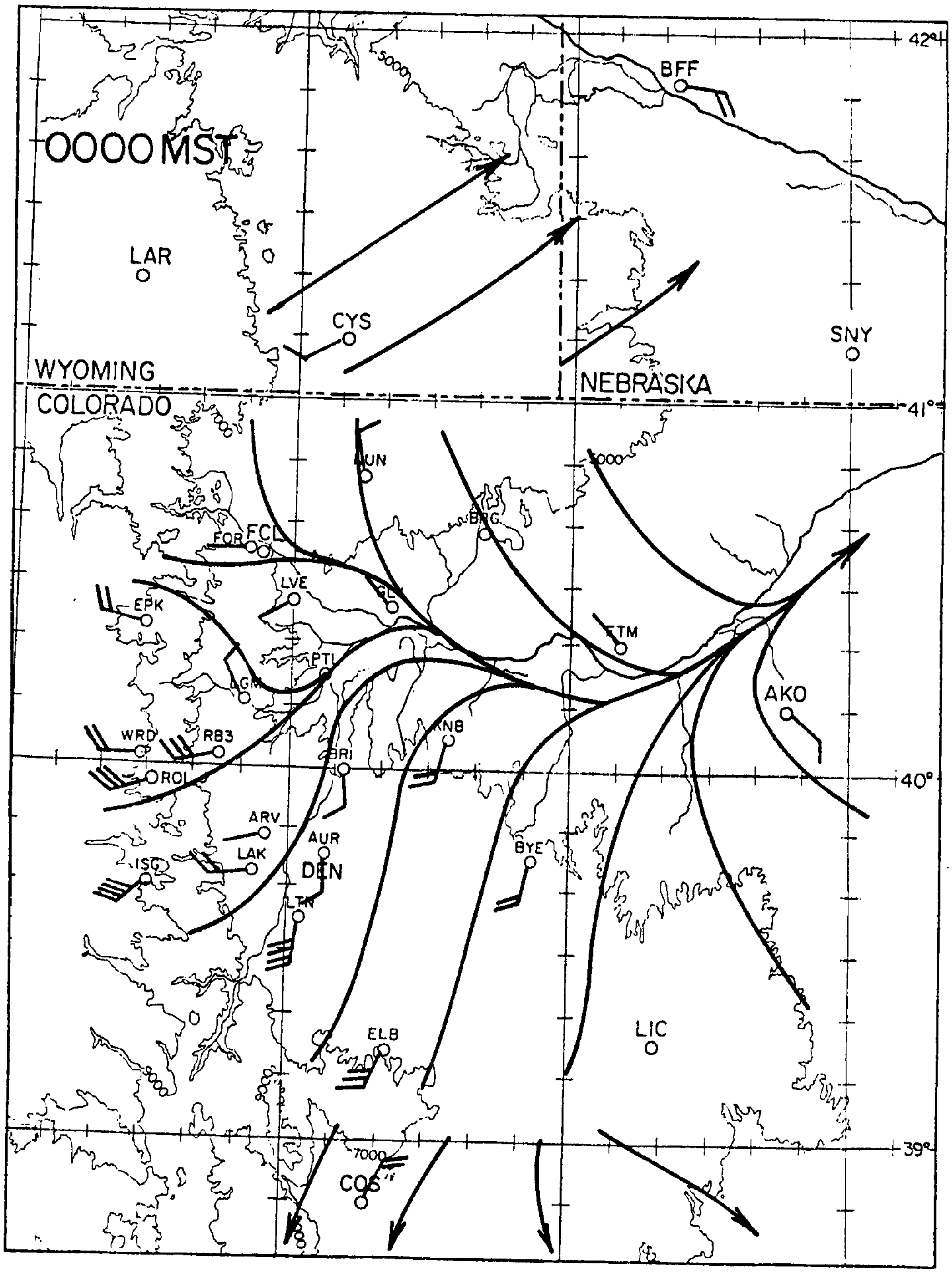

Fig. 2. Surface streamline analyses for 0000 Mountain Standard Time (MST). Plotted winds are in m s^{-1} (one full barb = 1 m s^{-1}).

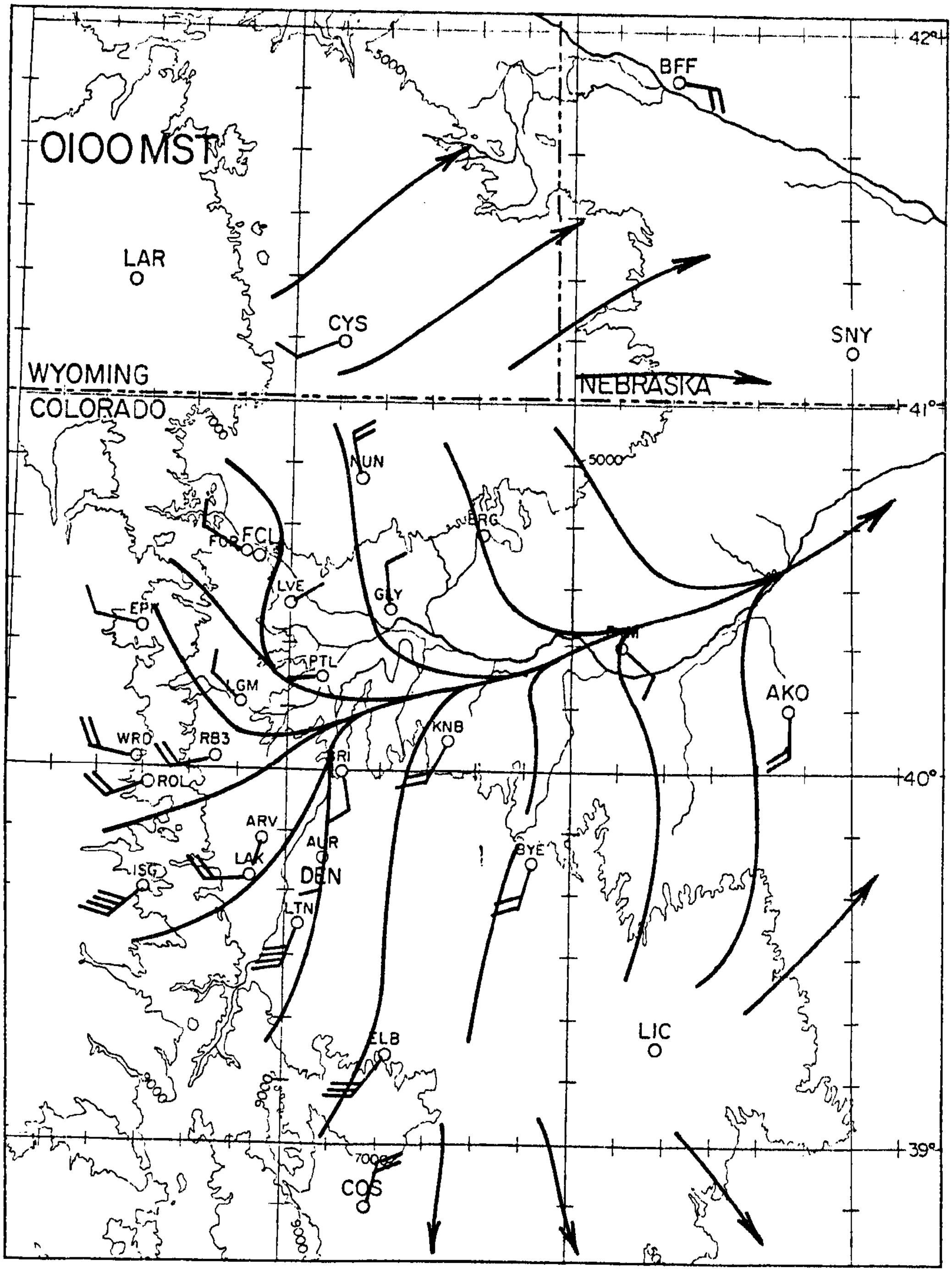

Fig. 3. As in Fig. 2, except for 0100 MST.

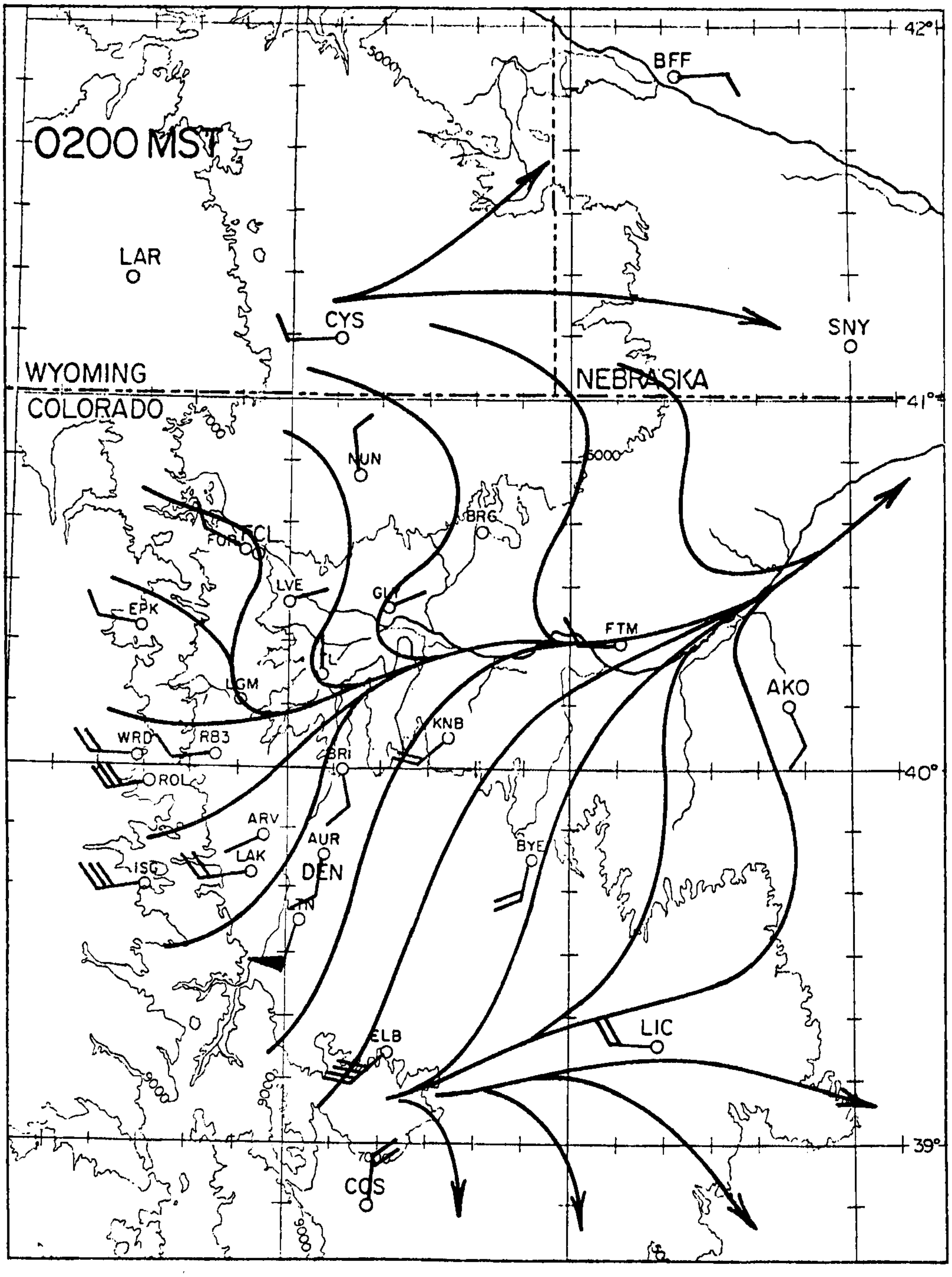

Fig. 4. As in Fig. 2, except for 0200 MST.

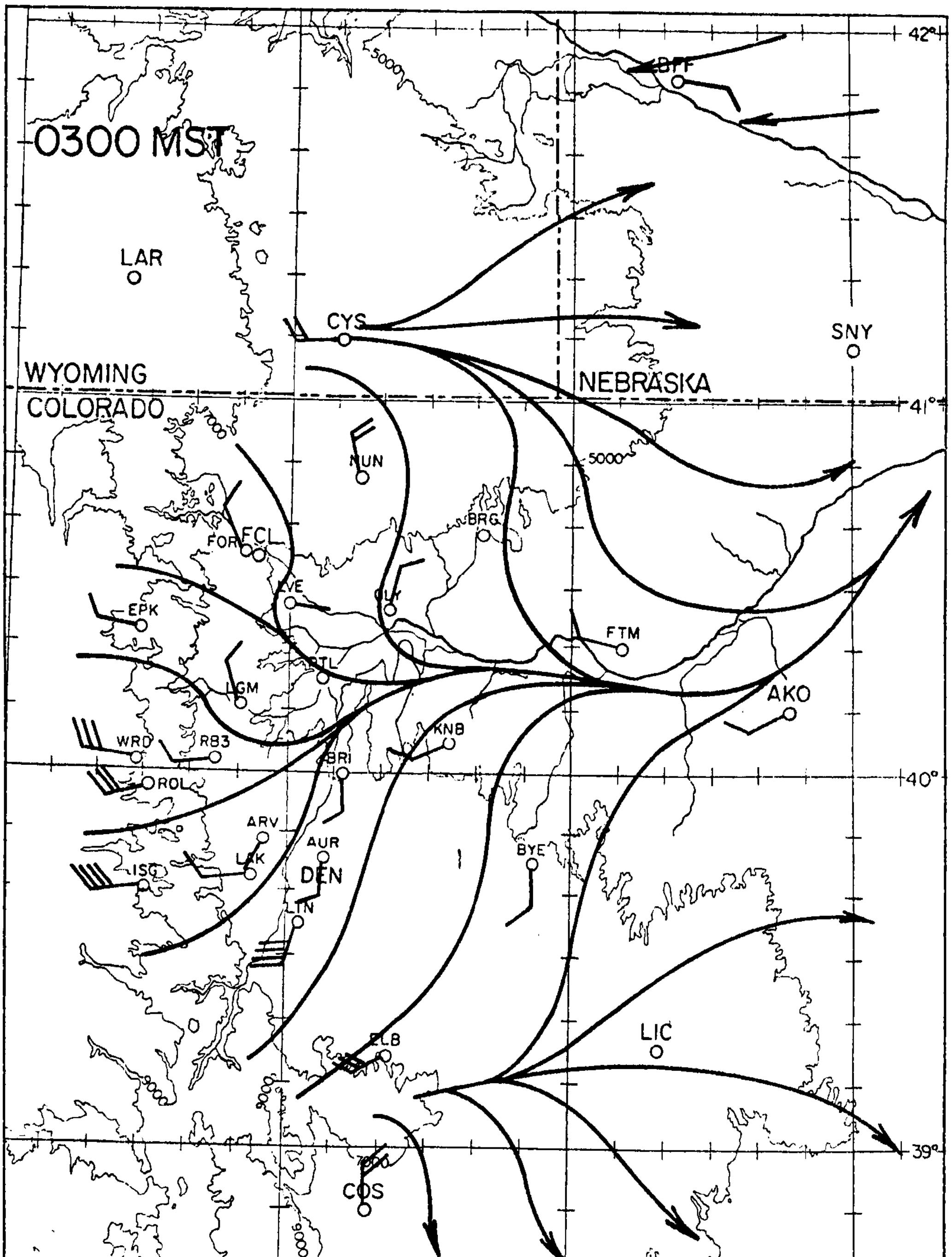

Fig. 5. As in Fig. 2, except for 0300 MST.

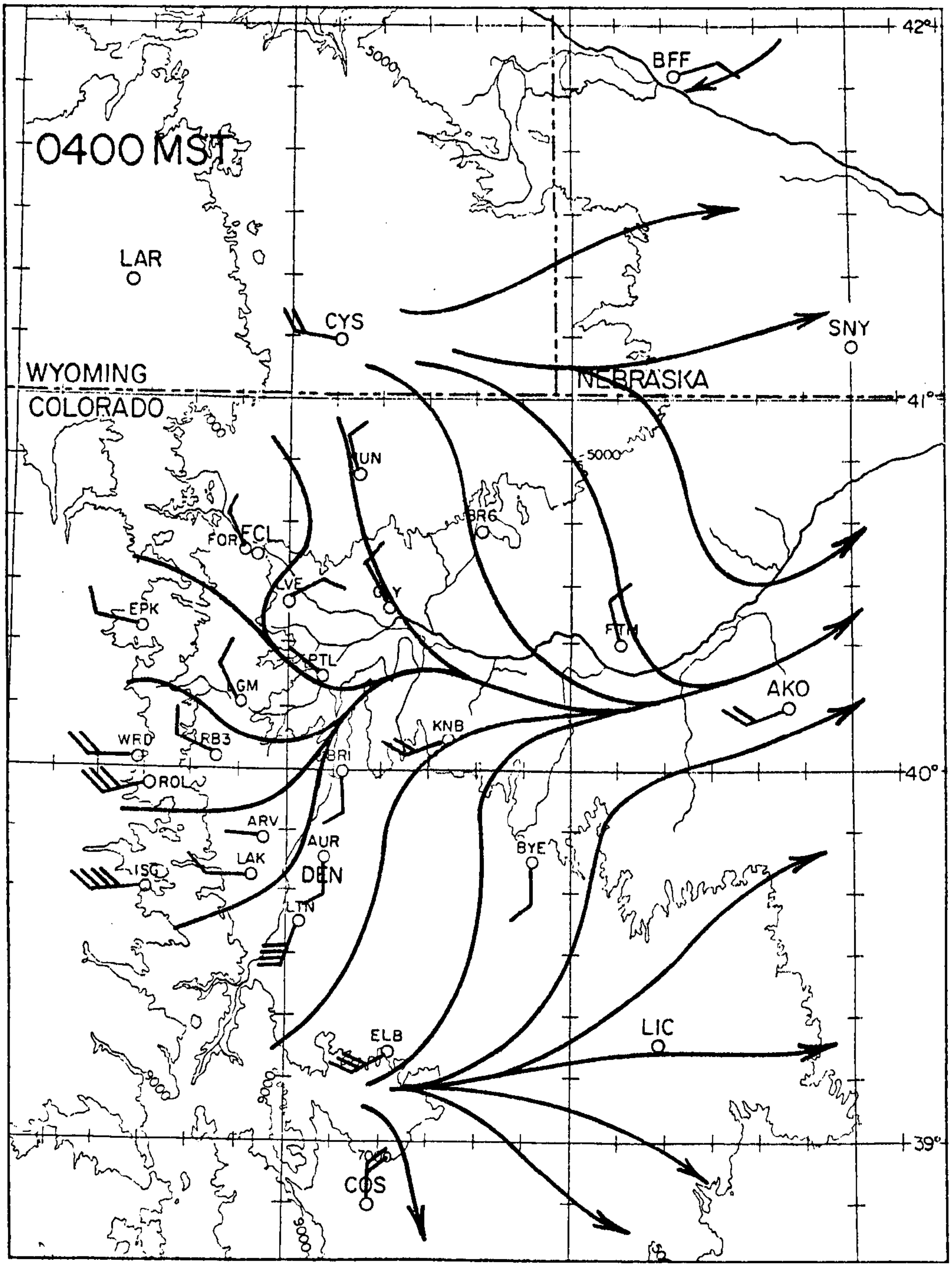

Fig. 6. As in Fig. 2, except for 0400 MST.

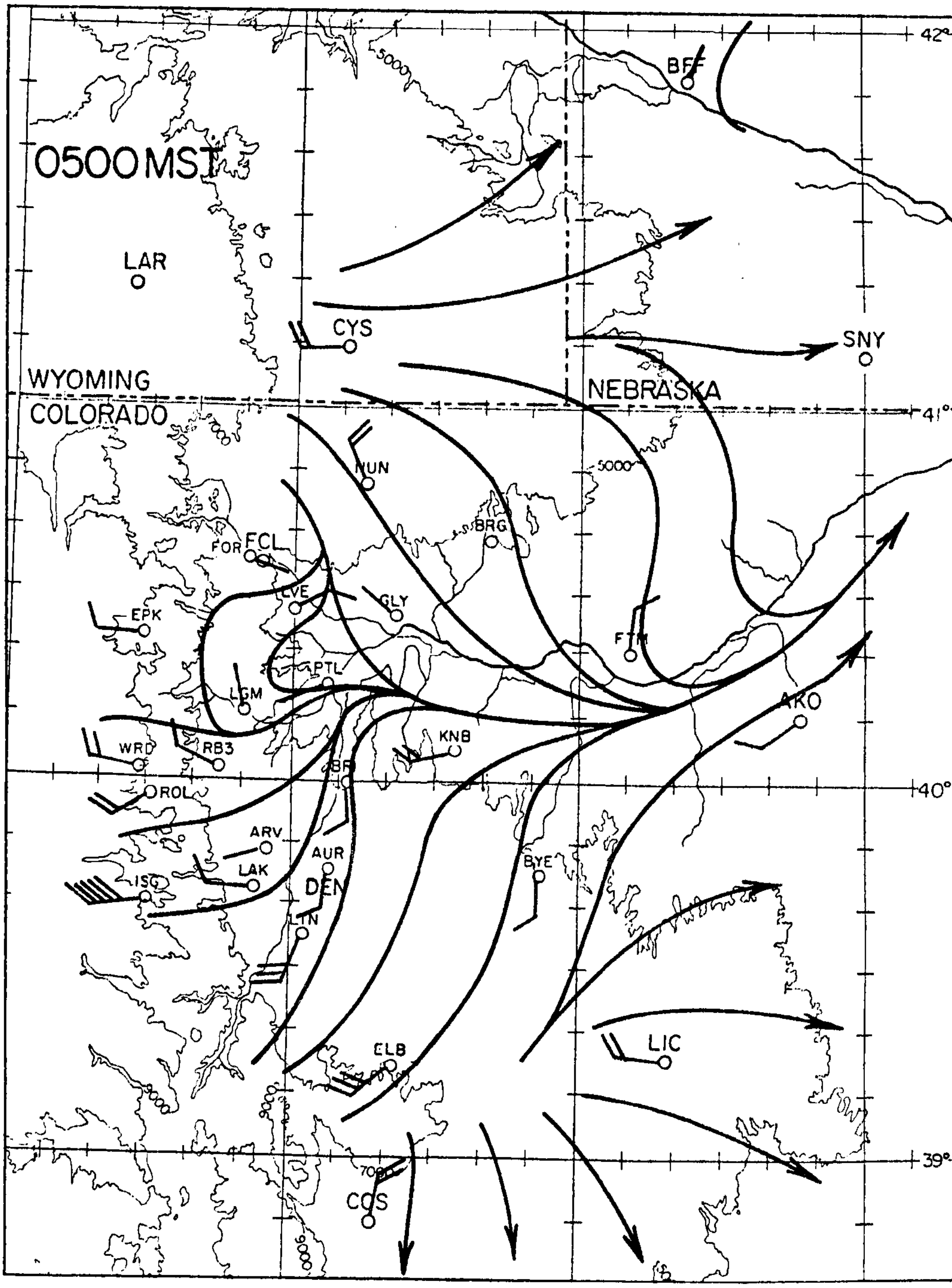

Fig. 7. As in Fig. 2, except for 0500 MST.

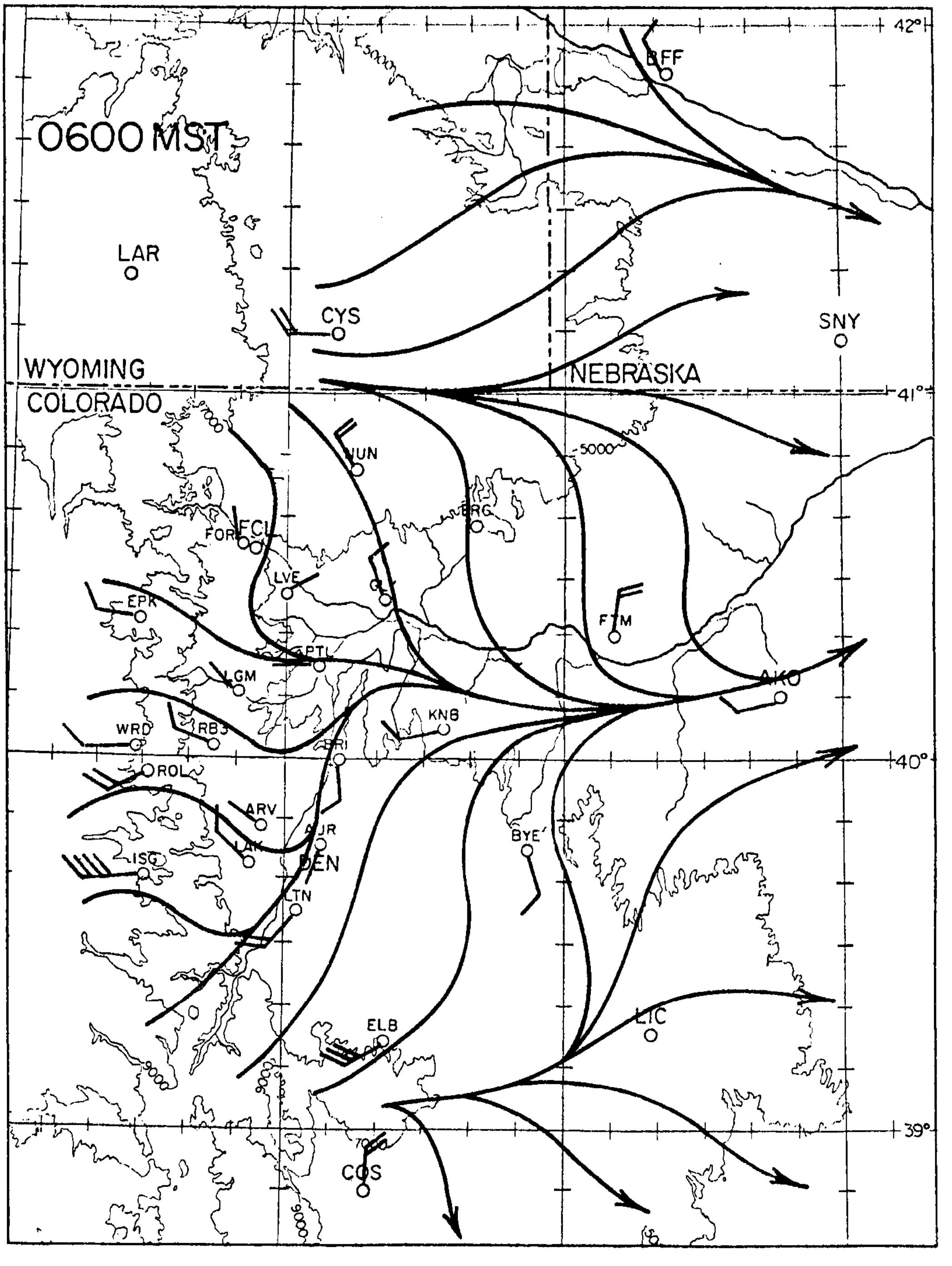

Fig. 8. As in Fig. 2, except for 0600 MST.

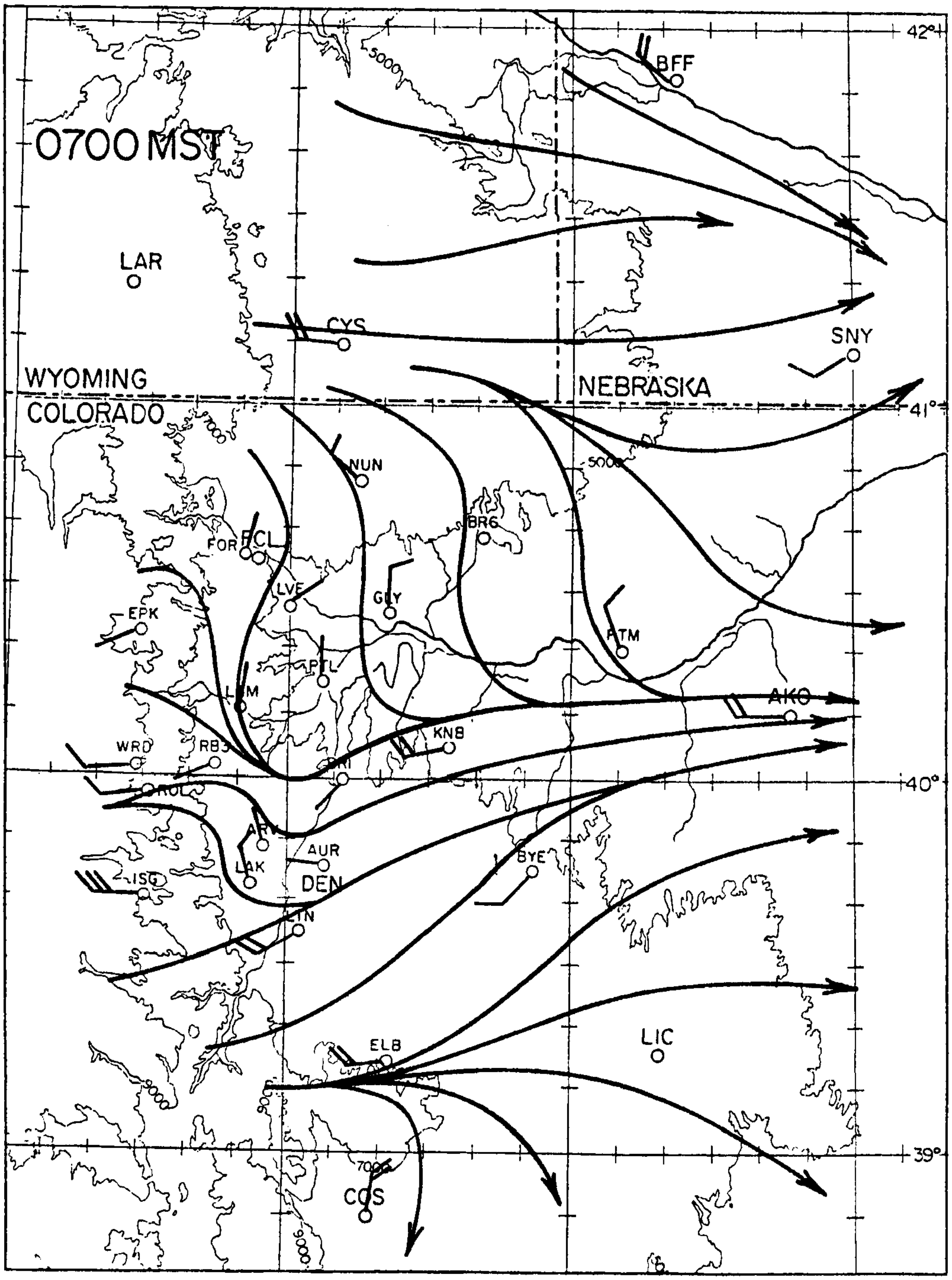

Fig. 9. As in Fig. 2, except for 0700 MST.

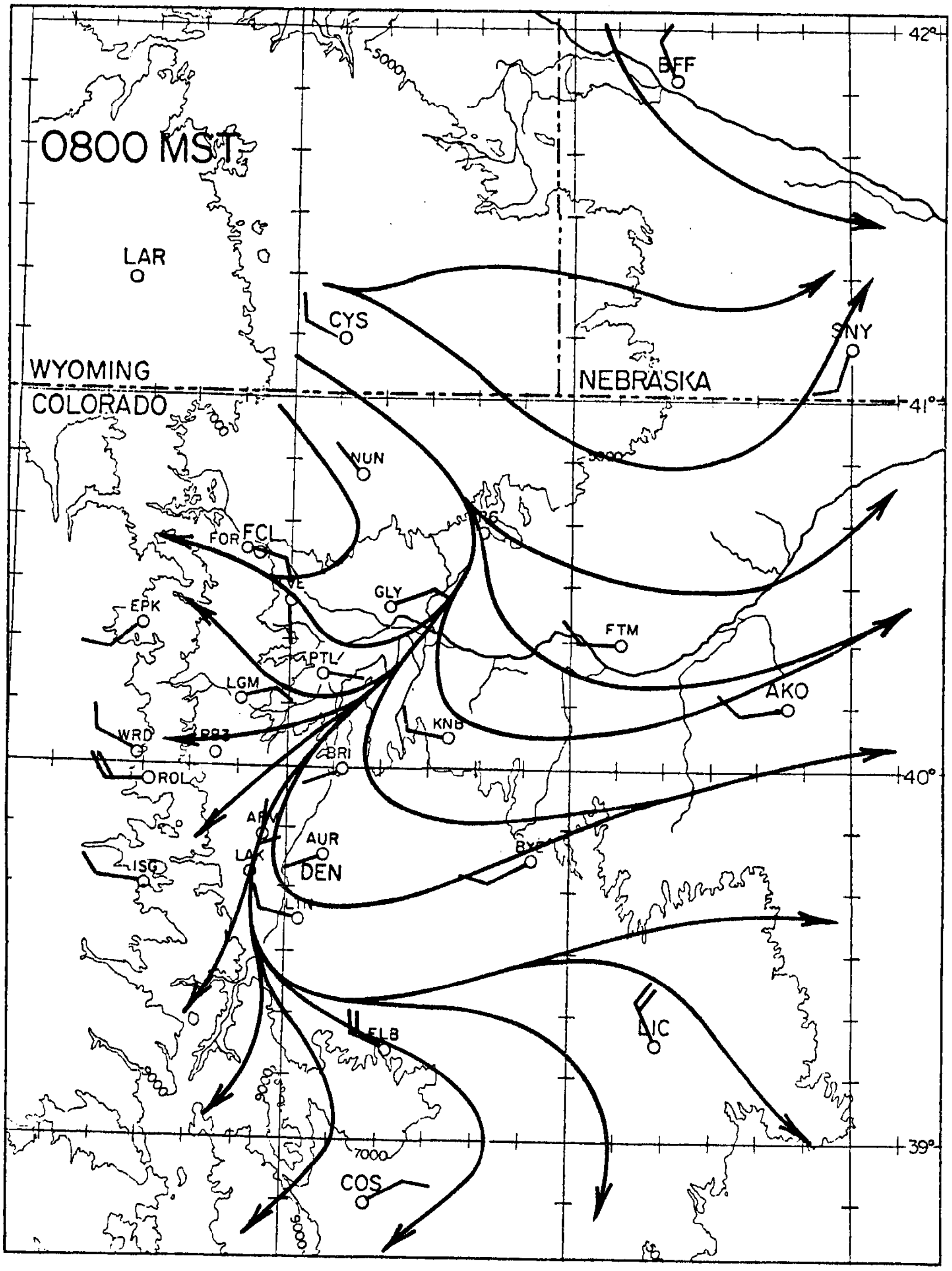

Fig. 10. As in Fig. 2, except for 0800 MST.

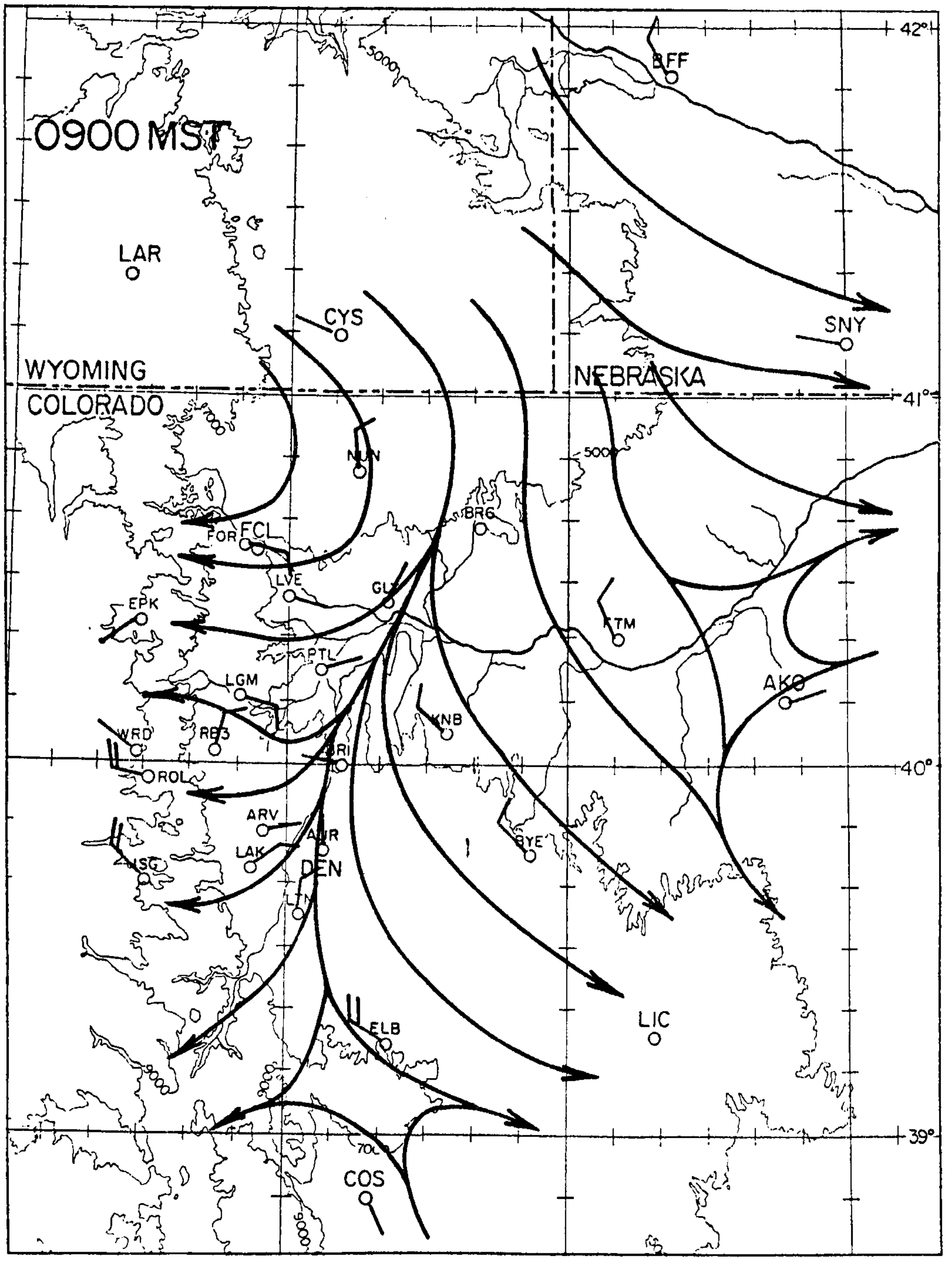

Fig. 11. As in Fig. 2, except for 0900 MST.

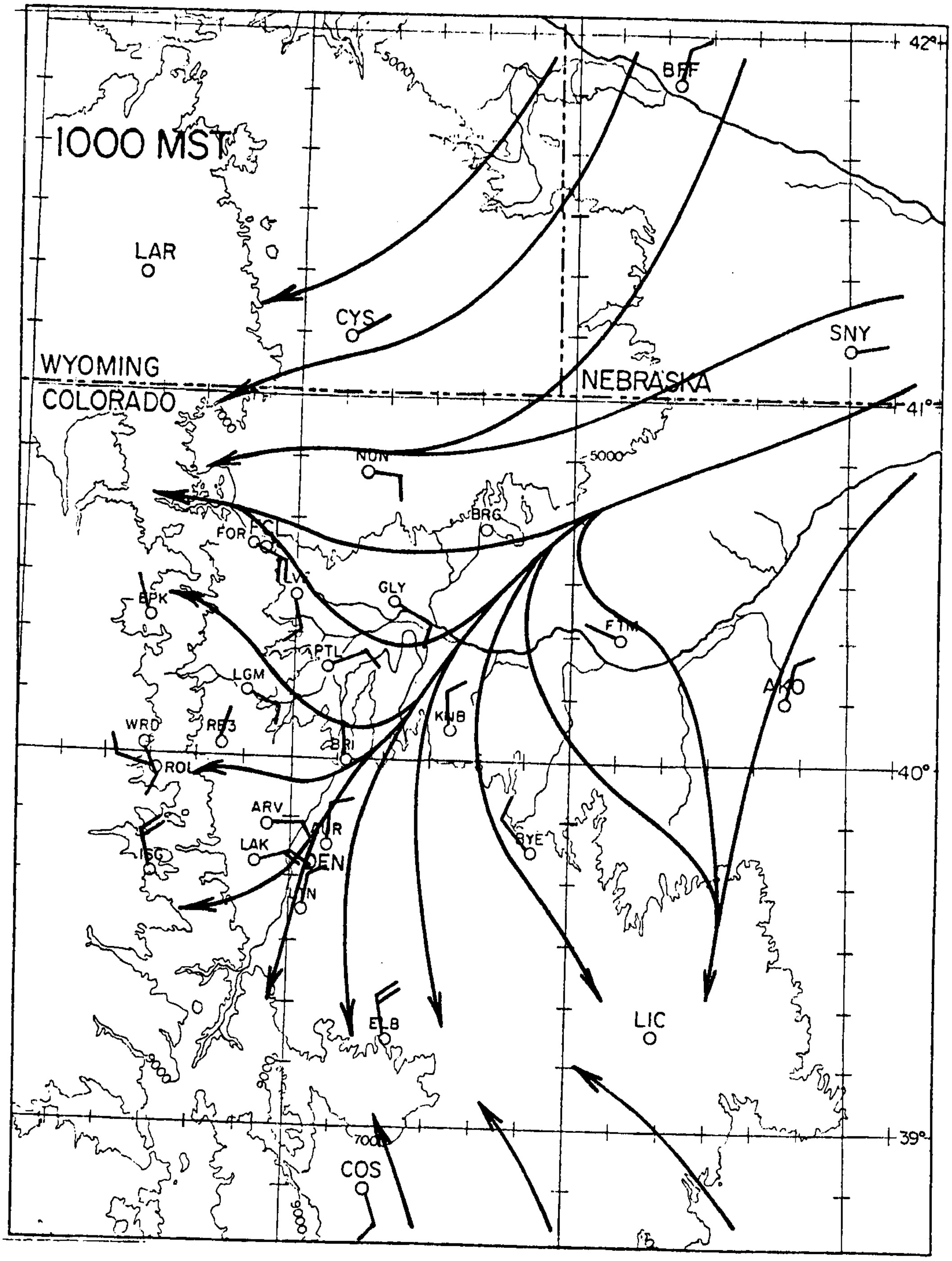

Fig. 12. As in Fig. 2, except for 1000 MST.

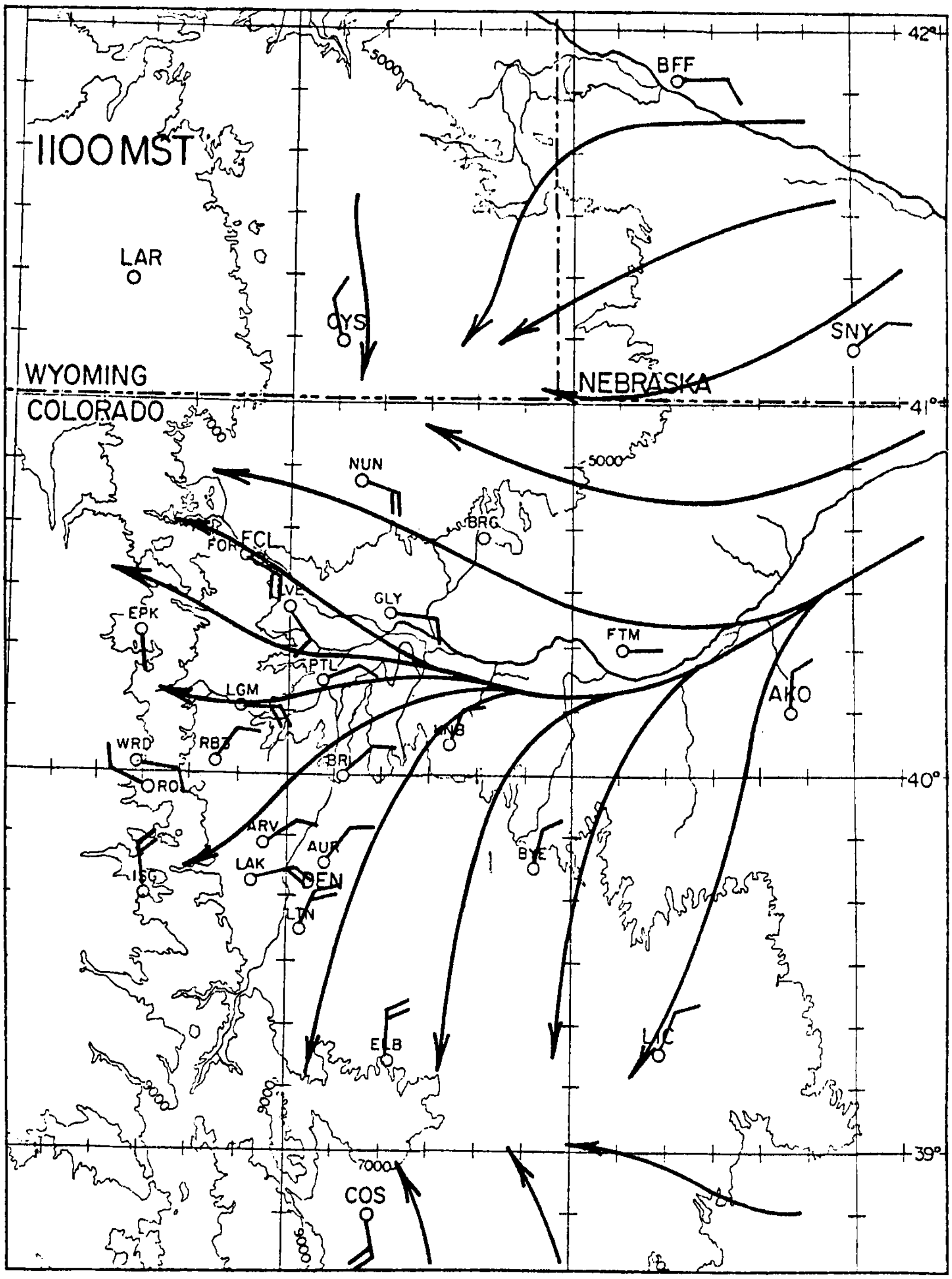

Fig. 13. As in Fig. 2, except for 1100 MST.

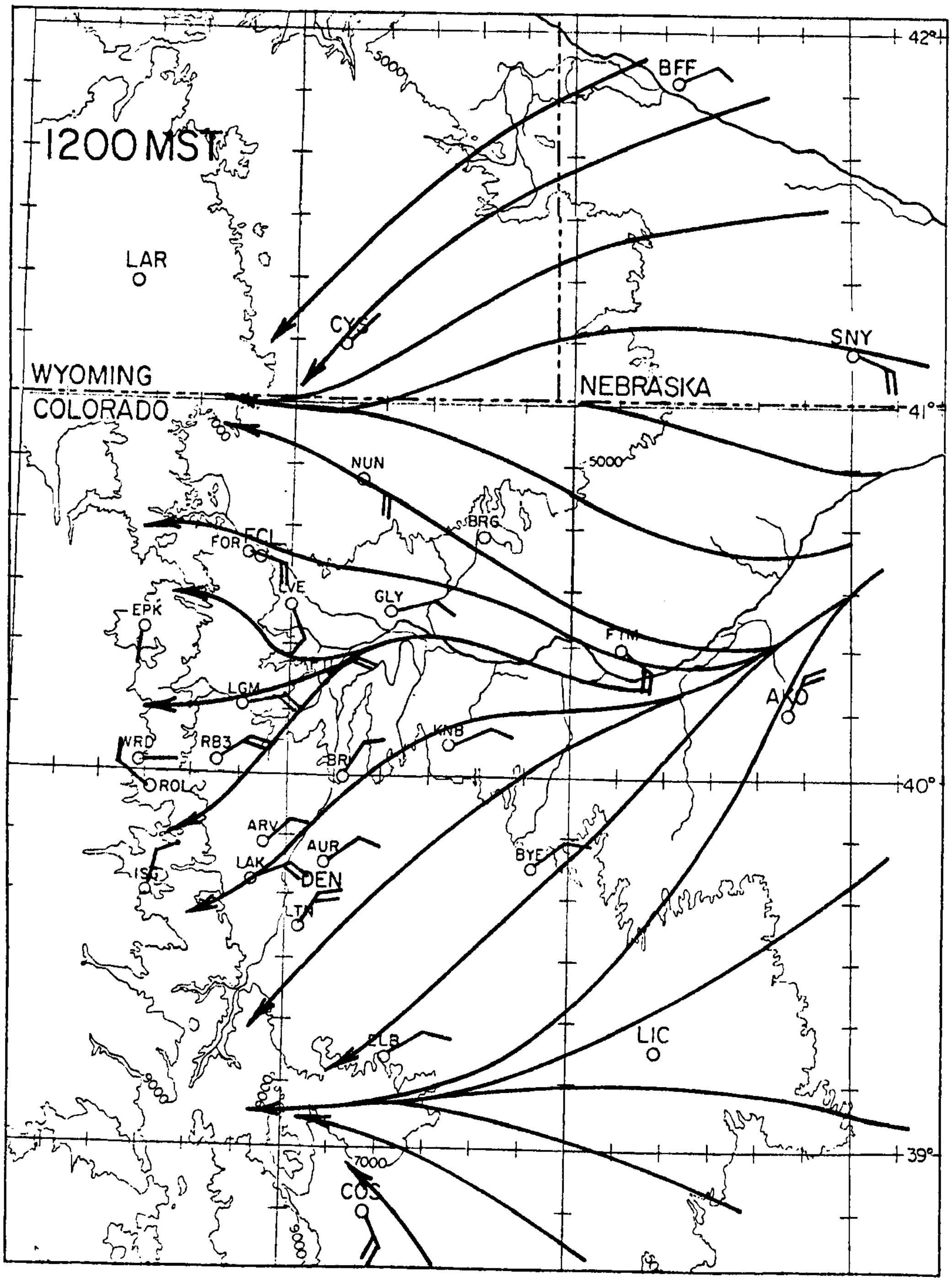

Fig. 14. As in Fig. 2, except for 1200 MST.

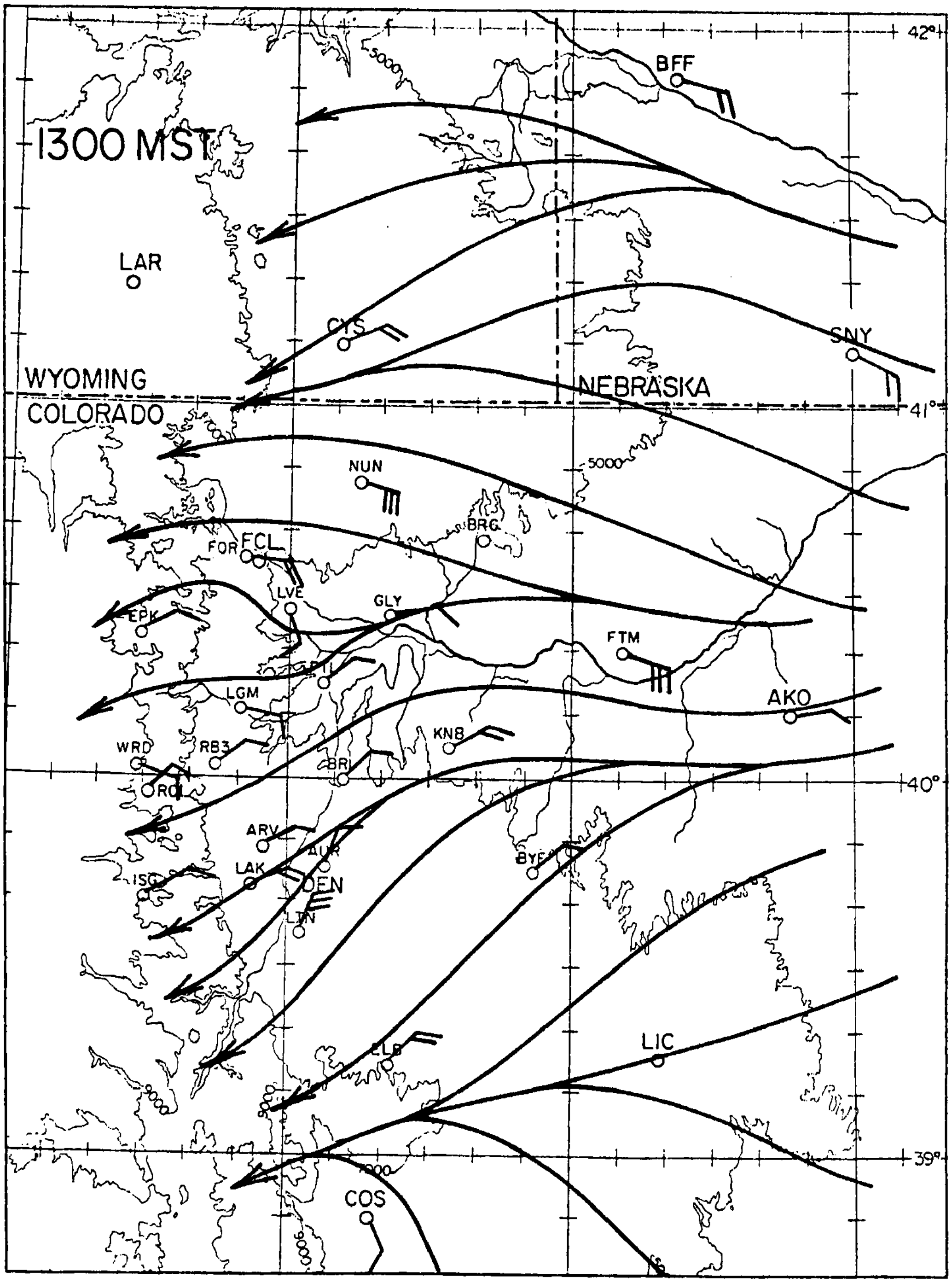

Fig. 15. As in Fig. 2, except for 1300 MST.

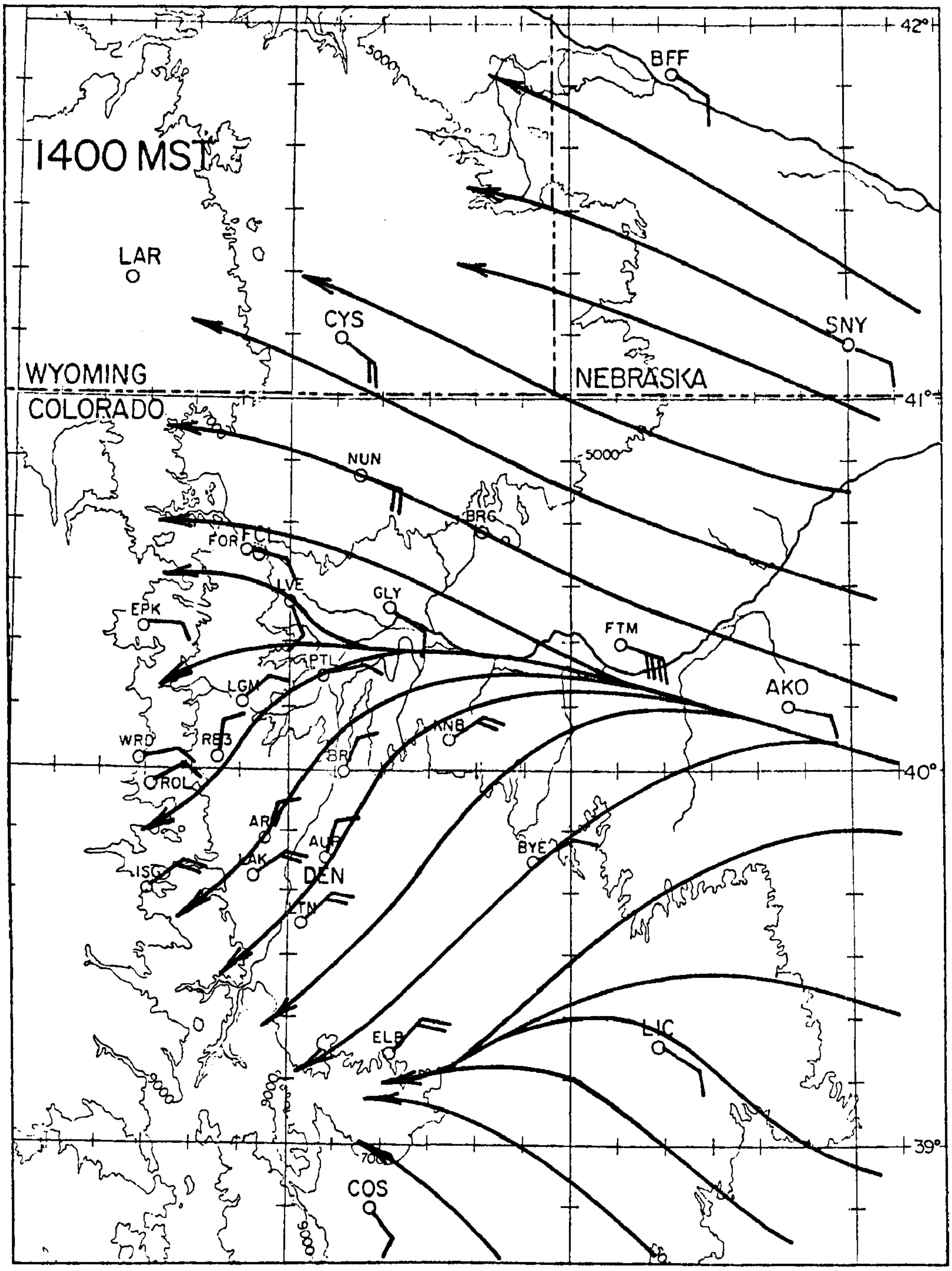

Fig. 16. As in Fig. 2, except for 1400 MST.

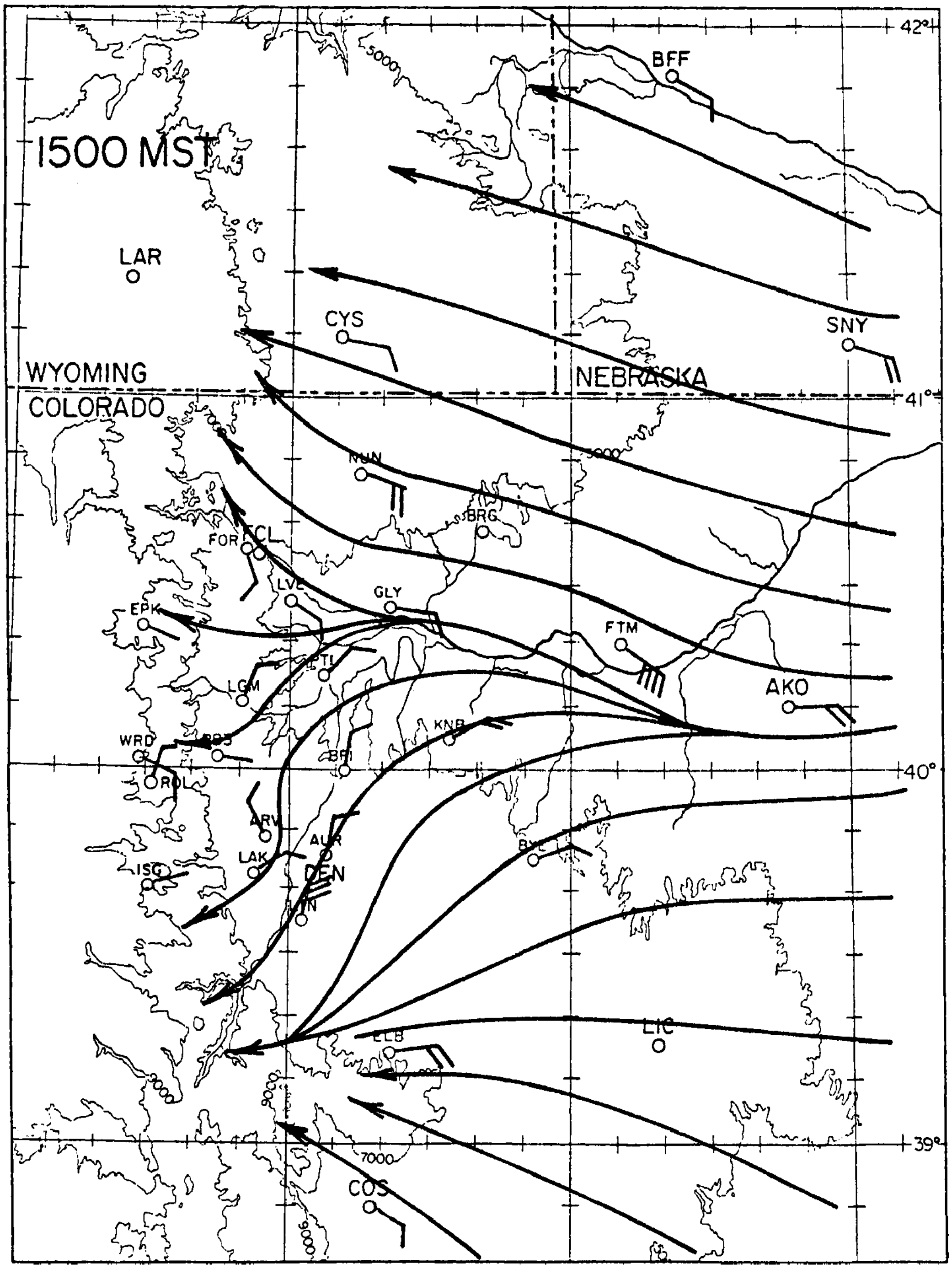

Fig. 17. As in Fig. 2, except for 1500 MST.

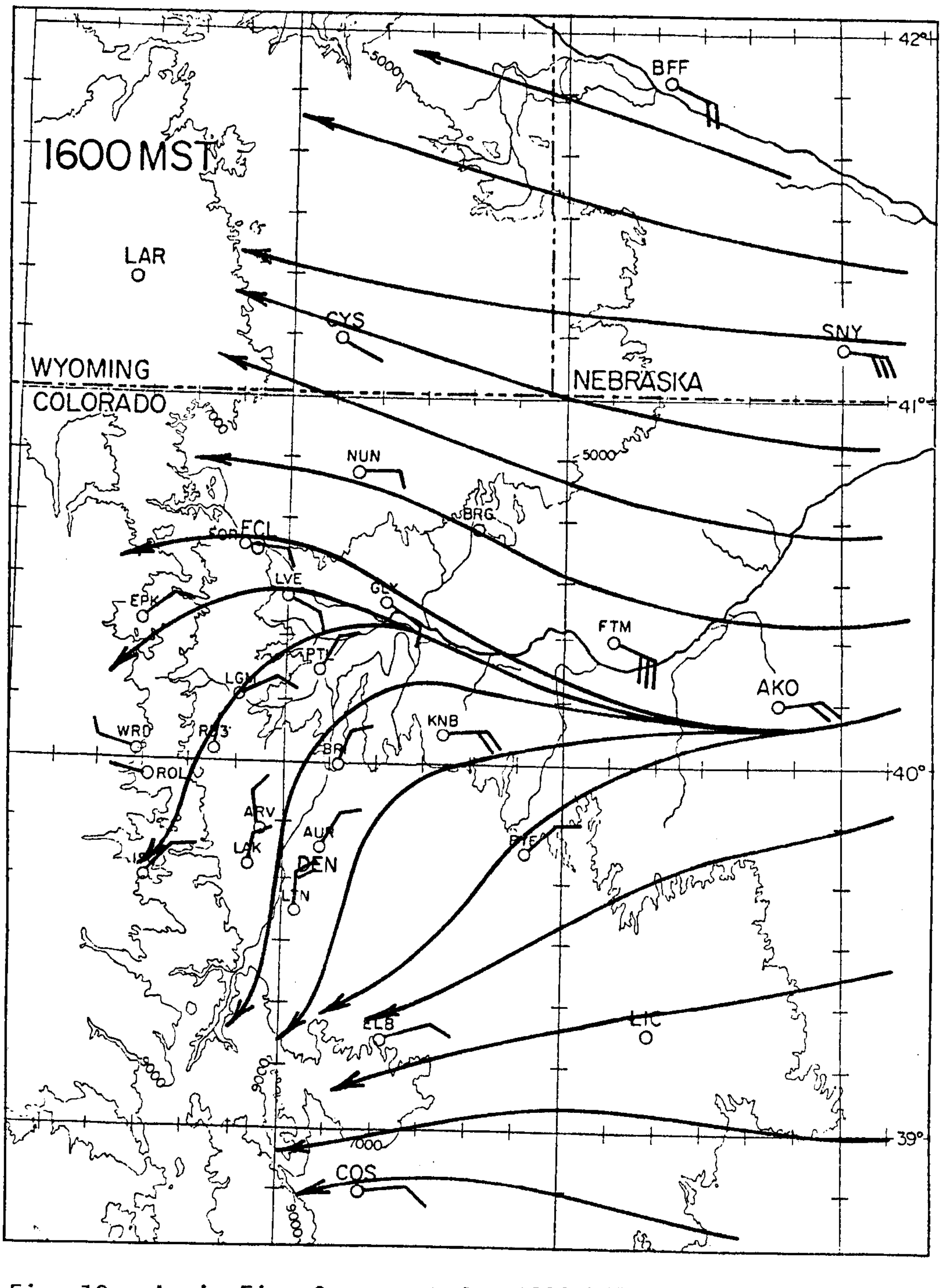

Fig. 18. As in Fig. 2, except for 1600 MST.

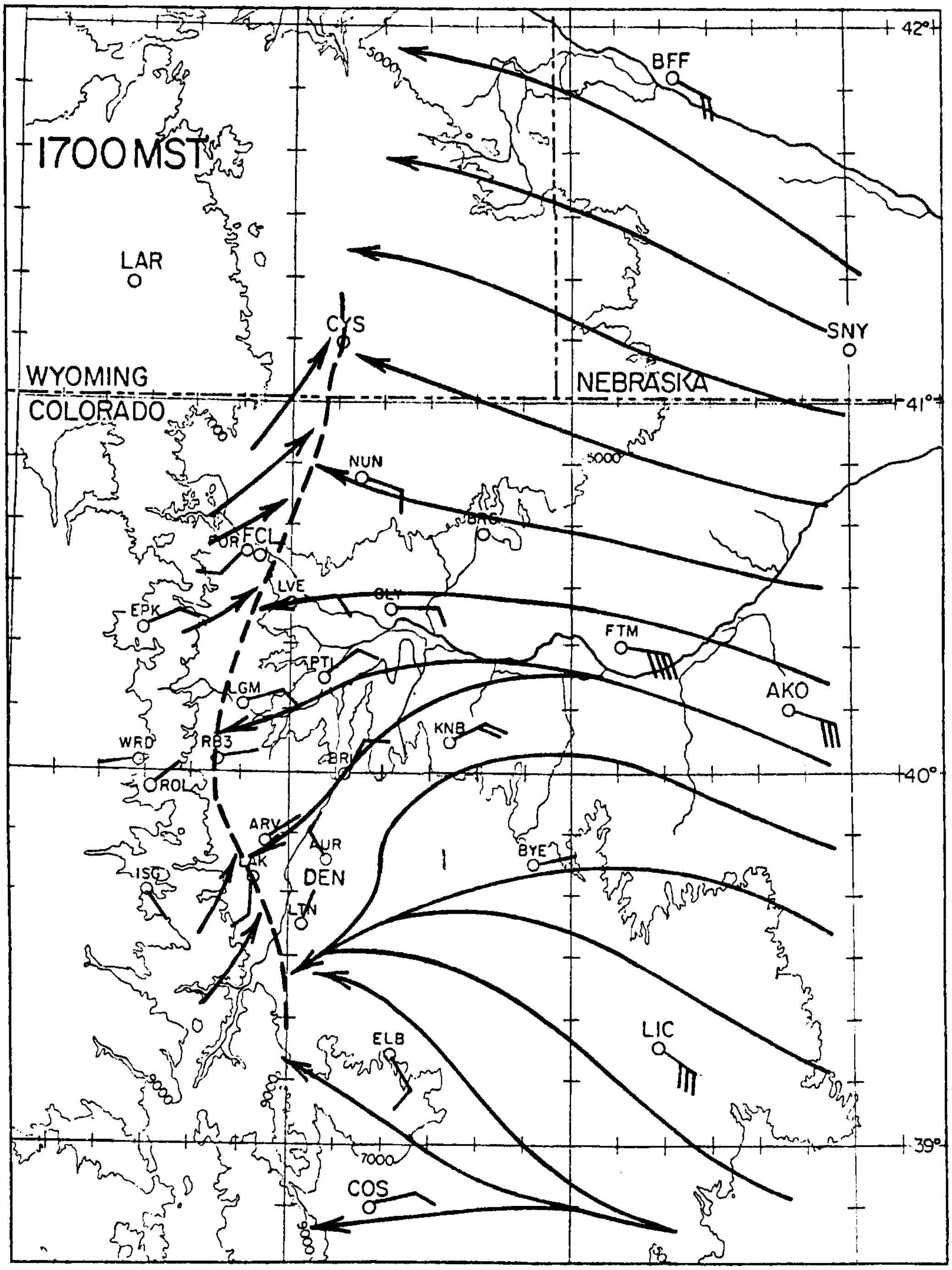

Fig. 19. As in Fig. 2, except for 1700 MST.

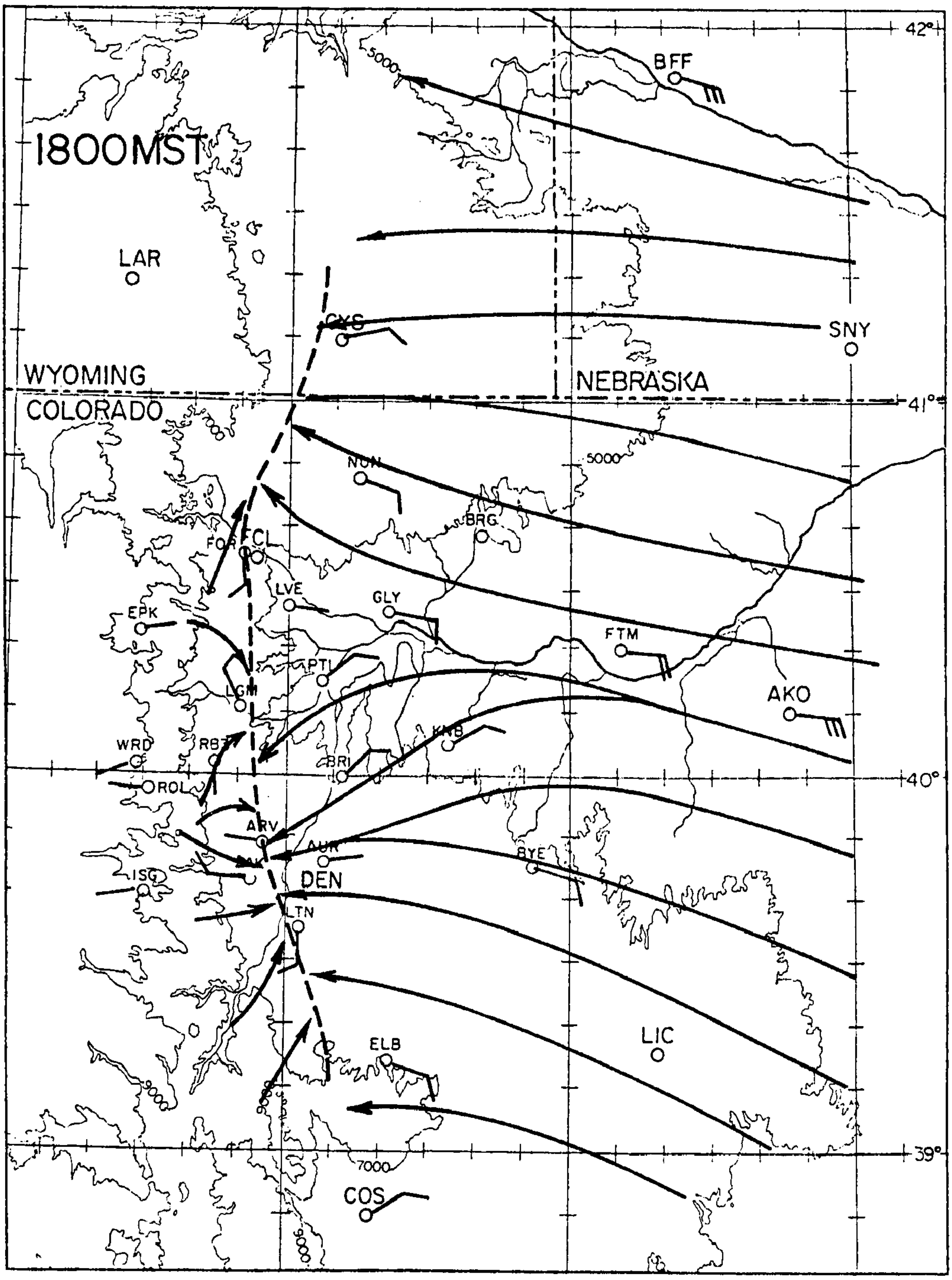

Fig. 20. As in Fig. 2, except for 1800 MST.

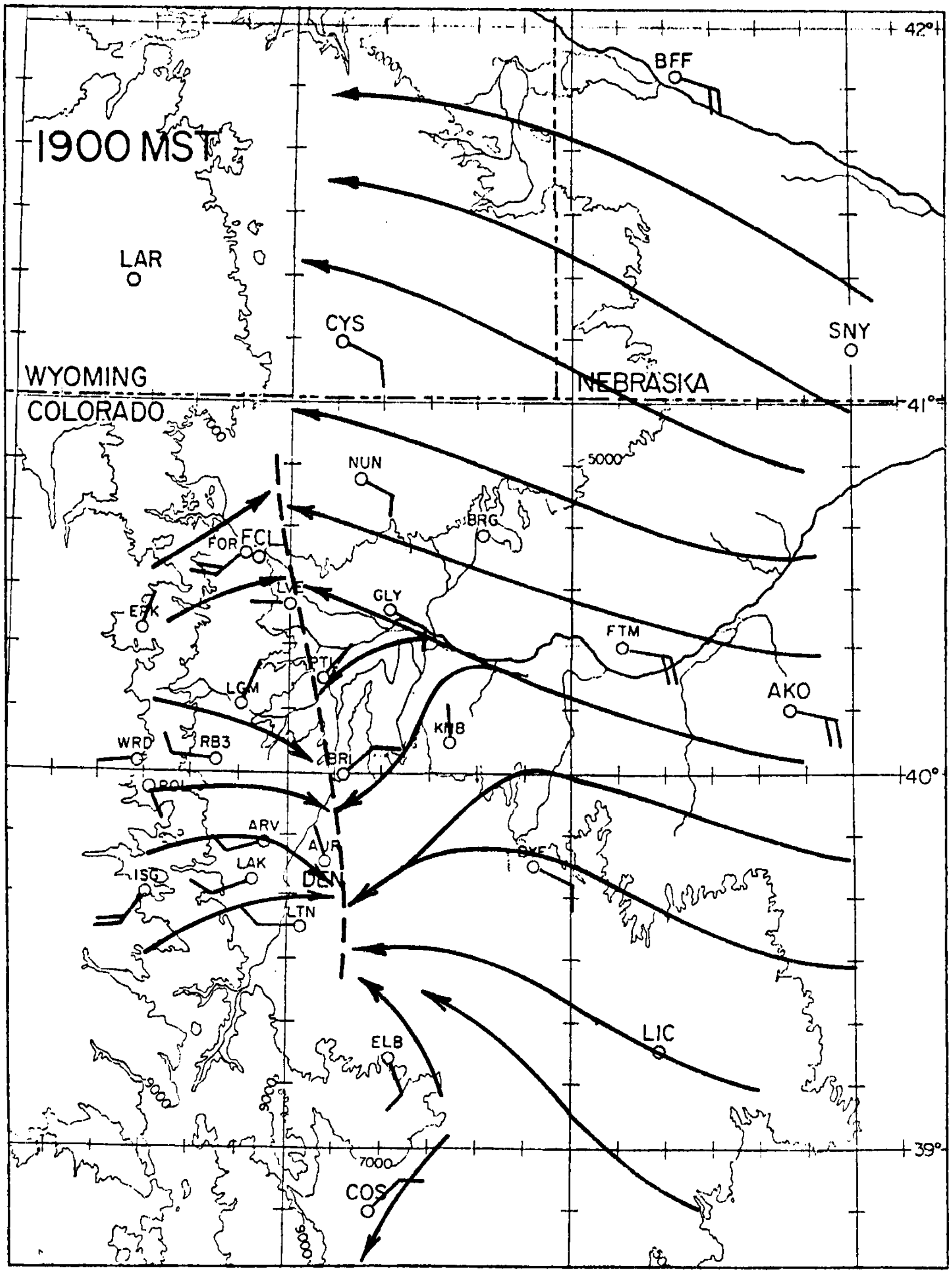

Fig. 21. As in Fig. 2, except for 1900 MST.

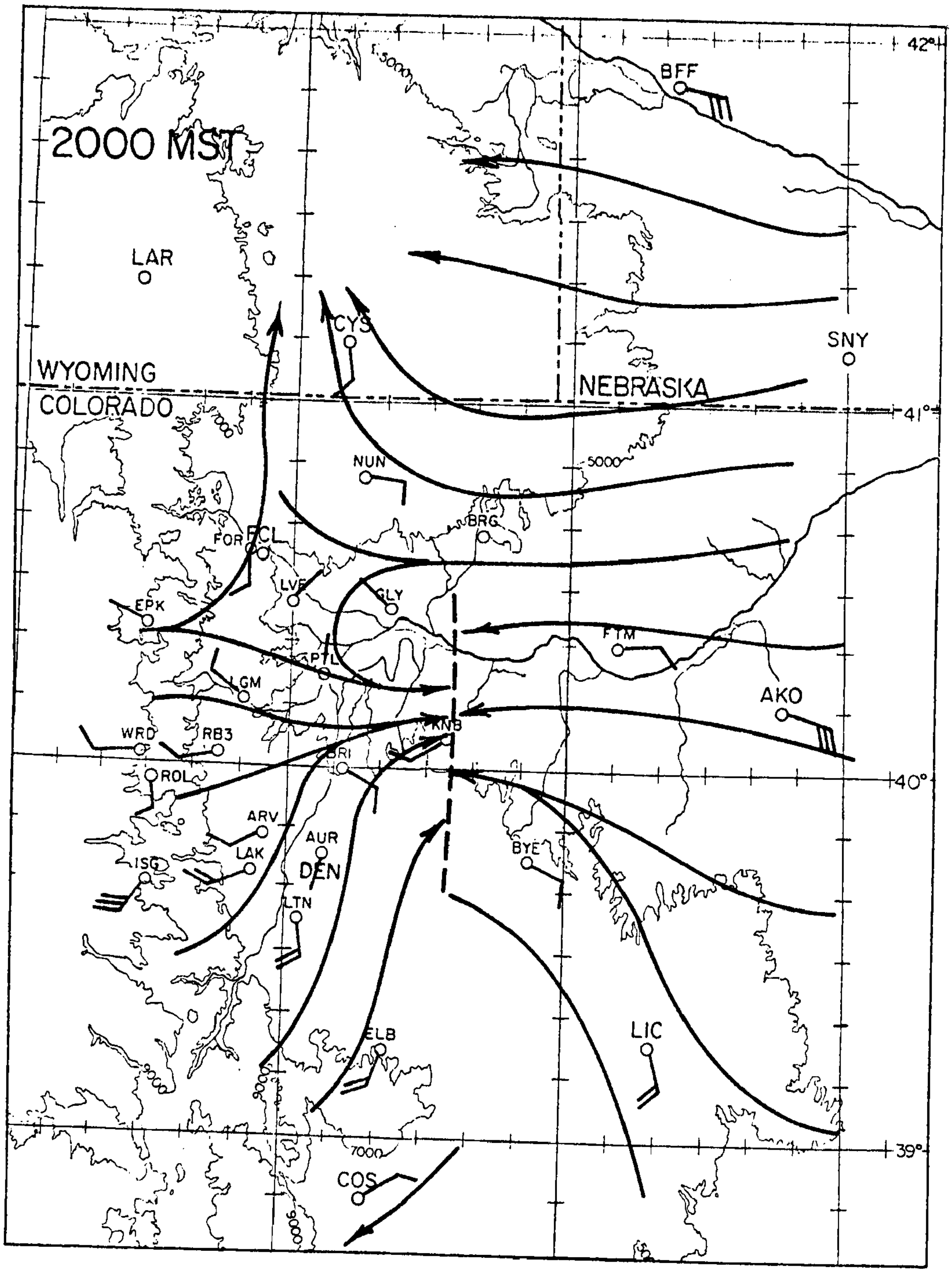

Fig. 22. As in Fig. 2, except for 2000 MST.

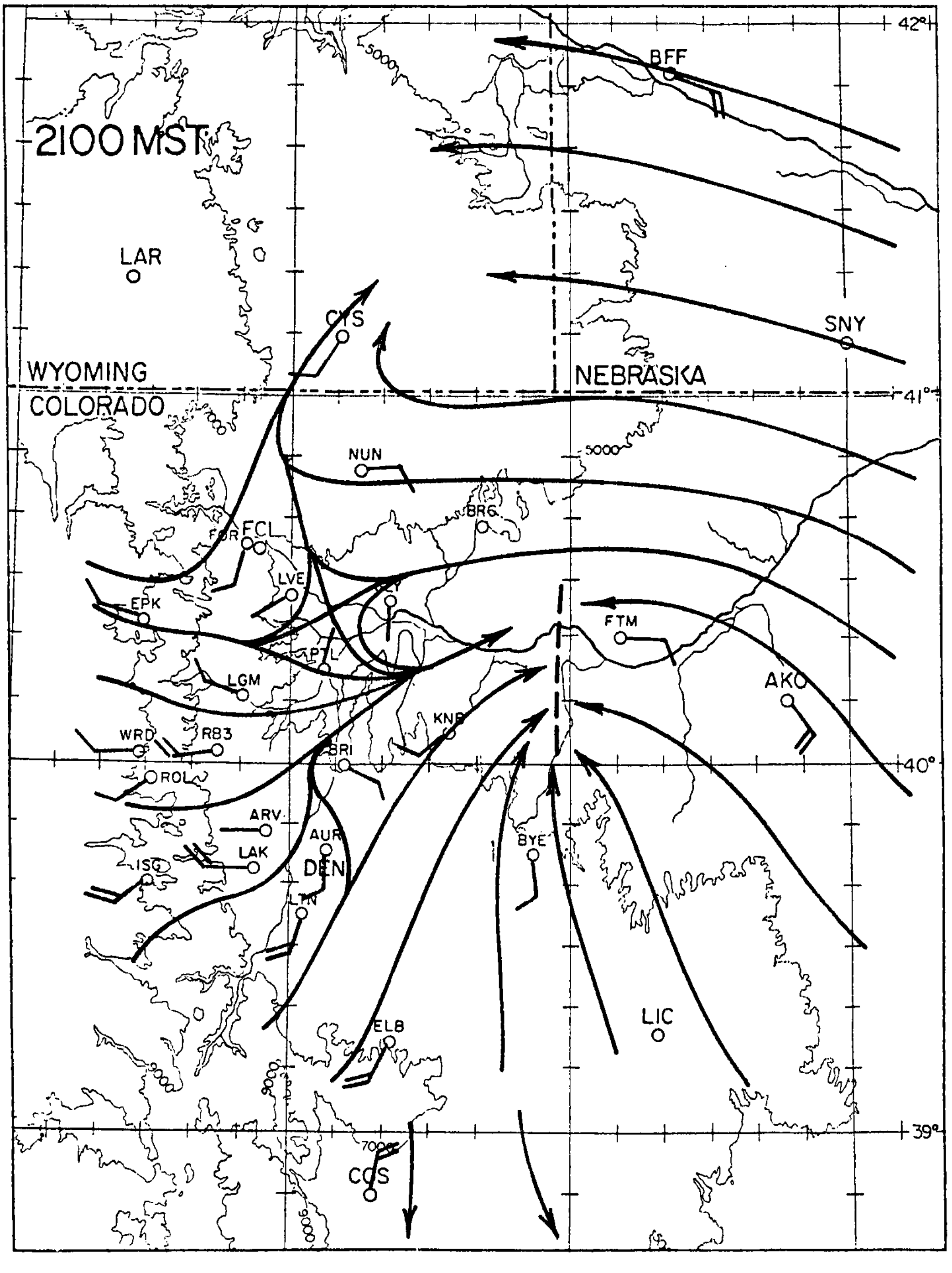

Fig. 23. As in Fig. 2, except for 2100 MST.

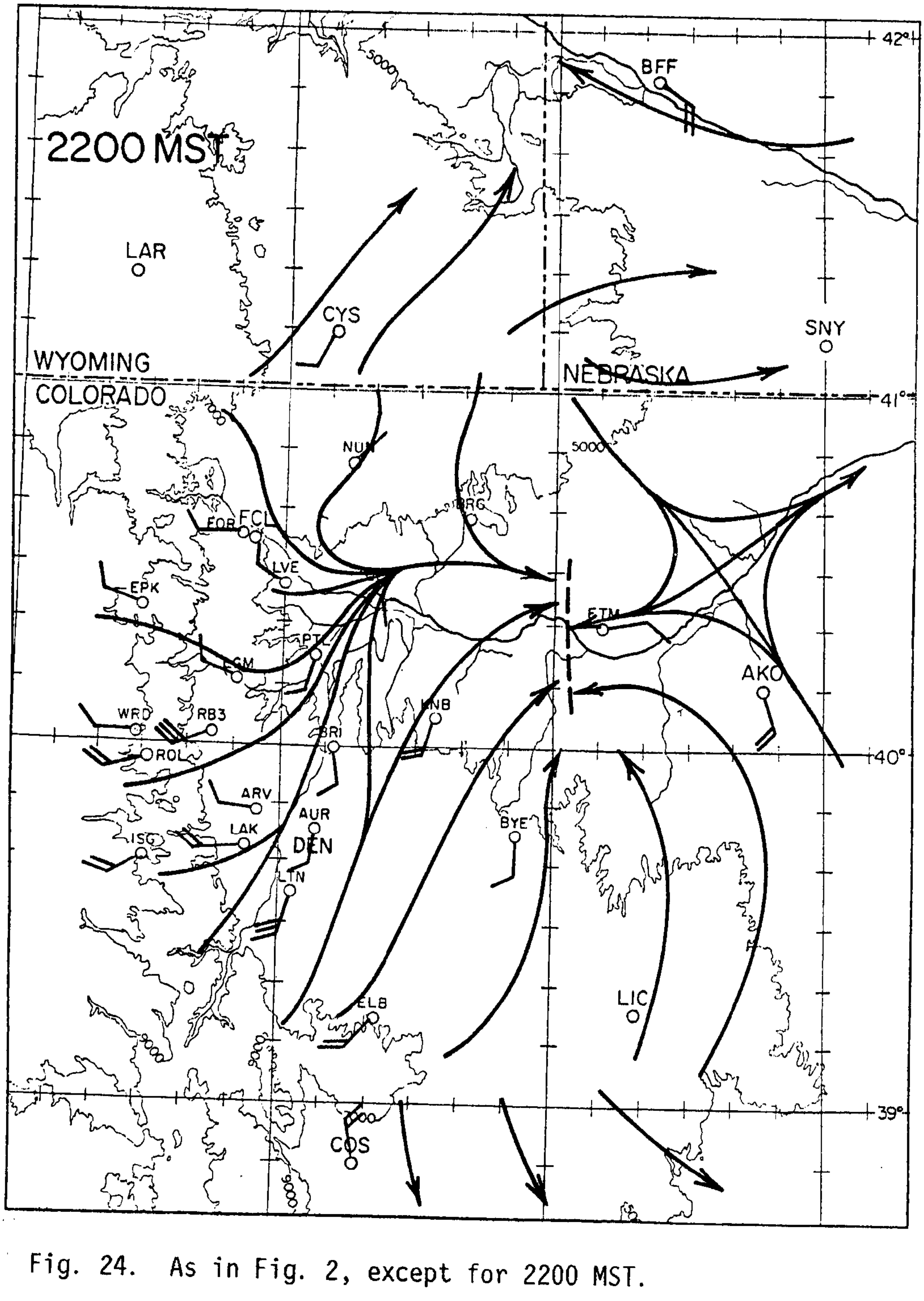

Fig. 24. As in Fig. 2, except for 2200 MST.

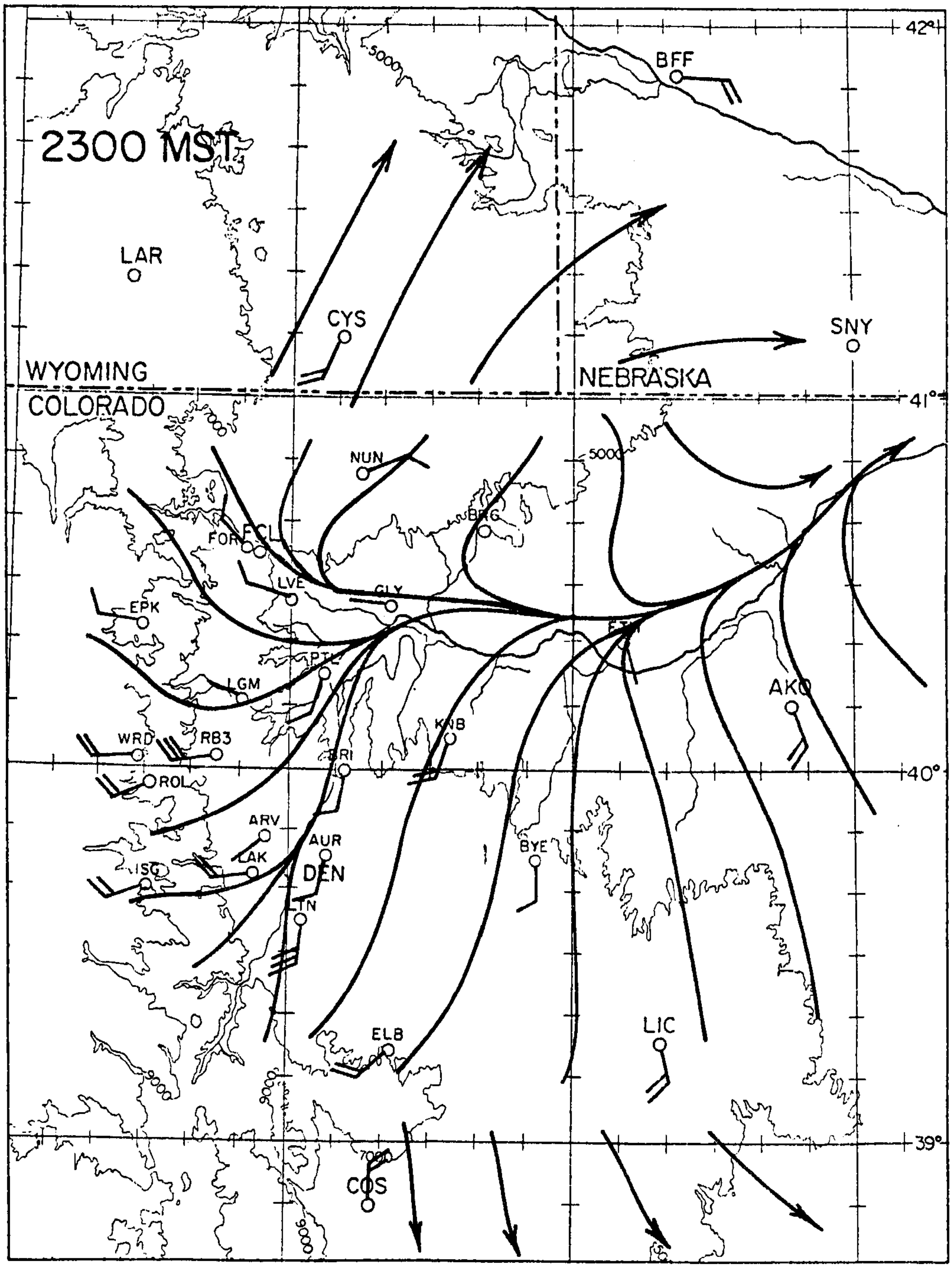

Fig. 25. As in Fig. 2, except for 2300 MST.

From 0700 MST to 0900 MST (Figs. 9-11) the effects of insolation on the east slope of the Continental Divide begin to be evident in the western part of the network as weak upslope flow begins there. By 0900 MST (Fig. 11) surface upslope flow has been generated over much of the region to the west of Denver (DEN) (not at the highest stations, however) while downslope flow persists to the east over most of the east-west ridges. By 1100 MST (Fig. 13) upslope flow has developed nearly over the entire region, finally extending by 1300 MST to the level of the highest stations (Fig. 15). Upslope flow over most of the region continues to 1700 MST (Figs. 16-19), at which time there is an indication of a flow reversal at the lower elevation stations over the western part of the network with downslope flow meeting upslope flow along a north-south line near Denver's longitude. This confluence line marking the onset of downslope flow progresses eastward for the next ~ 4-5 hours (Figs. 20-24) with a return to typical drainage flow pattern by late evening (2300 MST, Fig. 25).

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

5. Relationship of Mean Flow Patterns to Thunderstorm Activity

During July most precipitation that occurs over the region of this study can be attributed to afternoon thunderstorms. Typically, the first showers of the day develop along the continental divide or in certain preferred regions along the foothills or ridges extending into the plains. Dirks (1969), Wetzel (1973), Henz (1974) and Karr and Wooten (1976) have carried out analyses of thunderstorm development over Colorado to the lee of the Rocky Mountains and have identified favored regions for the development of cumulonimbus clouds or mesoscale convective systems. Wetzel, Henz and Karr and Wooten prepared climatologies of radar echoes based on data from the WSR-57 10 cm radar at Limon, CO. The frequency of radar echoes over the region presented as a percent deviation from the azimuthally-averaged mean at each radius from Limon is shown in Fig. 26 for the summers of 1971 and 1972 (from Wetzel, 1973). Three favored regions for echo occurrence appear: (1) the eastern slopes of the continental divide, (2) the Palmer Lake Divide and (3) the Cheyenne Ridge. Henz (1974) obtains similar results and finds the average time of maximum thunderstorm echo generation in the preferred regions to be between 1200 and 1300 MST. Karr and Wooten (1976) also present similar findings.

In Fig. 26 the mean surface flow at 1100 for July 1981 is superimposed upon the radar climatology for the summers of 1971 and 1972. Despite the fact that two analyses are for different periods of time, there is a strong suggestion that the preferred regions for development coincide in most instances with zones of maximum surface confluence (and convergence) 1 to 2 h earlier. The character of the surface flow, which is strongly controlled by surface heating and topographic effects, does

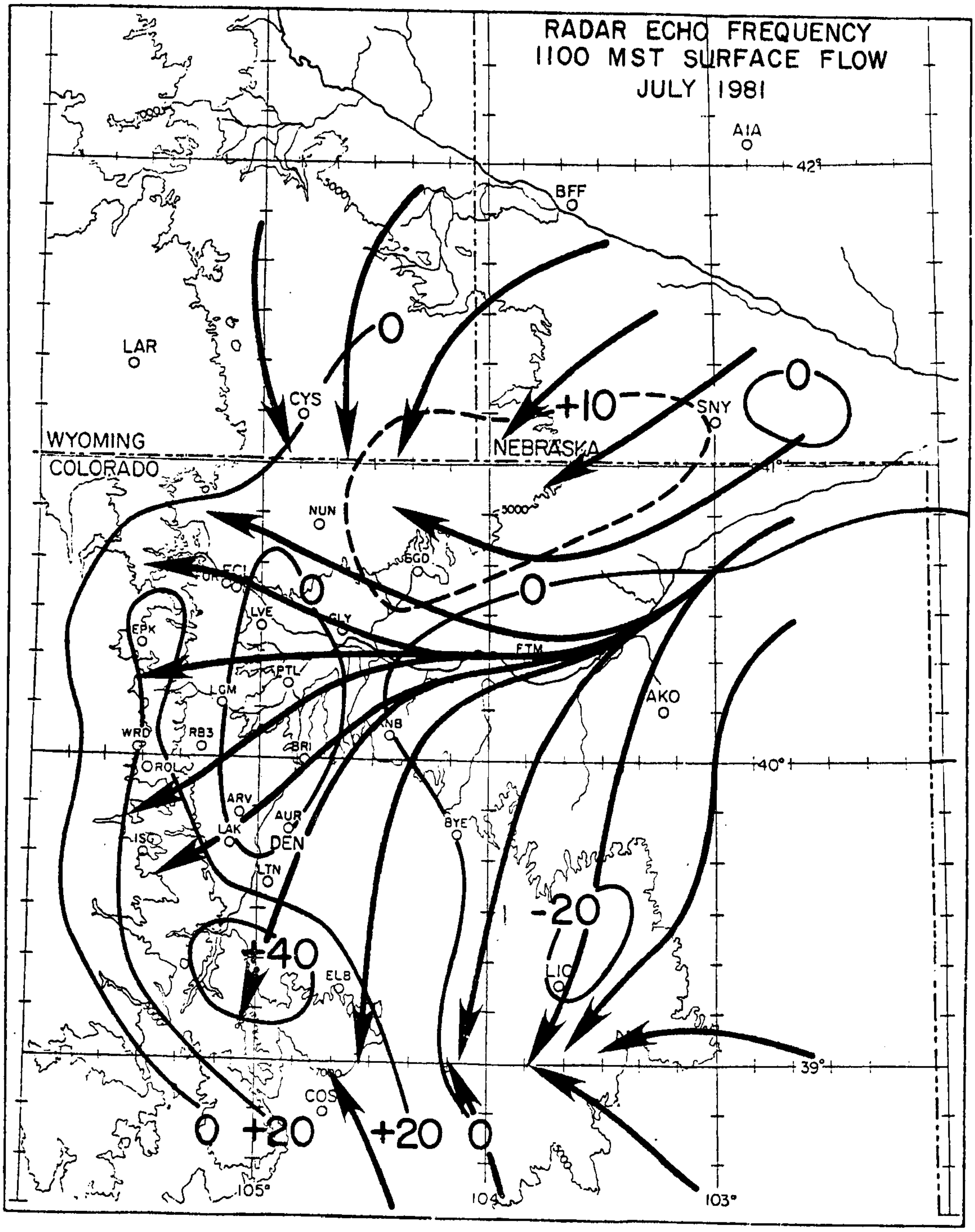

Fig. 26. Radar echo frequency as determined by Limon, CO, WSR-57 radar given as percent deviation from azimuthally-averaged mean at each radius from Limon (reproduced from Wetzel, 1973). Surface streamlines are shown for 1100 MST.

vary under different synoptic conditions. This variation is currently under detailed study (Toth). The synoptic controls probably contribute to a preference for thunderstorm generation in one region over another on any particular day (Henz, 1974). Of course, other factors such as the direction of slope faces and moisture availability can exert important controls on the preferred locations for thunderstorm genesis.

The study by Wetzel (1973) indicates that there normally occur over north central Colorado two cycles of convective activity during the day. He finds that the first major storms that develop appear along the Cheyenne Ridge and Palmer Lake Divide in the early afternoon and later propagate eastward out of the region. A secondary maximum appears later in the early evening in the upper reaches of the South Platte River basin. The eastward progression of this secondary feature coincides very well with eastward movement of the confluence line in Figs. 20-24 after 1700 MST. The fact that these two studies are based on analyses from different years and months and yet show consistent patterns in terms of radar echo tracks and surface flow fields strikingly illustrates the persistence and dominance of diurnal forcing in the region.

Preliminary investigation of the behavior of the downslope onset on days with and without thunderstorm activity indicates that similar behavior apparently occurs on both types of days. This finding implies that the Banta and Cotton (1981) mechanism of downward mixing of westerly momentum from aloft by the growth of the convective boundary layer to ridgetop elevations may be a plausible explanation for the downslope onset that occurs before sunset. Other factors, however, such as shading of the east slopes of the Continental Divide by early afternoon convection, may help to explain the timing of this circulation feature.

On nonthunderstorm days a small sample of cases suggests that the eastward progression of the N-S confluence line is delayed by an hour or so. Therefore, on days which thunderstorms do develop, it may be that an enhancement of surface westerlies, perhaps related to the downward transport of westerly momentum by cumulonimbus downdrafts (Erbes, 1978), contributes to an earlier eastward advancement of the downslope onset. The role this eastward propagating confluence line plays in initiating or modulating the early evening thunderstorm maximum (Wetzel, 1973) is not clear and further study is needed.

The preference for thunderstorm development along the Cheyenne Ridge and Palmer Lake Divide rather than the adjacent river valleys to their north or south is evident in the July average precipitation pattern over the region (Fig. 27). Precipitation maxima extend eastward from the east-west ridges in the mean for July. In 1981 (Fig. 28) the pattern was somewhat anomalous with much above normal precipitation along the Cheyenne Ridge and slightly below normal along the Palmer Lake Divide.

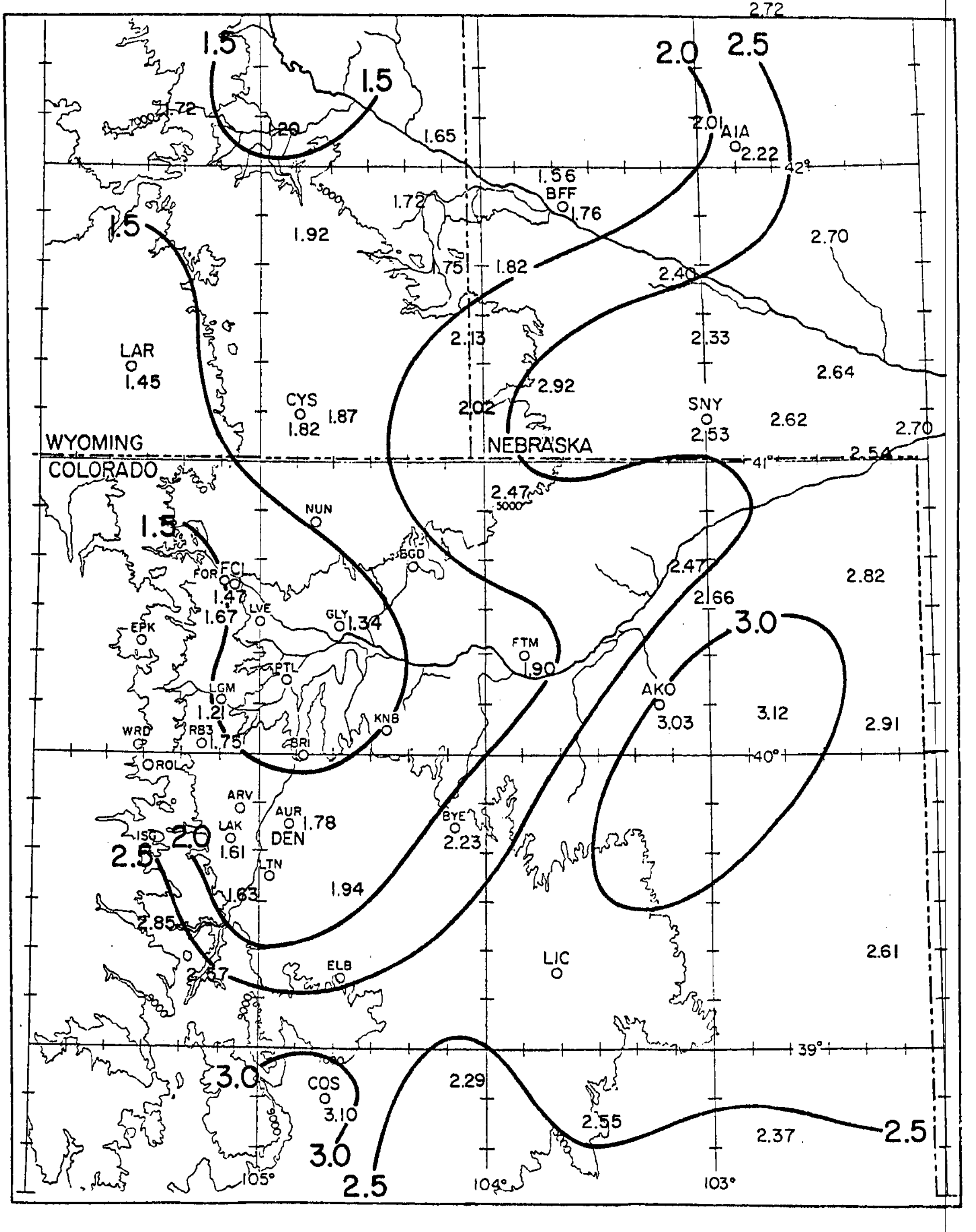

Fig. 27. July average precipitation over the region of this study (inches).

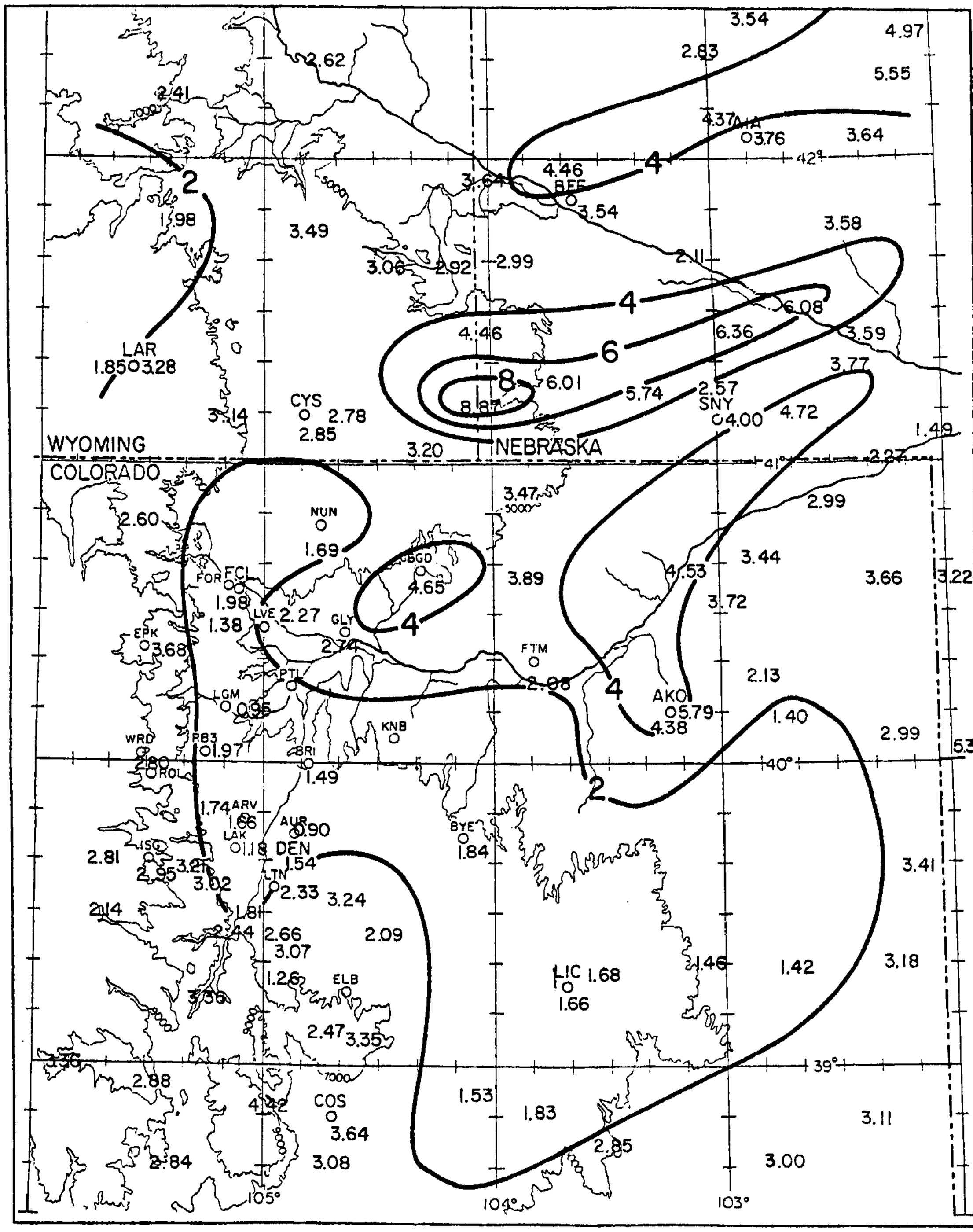

Fig. 28. July 1981 precipitation (inches).

6. Comparison of Summer and Fall Flow Patterns

The slope flows that develop on clear, undisturbed days are similar throughout the year (e.g., as noted for the Denver area by Haagenson, 1979). A sequence of four streamline analyses for 11 November 1981 from 0500 MST (1.7 hours before sunrise) to 1700 MST (10 minutes after sunset) is shown in Fig. 29-32. The pattern of drainage flow off the higher terrain into the river valleys at 0500 in November is basically the same as it is in July. By 0900 (2.3 hours after sunrise) drainage flow persists over most of the region, but weak upslope flow toward the continental divide has begun in the western part of the network. Upslope flow has developed over most of the region at 1300 and continues to ∿ 105°W until 1700, at which time downslope flow appears along the eastern slopes of the Rockies and the northern portion of the Palmer Lake Divide. Relative to sunset the onset of the evening downslope flow begins 2 hours later on 11 November than the average time for July (∿ 1 hour before sunset vs. 3 hours before sunset, respectively). This difference can probably be attributed to the occurrence in the July case of the late afternoon thunderstorm systems (discussed in Section 5) which move off the Continental Divide and are accompanied by downdrafts and westerly winds to their rear.

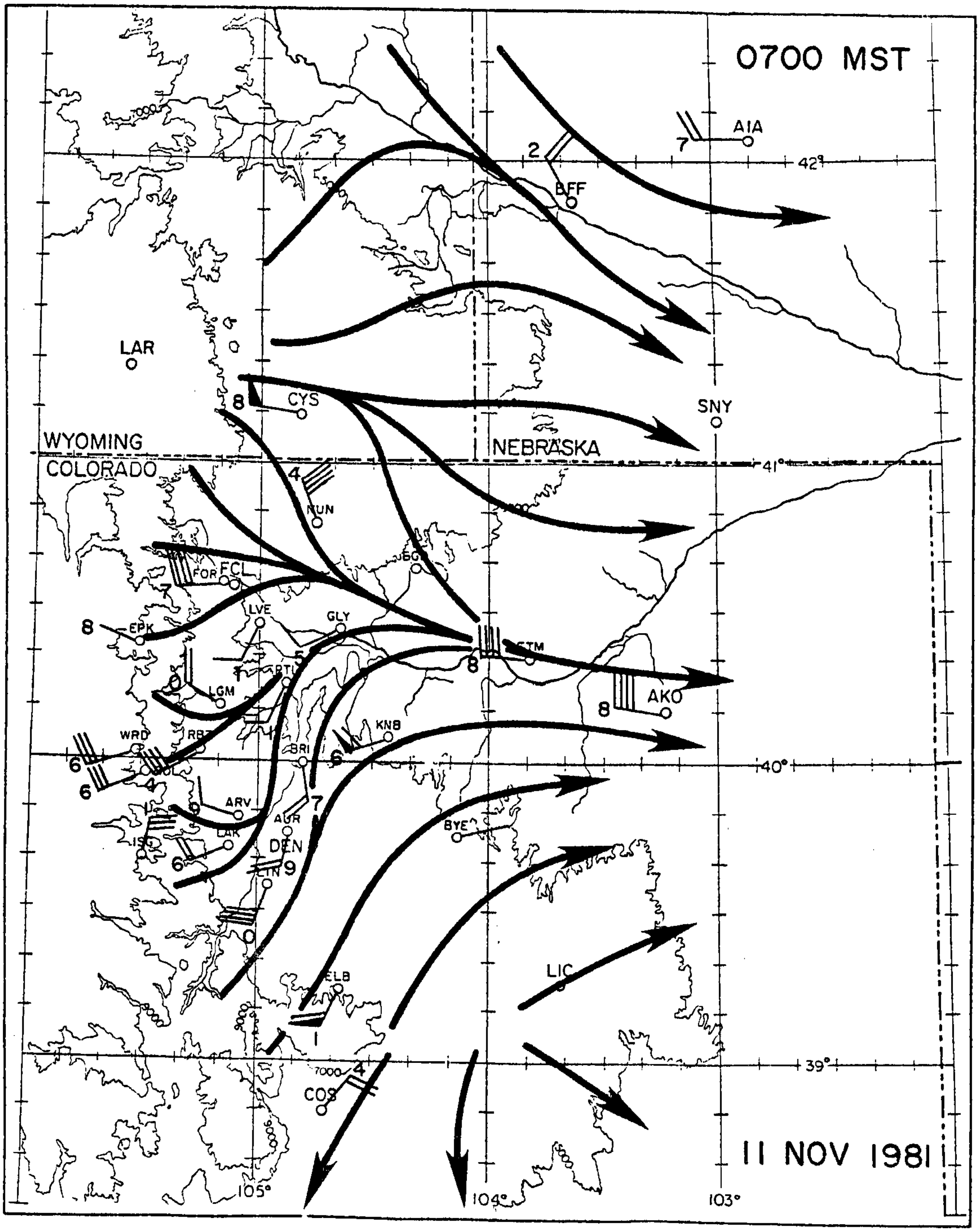

Fig. 29. Surface streamline analyses at 0700 MST for 11 November 1981. Wind speeds are in m s^{-1} (one full barb = 1 m s^{-1}). This day was clear with weak synoptic-scale pressure gradient over Colorado.

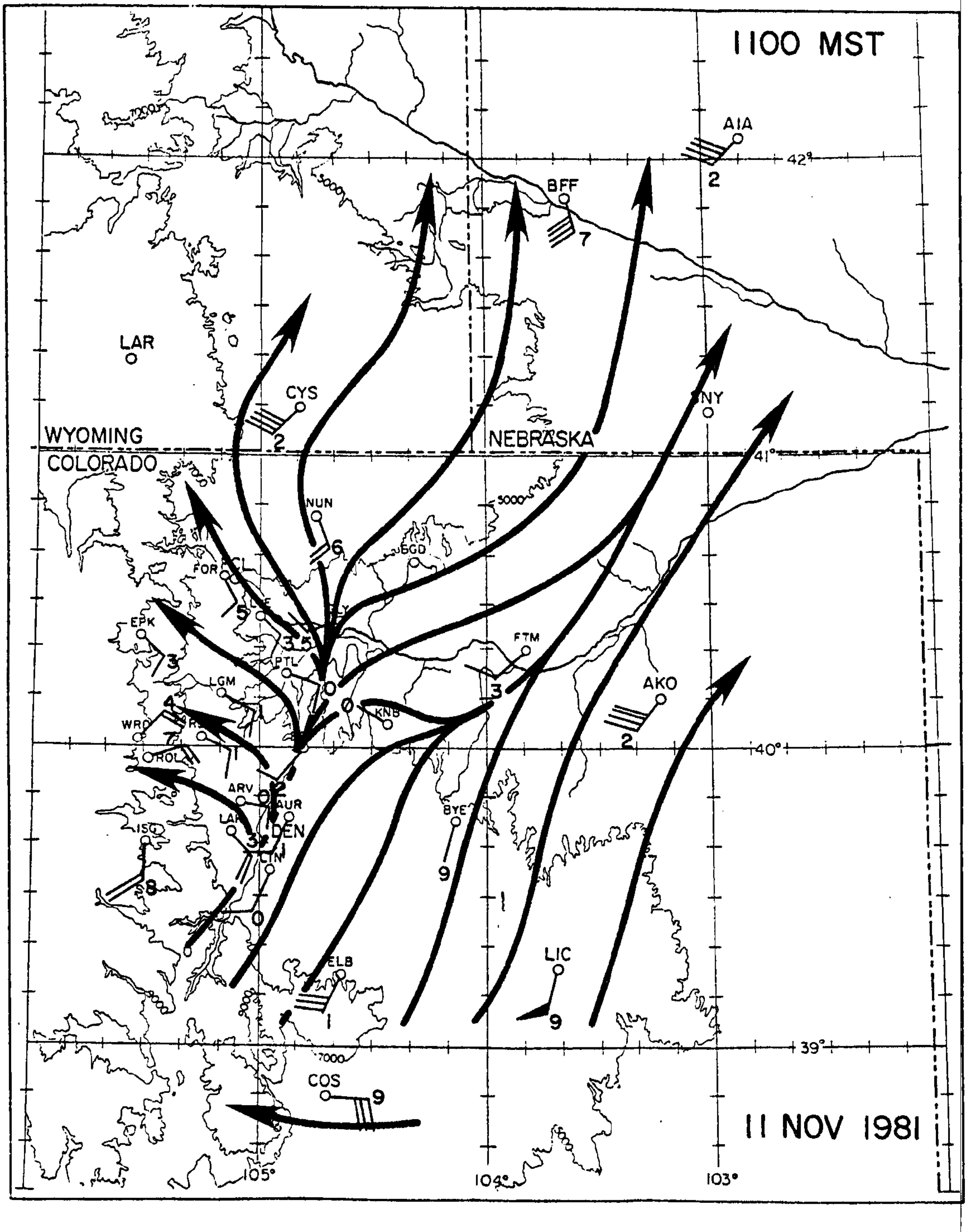

Fig. 30. As in Fig. 29, except for 1100 MST.

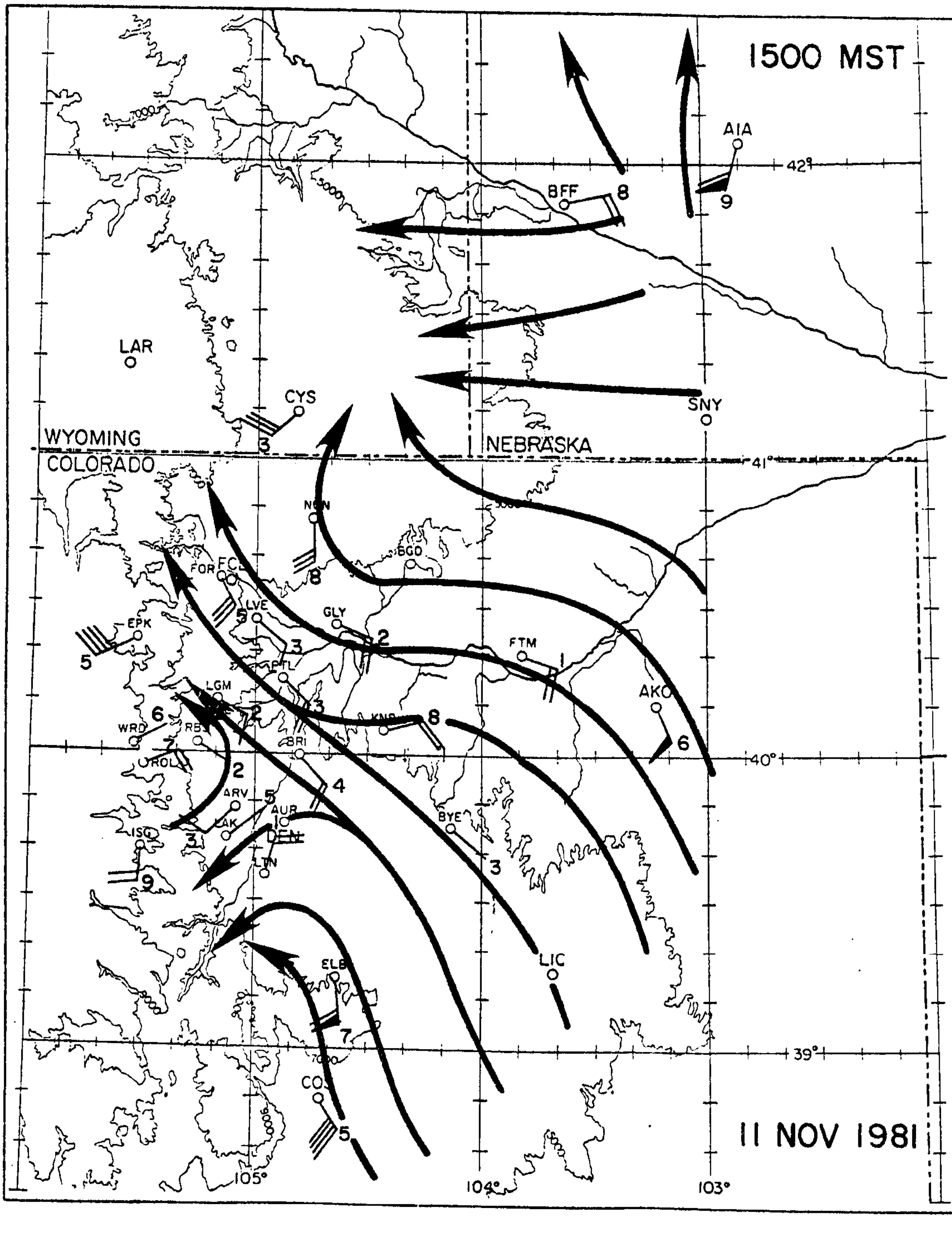

Fig. 31. As in Fig. 29, except for 1500 MST.

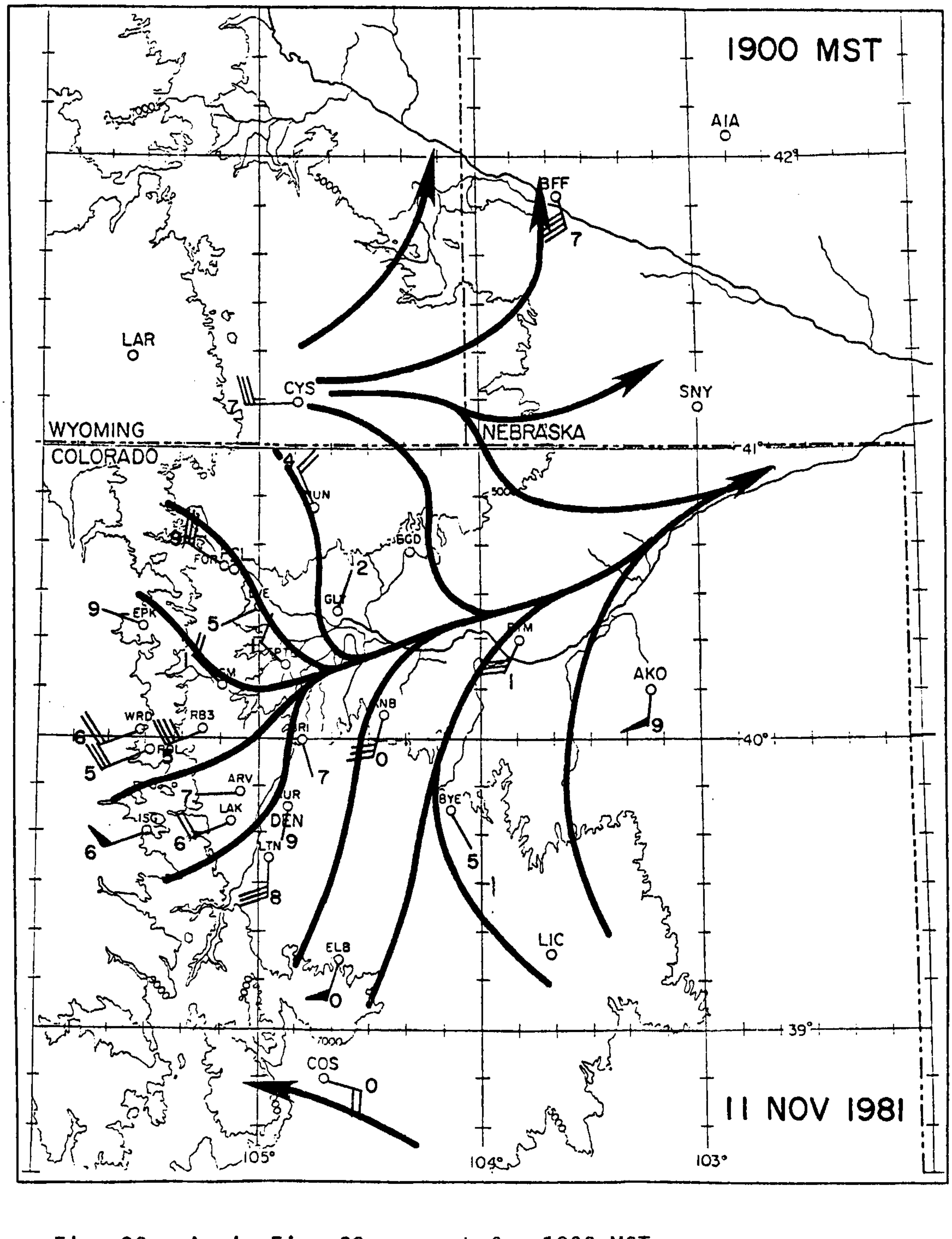

Fig. 32. As in Fig. 29, except for 1900 MST.

7. Summary and Conclusions

Surface wind data from 20 PROFS surface mesonetwork stations have been analyzed for the month of July 1981 to determine characteristic flow patterns over northeast Colorado. It has been found that diurnal forcing by radiative heating exerts a dominant control on the flow fields with a basic pattern of drainage flows at night and upslope flows in the daytime. During this summer month local confluence is found at midday along major east-west ridges in the region (e.g., Cheyenne Ridge and Palmer Lake Divide) and, consequently, these ridges are preferred regions for afternoon thunderstorm activity. Late in the afternoon there is a preferred development of thunderstorms just west of the upper reaches of the South Platte River basin followed by propagation toward eastern Colorado later in the evening. This pattern of thunderstorm development and movement is evident in the mean streamline patterns for July. The extent to which this circulation feature is a consequence of downward mixing of westerly momentum by the growth of the convective boundary layer (Banta and Cotton, 1981) or is somehow caused by the early afternoon development of cumulonimbus along the continental Divide is not fully known and further study is required.

A comparison of the mean July surface flow is made with a single fall case (11 November 1981) and it is found that the flow patterns, both day and night, are quite similar. The only significant difference occurs in the late afternoon and is associated with the lack of thunderstorm activity in the November case.

This paper reports only preliminary findings from analysis of PROFS surface mesonetwork data. The greatest value of analyses like those shown here will accrue following stratification of the data into different classes, e.g., different patterns of large-scale synoptic forcing moisture availability, degree of convective activity, etc., and integration of the data with satellite climatological studies. Short term weather forecasts should benefit from a knowledge of local topographic controls on convection and their variation with synoptic conditions. Further, factors such as enhanced upslope flow, thunderstorm outflow regions, etc., may be better defined for the forecaster by vector removal of the normal diurnal components of the wind from observations. Further research into some of these areas is in progress and will be reported on at a later time.

8. Acknowledgments

The authors thank Machel Sandfort for typing the manuscript. Part of this work has been supported by the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration under Grant No. NA81RA-H-00001, Amendment 2, Item 4, and the Cooperative Institute for Research in the Atmosphere at Colorado State University.

REFERENCES

Banta, R. 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.

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

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

Dirks, R.A., 1969: A climatology of central Great Plains mesoscale convective systems. Tech. Report E-10-68G, Dept. of Atmospheric Science, Colorado State University, Ft. Collins, 60 pp.

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

Erbes, R. 1978: A kinematic description of some Colorado thunderstorms. M.S. thesis, Colorado State Univ., Fort Collins, 103 pp.

George, R.L., 1979: Evolution of mesoscale convection systems over mountainous terrain. M.S. thesis, Colorado State Univ., Fort Collins, 160 pp.

Haagenson, P.L., 1979: Meteorological and climatological factors affecting Denver air quality. Atmos. Environ., 13, 79-85.

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.

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

Holzworth, G.C., 1964: Estimates of mean maximum mixing depths in the contiguous United States. Mon. Wea. Rev., 92, 235-242.

Johnson, R.H. and J.J. Toth, 1982: Topographic effects and weather forecasting in the Colorado PROFS mesonetwork area. Preprint Volume: 9th Conference on Weather Forecasting and ANalysis, June 28-July 1, 1982; Seattle, WA, 440-445.

Kaimal, J.C., 1978: NOAA instrumentation at the Boulder Atmospheric Observatory. Preprints: 4th Symposium on Meteorological Observations and Instrumentation, Denver, 10-14 April, Amer. Meteor. Soc.

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

Maddox, R.A., 1981: The structure and life-cycle of midlatitude mesoscale convective complexes. Ph.D. thesis, Colorado State Univ., Fort Collins, 311 pp.

Reiter, E.R. and J.L. Rasmussen, editors, 1967: Proceddings of the Symposium on Mountain Meteorology. Colorado State University, Fort Collins, 26 June, 1967, Atmospheric Science Paper No. 122, 221 pp.

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

Smith, Jeffrey, K., 1982: Undisturbed clear day diurnal wind and temperature in northeastern Colorado. M.S. Thesis, Colorado State University, Fort Collins.

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

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

SURFACE MESONET STATIONS

The network is spread over 7,000 square miles along the northern Front Range and adjoining high plains in Colorado. The station locations were selected on the basis of several considerations: the special requirements of mesoscale weather forecasting in the area, physical accessibility and security, availability of power and telephone lines, presence of a suitable building, and cooperation of the site owners. Although the result is not a near grid, the network does give a fairly good representation of northern Front Range weather. Three sites are high-altitude stations at 11,500, 10,000, and 9,000 feet MSL. The most distant station is 80 miles from Boulder. Most have year-round road access, but four are located on side roads up to ½ mile from the nearest county road. Four are at airports.

Station Name	NWS Abbreviation	Location (Co.,Bldg.,	Coordinates	Altitude (feet)	Individual Site Characteristics
Arvada	ARVC2	Jefferson, air pollution monitoring trailer at 57th and Garrison	39 47'N 105 06'W	5,390	urban, slight knoll, trees, irrigation 100 ft either side of trailer
Aurora	AURC2	Adams, NWS at Stapleton Intl. Airport	39 45'N 104 52'	5,330	airport site, open, flat, urban area with trees to S
Boulder	BOUC2	Boulder, RL-3 at 30th and Arapahoe	40 01'N 105 15'W	5,280	urban, 1-2 miles from foothills; top of 6-story building

Briggs-dale	BGDC2	Weld, 100ftwest of Hereford Rd., 1 mile N of Briggsdale	40 38' 104 20'	4,865	high dry plains some trees to E
Brighton	BRIC2	Weld, private residence at 13595 Weld Co. Rd. No. 2	40 00'N 104 48'W	4,980	riverbottom, many trees, heavily irri-fated farmland
Byers	BYEC2	Adams, private residence on Route 36	39 45 N 104 08 W	5,100	flat, large garden nearby, shelter belt of trees 100 ft. to N
Elbert	ELBC2	Elbert, Running Creek Field Sta.	39 13'N 104 38'W	7,040	gentle slope, grassy, no trees
Estes Park	EPKC2	Larimer, Rocky Mtn. Natl. Park headquarters	40 22'N 105 34'W	7,800	enclosed valley in mountains, moderate pine cover
Fort Collins	FORC2	Larimer, CSU Atmos. Science Building	40 35'N 105 08'W	5,280	top of 4-story building;foothills ½ mile to W
Fort Morgan	FTMC2	Morgan, Ft. Morgan Municipal Airport	40 20'N 103 49'W	4,500	rolling irrigated farmland 4 miles N of Platte River
Greeley	GLYC2	Weld, Weld Co. Municipal Airport	40 26'N 104 38'W	4,640	riverbottom, irrigated farms, sprinkler system near instrument shelter
Idaho Springs	ISGC2	Clear Creek	39 40' 105 30'	11,500	peak of Squaw Mtn., 5 miles SE of Idaho Spgs.
Keenes-burg	KNBC2	Weld, Weld Cen-tral High School	40 04' 104 30'	4,990	rolling irrigated farmland
Lake-wood	LAKC2	Jefferson Co., Lakewood Fire Station at 13155 W Alameda	39 42' 105 08'	6,010	suburban; first hogback of Rockies rises ¼ mile W of station
Little-ton	LTNC2	Arapahoe, air pollution monitoring trailer	39 34' 104 57'	5,740	rolling grassy knoll next to Highland Reservoir (with concrete cover)

Long-mont	LGMC2	Boulder, Longmont Municipal Airport	40 10' 105 10'	5,030	flat irrigated farmland, sparse tree growth on irrigation ditches
Love-land	LVEC2	Larimer, Boyd Lake water treat-ment plan, U.S. Highway 34	40 24' 105 02'	4,960	slightly rolling prairie ¼ mile S of Boyd Lake
Nunn	NUNC2	Weld, Pawnee Nat. Grasslands Experiment Station	40 48' 104 47'	5,360	slightly rolling prairie, very dry soil
Platte-ville	PTLC2	Weld, 2 mi. NNW of Platteville	40 15'N 104 52'W	4,780	irrigated farmland near confluence of Platte and St. Vrain Rivers
Rollins-ville	ROLC2	Gilpin, Fritz Peak NOAA Observatory	39 54' 105 29'	9,020	station on mountain peak. Tree cover ends below station
Ward	WRDC2	Boulder, 3 mi SW of Ward, Univ. of Colo. Mtn. Research Station	40 02'N 105 32'W	10,000	on SE side Niwot Ridge, rocky clearing