Undisturbed Clear Day Diurnal Wind and Temperature Pattern in Northeastern Colorado

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ABSTRACT OF THESIS

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TEMPERATURE PATTERN IN NORTHEASTERN COLORADO

Data collected by the PROFS mesometeorological network was used to study the undisturbed clear day wind and temperature pattern along the Front Range in northeastern Colorado in Autumn. Three days and three nights were available for study.

A diurnal wind regime was observed which consisted of daytime upslope and nighttime downslope winds with components directed toward both the Front Range and the Cheyenne and Palmer Ridges.

The transition from downslope to upslope in the morning takes one to three hours at each station and involves a distinct break between the wind systems. The transition begins in the foothills and mountains and spreads eastward, taking four to five hours to spread through the entire region. The strongest upslope winds occur in the northern part of the region, where there is a strong up-Cheyenne Ridge wind component. Speeds there are 5 to 8 knots. Upslope speeds elsewhere are 3 to 4 knots. Mountain wind speeds are site dependent.

The downslope winds also begin in the foothills and mountains and spread eastward, taking four to five hours to spread throughout the region. However, the transition at each individual station only takes half as long as the morning transition. The evening wind speeds are stronger than the upslope wind speeds, except in the northern part of

the region where there is a strong down-Cheyenne Ridge component. Speeds of 8 to 12 knots occurred in the foothills and on the Palmer Ridge, with downslope speeds of 5 knots or less elsewhere. As in the daytime, mountain speeds are site dependent. Between the foothills and South Platte River, the winds diminish in the early morning, but maintain their strength elsewhere.

The diurnal wind regime did not reach the eastern fringe of the PROFS study region. Here, strong southerly winds of 10 to 15 knots persisted throughout both day and night.

Maximum temperatures were found to be independent of height at elevations below 6000 feet MSL and strongly dependent on elevation above 6000 feet. At night, there is an inversion below around 5800 feet MSL with minimum temperatures strength of about 10°F/1000 feet, while minimum temperatures decrease with elevation above the inversion at 2½°F/1000 feet. The morning sounding from Denver shows that the surface temperature is 3 to 5°F cooler than the free air, with no variation with elevation.

Maximum temperatures generally occur in the small range of 1330 LST to 1500 LST. Minimum temperatures may occur anytime between midnight and 1 hour after sunrise.

The diurnal temperature range was observed to decrease with elevation and ranged from 40°F along the South Platte River to 20°F in the high mountains.

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CHAPTER I

INTRODUCTION

The large terrain variations in Colorado exert a strong influence on local meteorological conditions. The lee side of the Rocky Mountains is a well-known cyclogenesis region (Trewartha and Horn, 1980), for example. Even without synoptic forcing, the topography is an important meteorological control. A number of studies have shown that the diurnal wind regime of daytime upslope and nighttime downslope along the Front Range is a major factor in air pollution episodes in the Denver area (Riehl and Crow, 1962; Djordjevic et al., 1966; Riehl and Herkhof, 1970a; Crow, 1973). Johnson and Toth (1982) state that this diurnal wind regime plays an important role in summer thunderstorm formation. Riehl and Herkhof (1970b) found that the slowing of the wind due to high surface roughness is a major factor in the Larimer County, Colorado, air pollution problem.

This study will investigate the diurnal wind and temperature variations along the Front Range in northeastern Colorado on undisturbed clear days, using data collected by the NOAA Prototype Regional Observing and Forecasting Service (PROFS) mesometeorological network and archived at the Colorado Climate Center. It will be confined to Autumn, which was the only season archived when the study was undertaken. The specific topics the study will address are the nature and timing of diurnal wind direction and speed variations, geographic variations in the wind speed, and the relationship of temperature and the timing of maximum and minimum temperature with elevation in northeastern Colorado.

An undisturbed synoptic condition was defined to be a surface pressure gradient of less than one millibar per fifty miles, as determined from the NWS Surface Analyses, with no precipitation in the area.

A clear day was defined as a day in which the accumulated solar radiation at all stations before noon was greater than 50 percent of the extraterrestrial radiation received at the top of the atmosphere. The extraterrestrial radiation was calculated using a computer program developed by Conley (1982). Clear nights had to be defined in terms of the observed skycover at the Denver WSFO because of the lack of net radiometers. Only nights in which the average of the skycover observations was less than three-tenths and no more than two consecutive observations were three-tenths or higher, and only with cirrus clouds, were used.

CHAPTER II

LITERATURE REVIEW

Although prior to the installation of the PROFS Mesonet there have not been any studies of diurnal wind and temperature variations covering all of the Front Range and northeastern Colorado, there have been several studies conducted in parts of the area that are relevant to this study.

Riehl and Crow (1962) found that severe air pollution episodes in the Denver metropolitan area occurred on undisturbed clear days. They selected four severe pollution days in January and March, 1962 for study. These days showed a consistent diurnal wind regime. The nighttime winds were light and variable. In the early morning, the winds along the foothills became downslope and the winds in the Denver Basin became downriver. The downslope and downriver winds increased throughout the morning, except in the northern suburbs where the downriver flow was blocked by the topography. Around noon, the wind reversed to upriver and upslope, beginning first in the northern suburbs and spreading southward. The upriver and upslope winds continued until around sunset, when the nighttime light and variable wind conditions set in.

The authors felt that the usual explanation for the daytime wind reversal to upslope, in which the air adjacent to the slope becomes warmer than the air at the same elevation over the plains due to the solar heating of the slope, resulting in a pressure gradient directed toward the slope, could not happen if the foothills were snow-covered, as several of the study days were. They proposed an alternate explanation. The high levels of pollution in the air which had piled up during the night against the high terrain in the northern suburbs shields that part of the metropolitan area from solar radiation. The rest of the area is heated by solar radiation in the morning. So the air in the northern part of the metropolitan area remains cold while the air over the rest of the area warms up. This cold air then moves south though Denver as a sort of miniature cold front.

Djordjevic et al. (1966), in another study of the Denver air pollution problem, analyzed 32 undisturbed days from January through March, 1965 and December, 1965 through February, 1966. They found four wind regimes. South-southwesterly drainage winds were observed 56 percent of the time, and were the usual winds between 1900 to 2200 LST and 1200 LST. North-northeasterly, or upriver, winds were observed 27 percent of the time, making up the bulk of the observations between 1200 LST and 1900 to 2200 LST. Eleven percent of the wind observations showed a transition between the south-southwesterly and north-northeasterly winds. The remaining 6 percent of the observations showed southeasterly winds.

Riehl and Herkhof (1970a) utilized the same data as Djordjevic et al. They found that winds in the eastern suburbs of Denver were always strong enough to ensure good ventilation of polluted air even while the winds in Denver were too slow for ventilation to occur owing to the greater surface roughness in Denver due to the greater density of buildings there. The authors also found that on some days the morning reversal to upriver winds does not reach the southern parts of Denver, leaving a convergence zone over the city. In addition, they reported that there was some variability in the timing of the upriver wind onset.

Crow (1973) studied the wind pattern in the Denver area on high air pollution days in November, 1973. As in the other studies, the polluted days had weak synoptic controls. He found that on most of the days the diurnal wind regime consisted of a nighttime downriver drainage flow and a daytime wind pattern that was coupled with the upper level flow. Only on one day did he observe an upriver flow. On this day, he found that the upslope flow began around 0700 LST (slightly before sunrise) in the northern part of the city. The wind reversal to upslope gradually moved southward. The nighttime drainage flow began between 1700 and 1800 LST (shortly after sunset).

Crow claimed that the nocturnal inversion was very thin over hills like Green Mountain and North and South Table Mountain. The thin inversion layer above these hills was destroyed rapidly after sunrise. The subsequent vertical mixing created a chimney effect over the foothills which induced an airflow toward the foothills. This explanation does not seem to be consistent with the observation that the morning wind reversal occurred earlier in the northern part of the Denver area than in the southern part. Rather, it would lead one to expect an easterly daytime wind blowing toward the foothills, beginning first in the western part of the city and spreading eastward.

Haagenson (1979) averaged the wind observations from the Denver Weather Service Forecasting Office from the period 1952-1969 for each season. He found that the average wind direction was north-northeasterly during the day and south-southwesterly at night in Autumn. The transition from south-southwesterly to north-northeasterly winds occurred in late morning while the transition north-northeasterly to south-southwesterly occurred in the early evening. The wind perturbations were larger during the day than during the night. Daytime perturbations were predominantly direction perturbations while nighttime perturbations were predominantly speed perturbations.

Riehl and Herkhof (1970b) studied the role of the wind flow in Larimer County, Colorado, air pollution episodes. They concentrated on the portion of Larimer County that is east of the foothills. The authors found a typical pattern of northerly (downslope off the Cheyenne Ridge) winds at night and southerly (upslope toward the Cheyenne Ridge) winds during the day. The daytime average wind speeds ranged from 3 miles per hour along the foothills to more than 5 miles per hour out on the plains. Nighttime average wind speeds ranged from 2 miles per hour along the foothills to 5 miles per hour out on the plains. Overall, the wind speed was less than 5 miles per hour 90 percent of the time along the foothills and 50 percent of the time along the eastern border of Larimer County (about 12 miles east of the foothills).

The first (and only) study of winds in the PROFS region was conducted by Johnson and Toth (1982). They used wind observations for all available days without regard to weather conditions in July, 1981 from the PROFS Mesonet and the Akron, Colorado Springs, and Limon, Colorado, Cheyenne, Wyoming, and Scottsbluff and Sydney, Nebraska National Weather Service offices. The hourly wind observations were vector-averaged after observations with speeds that were more than two standard deviations from the mean were removed (in an attempt to filter out wind observations from synoptic disturbances).

The authors found a diurnal wind regime. The early morning wind flow consisted of downslope flow off of the Cheyenne and Palmer Ridges converging into the South Platte River Basin. By 0900 LST (about four hours after sunrise), upslope flow toward the Front Range had begun along the foothills, but not in the high mountains. By 1300 LST, upslope flow toward the Front Range was observed at all stations. At 1700 LST (about two and a half hours before sunset), downslope drainage flow was observed at the stations along the foothills. Over the next three to four hours, the wind shift to downslope flow proceeded eastward. The morning transition from downslope to upslope flow took about three hours to spread throughout the entire region, while the evening transition from upslope to downslope took four to five hours.

They also analyzed hourly wind observations for one day in November (Nov. 11). A similar diurnal wind pattern to that of July was found, except that the evening transition to downslope wind flow began one hour before sunset in November and three hours before sunset in July. The difference was attributed to the afternoon thunderstorms in July, which brought westerly momentum down to the surface in the late afternoon.

A number of studies of slope winds have been performed in other areas. Defant (1951) summarized early studies of upslope and downslope winds. He reported that the upslope winds occurred from slightly after sunrise to slightly after sunset, with downslope winds occurring during the rest of the time. The wind reversals occurred when the atmosphere was isothermal. The upslope wind reaches its greatest speed at the time of maximum insolation. The slope wind layer was 100 to 200 meters thick with the nighttime downslope layer being thinner than the daytime upslope layer. Downslope speeds were less than upslope speeds.

Defant explained the formation of slope winds in terms of the difference in temperature between the air adjacent to the slope and the air at the same elevation over the plain. The slope becomes heated during the day and, in turn, it heats the air adjacent to it. This air becomes warmer and, therefore, less dense than the air at the same elevation over the plains, creating a pressure gradient directed toward the slope. At night, the air adjacent to the slope becomes colder and more dense than the air at the same elevation over the plains due to the cooling of the slope surface, creating a pressure gradient directed away from the slope.

Staley (1959) observed daytime upslope and nighttime downslope winds in the Columbia River Basin.

Davidson and Rao (1963), while studying valley winds in Vermont, found that balloons travelled upvalley at night in two of the valleys. The slopes of these valleys run counter to the slope of the regional topography, so that the downvalley winds are masked by the larger-scale downslope wind. They reported that the onset of downvalley and downslope winds was sudden.

Braham and Draginis (1966) observed the formation of a region of convection over slopes in the morning due to the heating of the slopes. This convection leads to the formation of upslope winds.

Flohn (1968) observed upslope winds on a larger scale. He found that the heating of the Tibetan Plateau in summer caused upslope flow on all sides of the plateau that lasted day and night throughout the summer and masked all diurnal wind regimes.

Manins and Sawford (1979) studied downslope winds on a gentle slope. They found that the onset of downslope winds was accompanied by an increase in atmospheric stability. Their study indicated that the net cooling of the downslope layer due to radiational cooling and heat flux was balanced by adiabatic warming. The downslope flow dissipated about an hour and a half after sunrise.

Whiteman (1980) found that the daytime boundary layer extended 1½ to 2½ kilometers above the ridge tops of valleys. He compared wind observations in and above the daytime boundary layer above the Eagle River Valley and in the daytime boundary layer over Grand Junction. He found that although the wind direction in the free atmosphere was the same at both locations, the wind within the boundary layer flowed in the direction of the mesoscale slope at each site.

Banta and Cotton (1981) observed three wind systems in undisturbed clear conditions in South Park, Colorado. The nighttime windflow was downslope, which was followed by a morning upslope. As the morning progressed, a very deep convective boundary layer formed. The turbulent mixing in the convective boundary layer brought momentum down from the gradient wind level, so that the afternoon wind was coupled with the gradient wind.

Several models of slope winds have been developed. Fleagle (1950) developed a model of downslope drainage winds which showed that the velocity was inversely proportional to the angle of elevation of the slope because the adiabatic warming of the downslope wind reduced the pressure gradient between the air adjacent to the slope and the air over the plain.

Thyer (1962) used a model to show upslope speeds were greatest at the top of the ridge and downslope speeds were greatest at the bottom of the ridge. He also showed that downslope winds were stronger and were in a thinner layer than upslope winds and that slope wind speeds are directly proportional to the elevation angle of the slope.

Orville (1964) developed a model of upslope flow. He show that a circulation cell formed over the slope. The center of the circulation cell moves from above the slope to above the ridge top as a convective column forms over the ridge.

Dirks (1969) modelled slope winds on the lee side of the Rocky Mountains. A region of strong convection was present over the ridge top by two hours after sunrise, with a circulation cell over the slope and upslope winds on the slope. Mass removed by the upslope wind was replaced by subsidence. The cell gradually expanded until it reached about 75 kilometers east of the slope. The upslope flow was one kilometer deep over the slope and slightly deeper over the plain.

The evening downslope began slightly before sunset at the top of the slope and spread to the entire slope in a half hour. Downslope winds developed over the plains in the next two hours. A circulation cell did not form at night. Instead, the downslope flow continued over the top of the remaining upslope winds until the upslope winds had dissipated everywhere.

He then developed a time-altitude section of westerly wind components for Denver based on observations from 28 undisturbed days from the summer of 1966. Below 3 kilometers agl, the wind had an easterly component between 0900 LST and 0300 LST, with a westerly component in the remaining 6 hours. Above 3 kilometers, the pattern was reversed.

CHAPTER III

DESCRIPTION OF THE PROFS MESONET AND THE STUDY AREA

The PROFS study area covers approximately 7000 square miles (Figure 3.1). It encompasses a region from the Eastern Slope of the Front Range on the west to 75 miles east of the foothills and from the Cheyenne Ridge in the north to the Palmer Ridge in the south. The South Platte River enters the region from the south, flows north through Denver, Brighton, and Platteville, and then turns east at Greeley and flows past Fort Morgan.

There were twenty stations in the network when this study began. A twenty-first, at Briggsdale, was installed on November 10, 1981 (Figure 3.2). Each station is equipped with an anemometer, a thermistor, a hygrometer, a tipping bucket rain gauge, and two pyranometers, one of which is horizontal and the other tilted 40 degrees to the south. Ten of the stations are equipped with forward scatter meters.

The instruments used in this study are the anemometers, the thermistors, and the horizontal pyranometers. The anemometers are Skyvan W102-P/AC anemometers made by Weather Measure Corporation. The accuracy was measured to be $\pm$ 3 degrees, with a 3 percent error in the speed. The thermistors are Yellow Springs Model YSI15133, which are accurate $\pm$ 5°F. The pyranometers are Ly-Cor, Incorporated Model LI-200S, accurate to within 5 percent (Pratt and Kaimal, 1982). The anemometers are mounted on the tops of meteorological towers, while

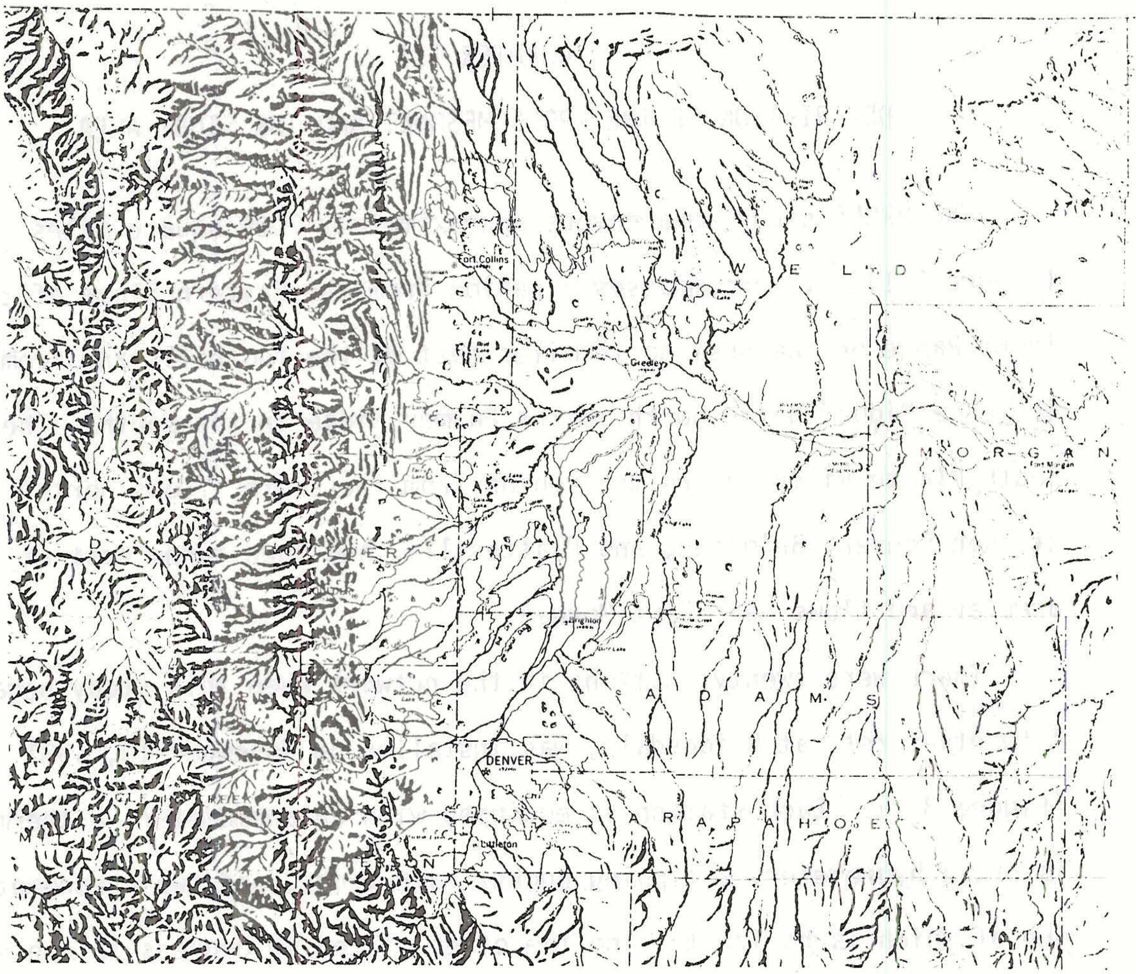


Figure 3.1. Relief map of PROFS region.

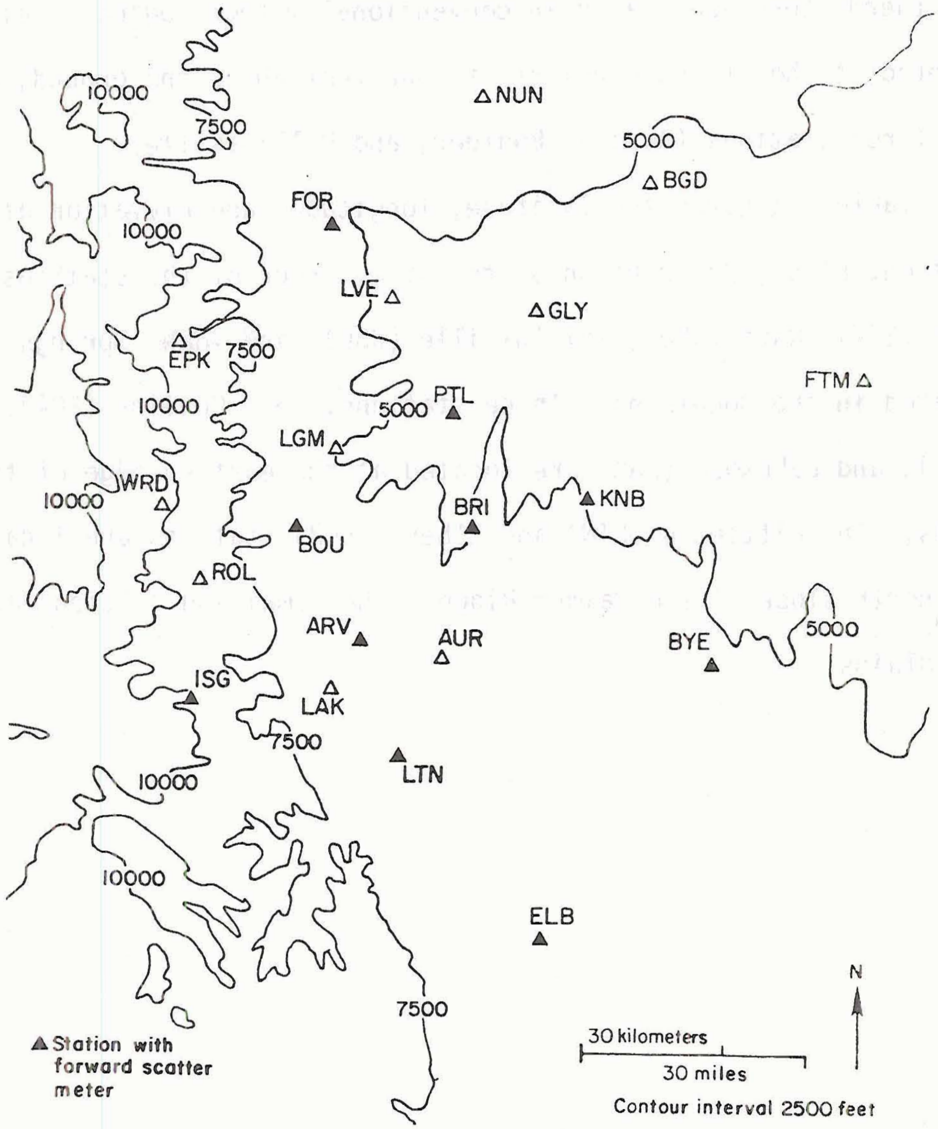


Figure 3.2. Map of PROFS mesometeorological network.

the pyranometers are mounted on booms on the south sides of the towers. The thermistors are placed in conventional meteorological shelters mounted at the standard height of four feet above the ground, except for three stations (Aurora, Boulder, and Rollinsville).

Table 3.1 gives the latitude, longitude, and elevation of each station, plus a description of the site. Four of the stations, Estes Park (EPK), Ward (WRD), Rollinsville (ROL), and Idaho Springs (ISG) are located in the mountains. Three stations, Fort Collins (FOR), Boulder (BOU), and Lakewood (LAK) are located at the eastern edge of the foothills, The Littleton (LTN) and Elbert (ELB) stations are located on the north slope of the Palmer Ridge. The remaining stations are on the plains.

Table 3.1. Location and description of PROFS Mesonet stations.

Arvada (ARV):

Lat. - 39°48' Long. - 105°05' Elev. - 5385 feet MSL

Located in a small park, "The Children's Garden," 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. - 5332 feet MSL

Located on the roof of the old Denver Weather Service Forecasting Office south of the east-west runways at Stapleton International Airport. The 10-foot tower and shelter are both on the roof of the two-story building. Though the surrounding terrain is smooth, there are trees and other obstructions to the south and west of the tower that disturb the wind flow from these directions. Surrounded by residential area.

Boulder (BOU/RB3):

Lat. - 40°01' Long. - 105°15' Elev. - 5344 feet MSL

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):

Lat. - 40°40' Long. - 104°20' Elev. - 4950 feet MSL

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 are no obstructions nearby to interfere with the windflow, and the soil is dry with short grass.

Brighton (BRI):

Lat. - 40°00' Long. - 104°48' Elev. - 4980 feet MSL

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.

Table 3.1. (continued)

Byers (BYE):
Lat. - 39°45' Long. - 104°08' Elev. - 5100 feet MSL
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°18' Elev. - 6992 feet MSL
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 around. The surface slopes gently up toward the Divide.

Estes Park (EPK):
Lat. - 40°23' Long. - 105°31' Elev. - 7770 feet MSL
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. No obstructions to the wind are nearby.

Fort Collins (FOR):
Lat. - 40°35' Long. - 105°05' Elev. - 5279 feet MSL
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. - 4550 feet MSL
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 a 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 grassland.

Table 3.1. (continued)

Greeley (GLY):
Lat. - 40°26' Long. - 104°38' Elev. - 4642 feet MSL
Located at the Weld County Airport, which is east of Greeley on Highway 263 near the confluence 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. - 11500 feet MSL
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 will interfere with the wind flow from that direction.

Keenesburg (KNB):
Lat. - 40°04' Long. - 104°26' Elev. - 4862 feet MSL
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 with no obstruction.

Lakewood (LAK):
Lat. - 39°42' Long. - 105°08' Elev. - 6009 feet MSL
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. - 5740 feet MSL
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 trees, hills, or buildings around that will obstruct the wind.

Table 3.1. (continued)

Longmont (LGM):

Lat. - 40°10' Long. - 105°10' Elev. - 5027 feet MSL

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. - 4960 feet MSL

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 smooth.

Nunn (NUN):

Lat. - 40°42' Long. - 104°47' Elev. - 5184 feet MSL

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. - 4790 feet MSL

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. - 9020 feet MSL

Located on a 200-foot high rock outcrop near the Fritz Peak Observatory. The anemometer and pyranometer are on a 13-foot tower. The rock outcrop is high enough that the station is free from surface radiation effects.

Table 3.1. (continued)

Ward (WRD):
Lat. - 40°02' Long. - 105°32' Elev. - 10,000 feet MSL
Located on the Niwot Ridge. The anemometer and pyranometer are mounted on a 20-foot tower.

CHAPTER IV

ANALYSIS OF DATA

A. Description of Data-Averaging Procedure

The CSU PROFS Mesonet data archive receives average, maximum, and minimum values for wind speed and direction, air temperature, dew point temperature, and solar radiation, average values for visibility, and total precipitation for each five minute period. Samples are collected at 10 second intervals from the PROFS network. At NOAA/ERL, the five-minute averages are then calculated from the thirty samples. The average wind direction is calculated by assigning a vector of unit length to each of the 30 wind direction samples and vector averaging the unit averages. The averages for the other parameters are obtained by averaging the 30 samples. The maximum and minimum values are the highest and lowest of the 30 samples, respectively.

For this study, 20-minute averages for wind and temperature were generated from the five-minute averages for the study period. The five-minute wind diection and speed averages were vector averaged to obtain the 20-minute averages.

B. Description of Synoptic Situation on Study Days

Due to problems in the archival system, only three days and three nights were available for this study. The data used were from two 36 hour sequences: October 6 12Z to October 8 0Z and November 11 0Z to

November 12 12Z. Table 4.1 contains the sunrise and sunset times for the study days and nights.

Table 4.2 shows the percent of extraterrestrial radiation that was received at each of the stations before noon for the three days, October 6 and 7 and November 11. Table 4.3 contains the Denver sky cover observations for the three nights, October 6 and November 10 and 11.

Appendix A contains the surface, 700 mb, and 500 mb charts for 12Z October 6, 0Z and 12Z October 7, 0Z October 8, and 0Z and 12Z November 11 and 12. Eastern Colorado was under a ridge during both periods, with light winds up to 500 mb, except 12Z October 6 and 0Z October 8 which had wind speeds of 20 knots or higher at 500 mb. The surface pressure gradient was less than 1 mb/50 miles throughout both periods over the PROFS study area. In October, the PROFS area was on the backside of a high, with a strong pressure gradient to the east of the area causing southerly flow over western Kansas and extreme eastern Colorado.

Appendix B contains the corresponding soundings for the Denver Weather Service Forecast Office (elev. 5300 feet msl). The afternoon, or 0Z (1700 LST), soundings all show a deep neutral or slightly unstable layer extending from the surface to around 700 mb or about 10,000 feet msl. On all 4 afternoon soundings, the wind direction at 700 mb differs from the gradient wind direction since the boundary layer extends to 700 mb. Two of the morning, or 12Z (0500 LST), soundings (October 7 and November 12) show an inversion of about 1100 foot depth (to about 6400 feet msl). The October 6 sounding shows a small unstable layer under an inversion. The November 11 sounding

Table 4.1 Sunrise and sunset times at Denver for the days and nights used in this study.

Day	Sunrise (LST)	Sunset (LST)
October 6, 1981	0601	1735
October 7	0602	1733
November 11	0640	1648

Night	Sunset (LST)	Sunrise (LST)
October 6, 1981	1735	0602
November 10	1649	0640
November 11	1648	0641

Table 4.2. Percentage of extraterrestrial solar radiation received at each station before 1200 LST.

Station	Date		
	10/6/81	10/7/81	11/11/81
ARV	55%	56%	53%
RB3	54	56	54
BRI	54	56	52
LGM	56	56	55
KNB	56	52	55
ROL	58	59	56
EPK	57	56	56
LAK	56	58	55
LTN	57	59	56
ISG	59	60	59
PTL	56	56	55
LVE	54	56	53
BYE	56	57	55
FOR	53	54	51
AUR	53	55	52
NUN	55	56	53
GLY	55	57	53
FTM	55	57	53
ELB	--	60	52
WRD	--	--	57
BGD	--	--	56

Table 4.3. Denver observed skycover for the three nights in the study.

Time (LST)	Date		
	10/6-7	11/10-11*	11/11-12
1700	0	3	0
1800	0	2	0
1900	0	2	0
2000	0	1	0
2100	0	1	0
2200	0	2	0
2300	0	2	0
0000	0	4	0
0100	0	4	0
0200	0	2	0
0300	0	5	0
0400	0	3	0
0500	0	3	0

* All observations were of Cirrus (Ci) clouds.

shows an isothermal layer extending up to 700 mb. The 700 mb wind was nearly parallel to the surface wind and perpendicular to the gradient wind at higher levels.

C. Wind and Temperature Data

Figures 4.1 through 4.12 contain maps of the 20-minute wind and temperature data at one hour intervals for the period October 6 0500 LST to October 7 1600 LST. Figures 4.13 through 4.24 contain similar maps for the period November 11 0500 LST to November 11 1900 LST.

The early morning hours are marked by very light drainage winds along the foothills and western plains, with stronger downslope winds in the mountains. Strong southerly winds of around 10 knots blow along the Palmer Ridge and eastern plains (Figures 4.8, 4.16).

The temperatures change little in the early morning. There is an inversion below around 6000 feet MSL, with a stable lapse rate above the inversion. Figure 4.25 contains a graph of the average minimum temperatures for the three mornings versus elevation. The minimum temperatures decrease above the inversion at a rate of about $2\frac{1}{2}$°F/1000 feet (calculated from a least squares linear regression using the MINITAB statistical package). However, there are wide variations from this rate due to local topography. For example, Estes Park, which is in a trapping valley, has a much colder average minimum temperature than predicted by the linear regression. Rollinsville, located on a high rock outcrop, has one of the warmer average minimum temperatures in the network.

Within the inversion layer, the coldest temperatures occur along the South Platte River. The rate of increase of temperature with

Figure 4.1. Map of 20 minute averaged data at 1 hour intervals for October 6 0500, 0600, 0700 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.2. Map of 20 minute averaged data at 1 hour intervals for October 6 0800, 0900 1000 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.3. Map of 20 minute averaged data at 1 hour intervals for October 6 1100, 1200, 1300 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.4. Map of 20 minute averaged data at 1 hour intervals for October 6 1400, 1500, 1600 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

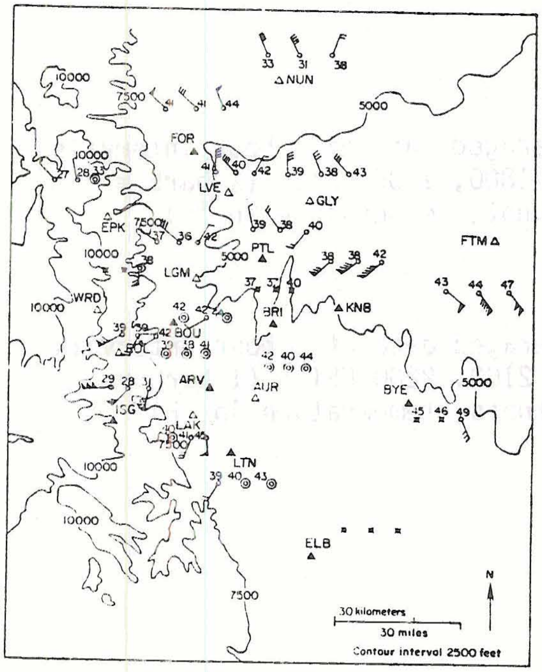


Figure 4.1

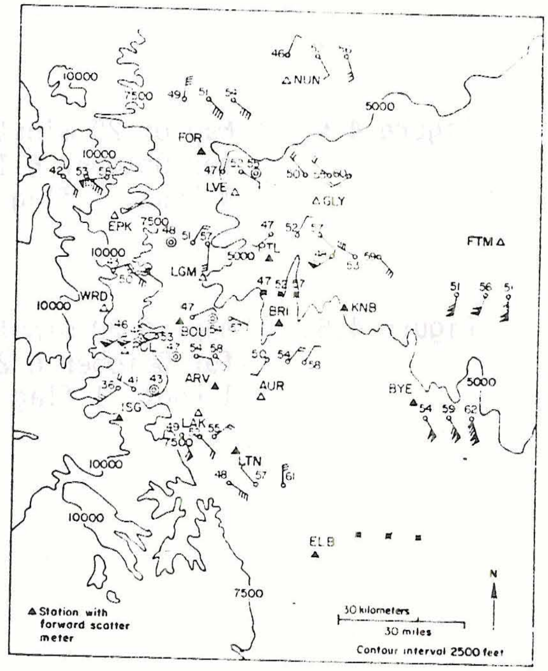


Figure 4.2

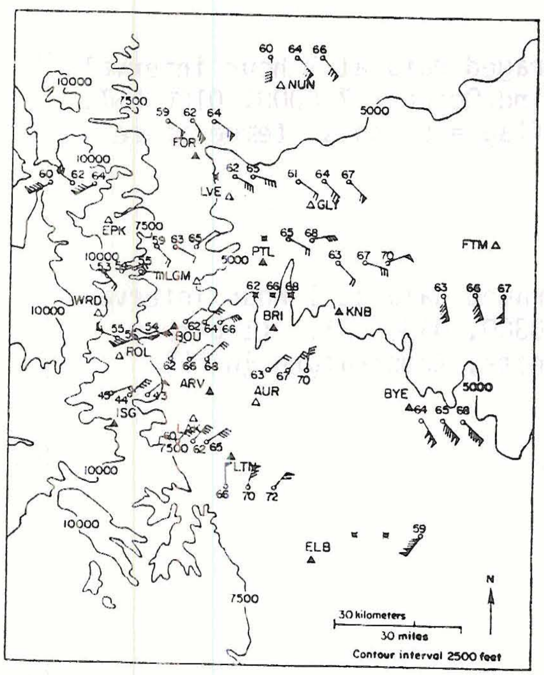


Figure 4.3

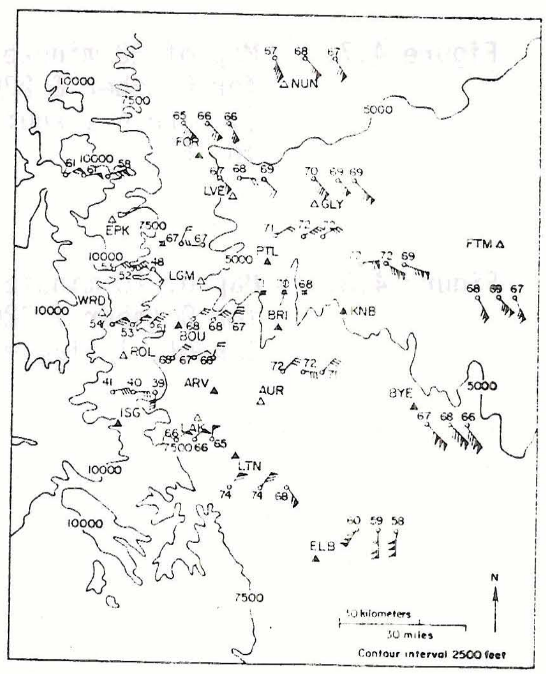


Figure 4.4

Figure 4.5. Map of 20 minute averaged data at 1 hour intervals for October 6 1700, 1800, 1900 LST. (1 barb = 1 knot, 1 flag = 5 knot, temperature in °F)

Figure 4.6. Map of 20 minute averaged data at 1 hour intervals for October 6 2000, 2100, 2200 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.7. Map of 20 minute averaged data at 1 hour intervals for October 6 2300, and Oceober 7 0000, 0100 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.8. Map of 20 minute averaged data at 1 hour intervals for October 7 0200, 0300, 0400 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

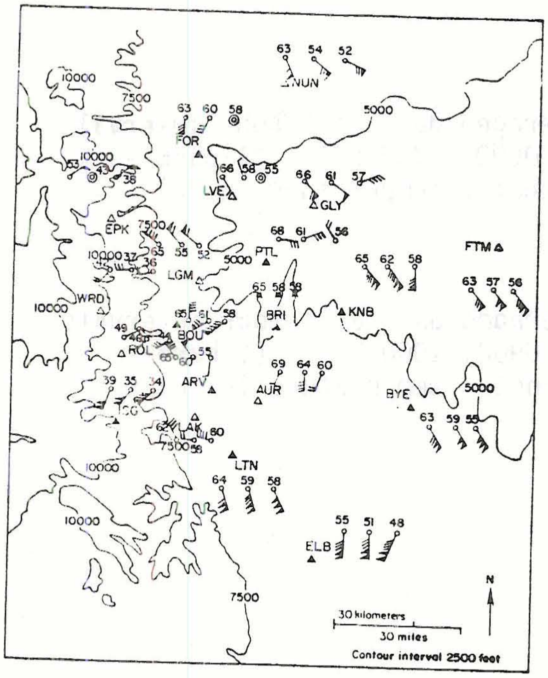


Figure 4.5

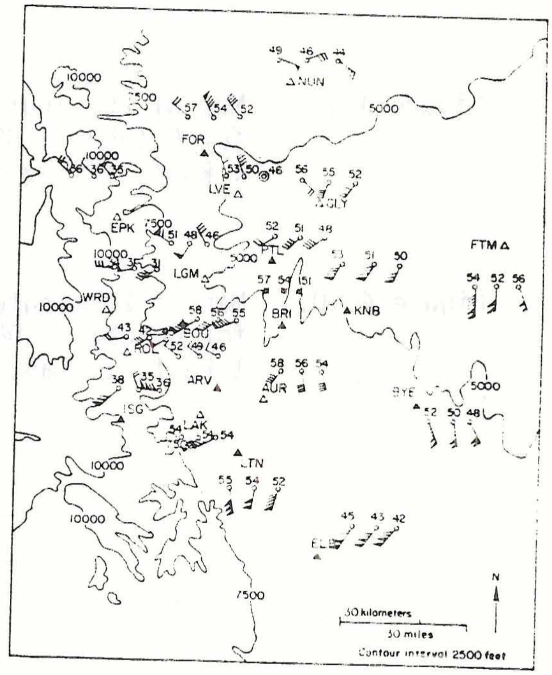


Figure 4.6

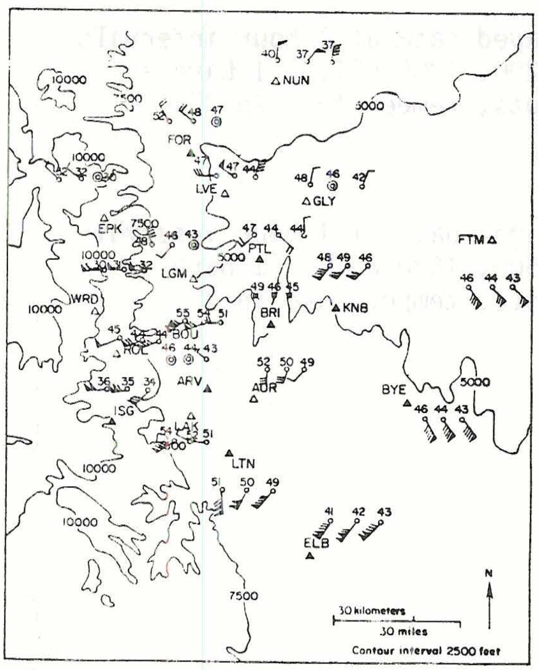


Figure 4.7

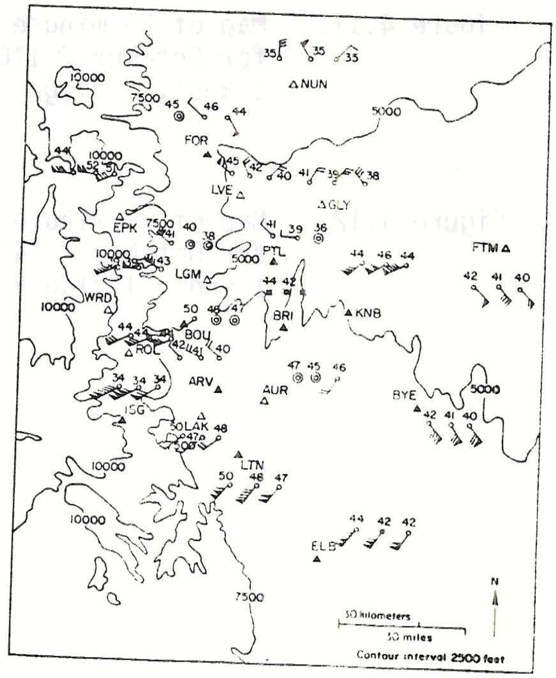


Figure 4.8

Figure 4.9. Map of 20 minute averaged data at 1 hour intervals for October 7 0500, 0600, 0700 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.10. Map of 20 minute averaged data at 1 hour intervals for October 7 0800, 0900, 1000 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.11. Map of 20 minute averaged data at 1 hour intervals for October 7 1100, 1200, 1300 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.12. Map of 20 minute averaged data at 1 hour intervals for October 7 1400, 1500, 1600 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

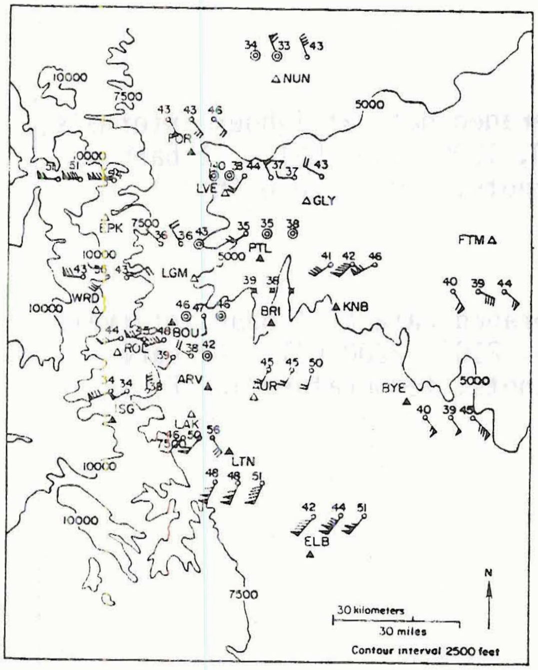


Figure 4.9

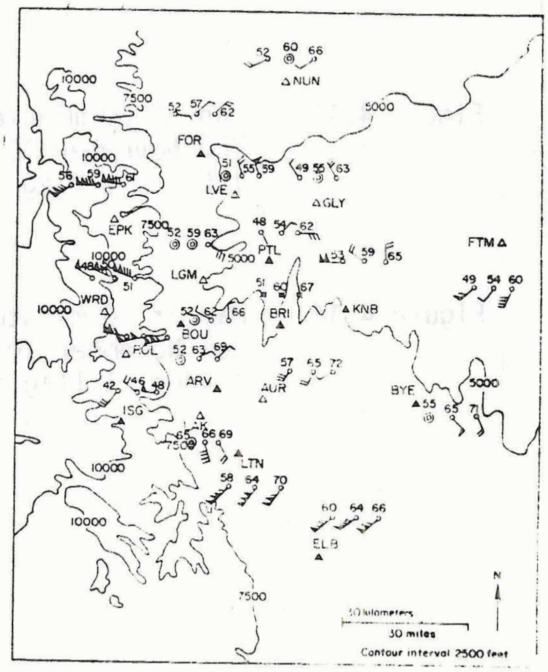


Figure 4.10

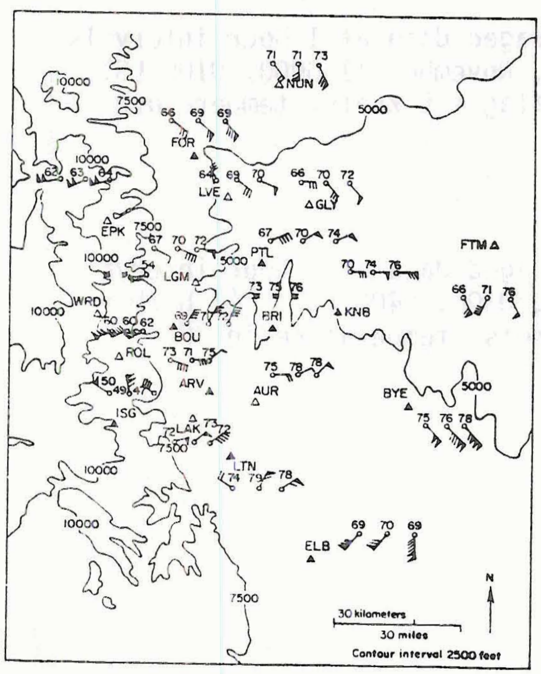


Figure 4.11

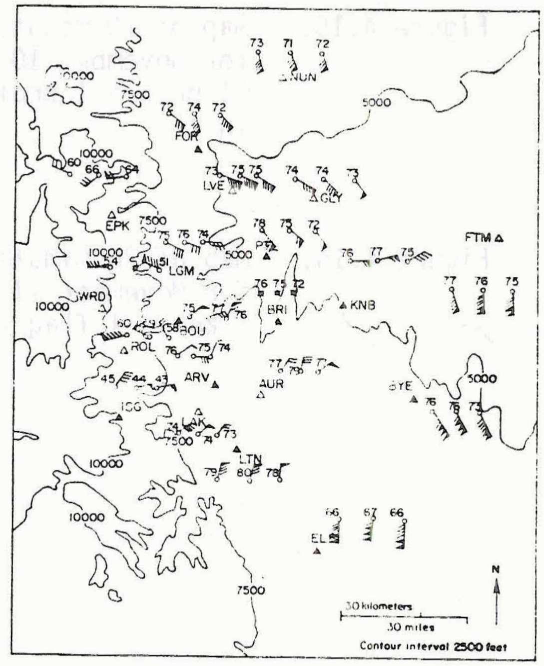


Figure 4.12

Figure 4.13. Map of 20 minute averaged data at 1 hour intervals for November 10 1700, 1800, 1900 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.14. Map of 20 minute averaged data at 1 hour intervals for November 10 2000, 2100, 2200 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.15. Map of 20 minute averaged data at 1 hour intervals for November 10 2300, November 11 0000, 0100 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.16. Map of 20 minute averaged data at 1 hour intervals for November 11 0200, 0300, 0400 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

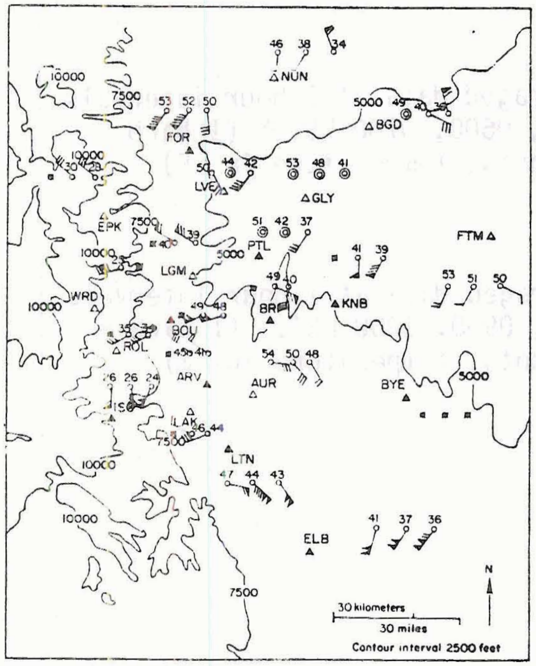


Figure 4.13

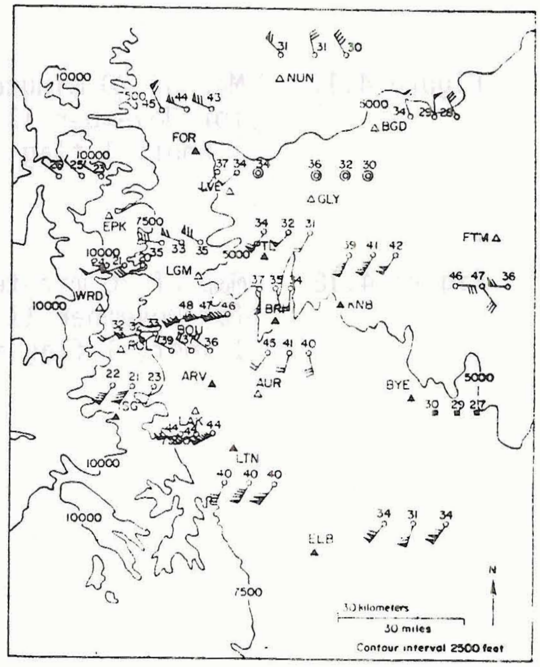


Figure 4.14

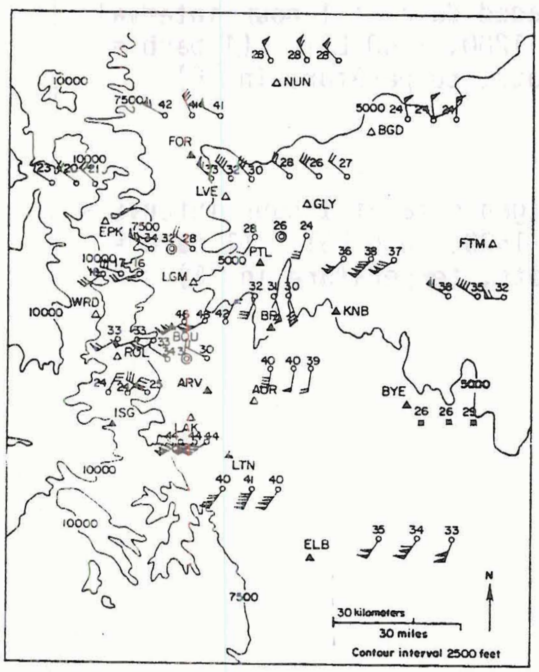


Figure 4.15

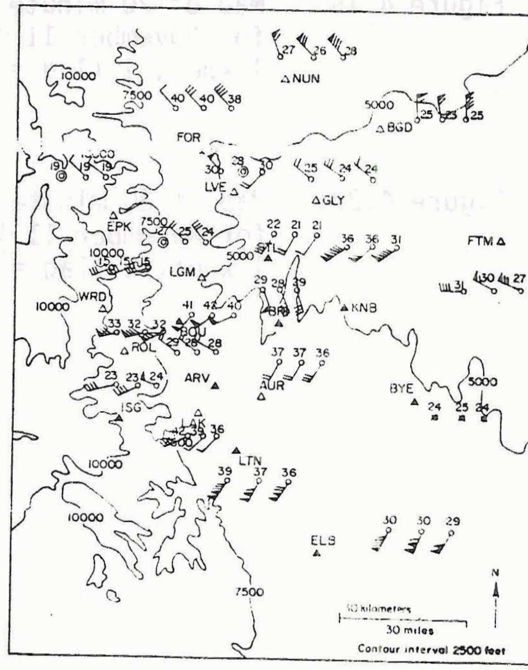


Figure 4.16

Figure 4.17. Map of 20 minute averaged data at 1 hour intervals for November 11 0500, 0600, 0700 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.18. Map of 20 minute averaged data at 1 hour intervals for November 11 0800, 0900, 1000 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.19. Map of 20 minute averaged data at 1 hour intervals for November 11 1100, 1200, 1300 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.20. Map of 20 minute averaged data at 1 hour intervals for November 11 1400, 1500, 1600 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

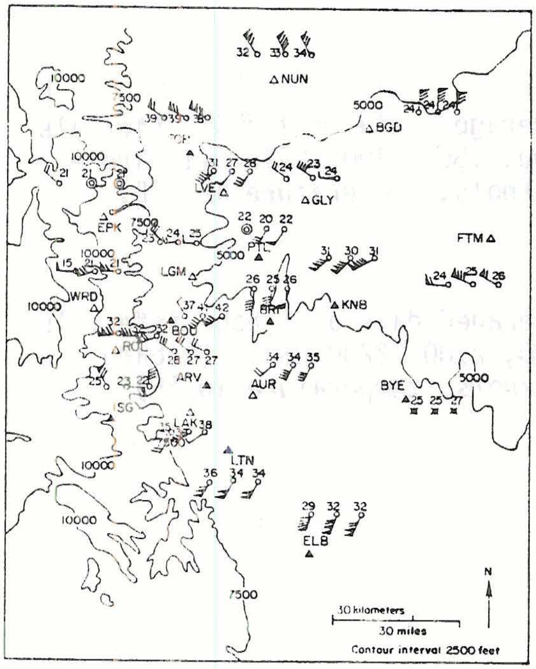


Figure 4.17

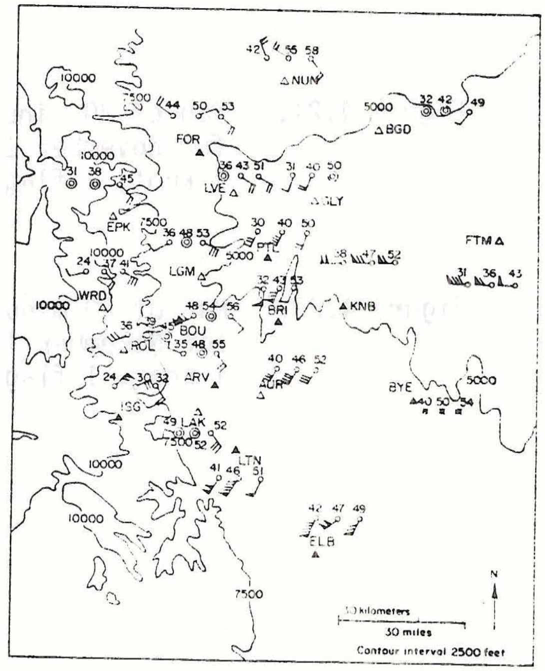


Figure 4.18

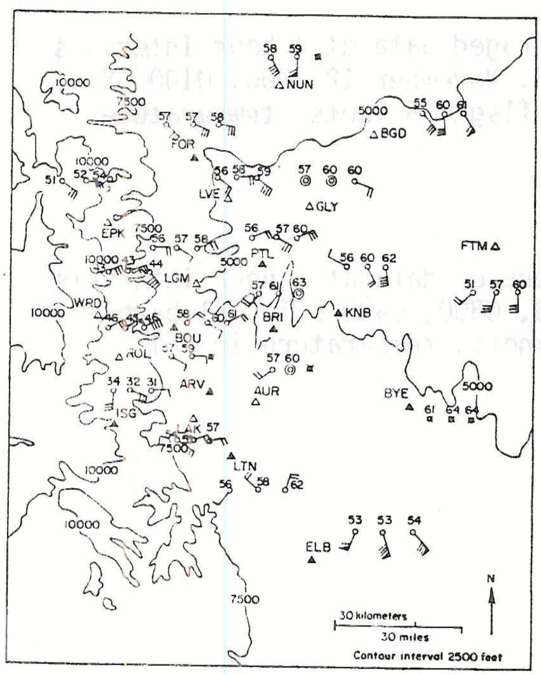


Figure 4.19

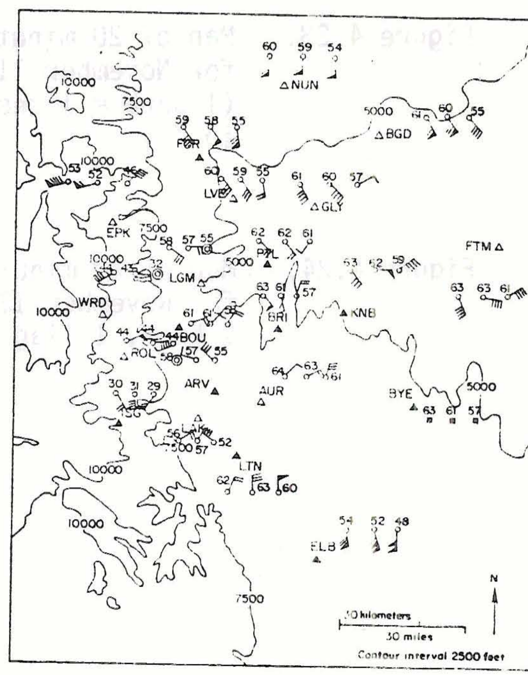


Figure 4.20

Figure 4.21. Map of 20 minute averaged data at 1 hour intervals for November 11 1700, 1800, 1900 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.22. Map of 20 minute averaged data at 1 hour intervals for November 11 2000, 2100, 2200 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.23. Map of 20 minute averaged data at 1 hour intervals for November 11 2300, November 12 0000, 0100 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

Figure 4.24. Map of 20 minute averaged data at 1 hour intervals for November 12 0200, 0300, 0400 LST. (1 barb = 1 knot, 1 flag = 5 knots, temperature in °F)

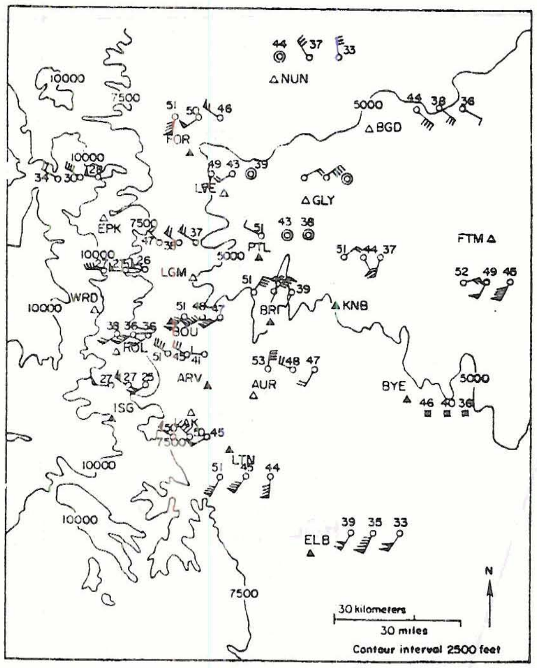


Figure 4.21

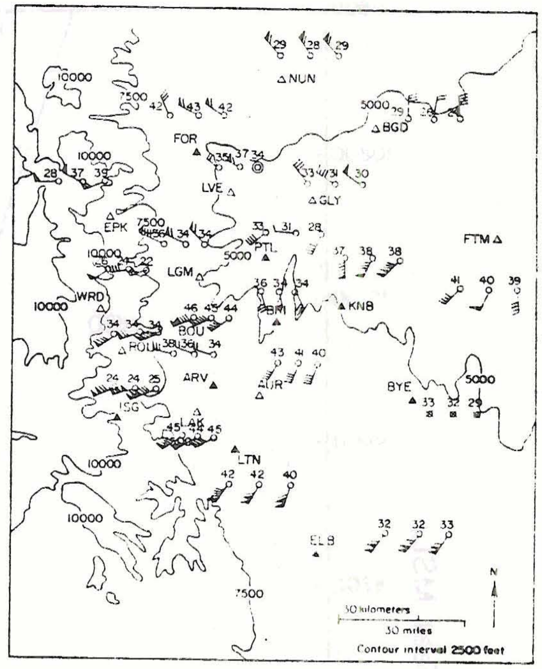


Figure 4.22

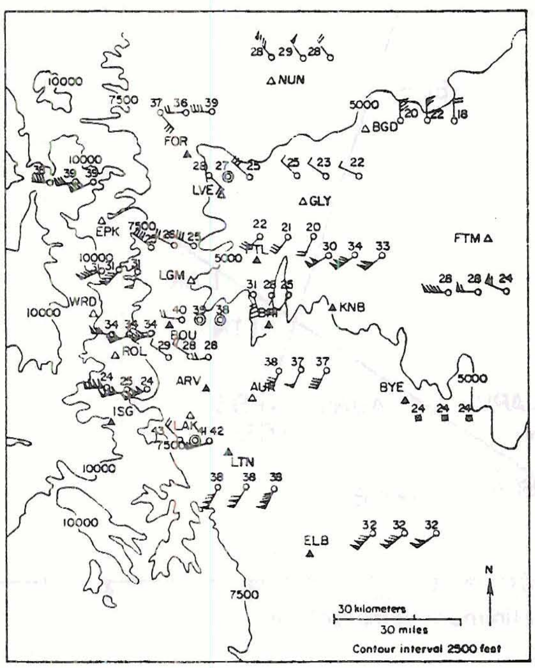


Figure 4.23

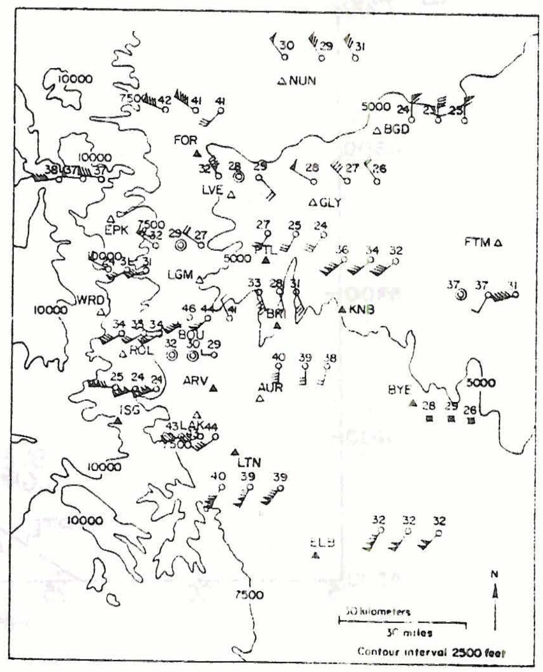


Figure 4.24

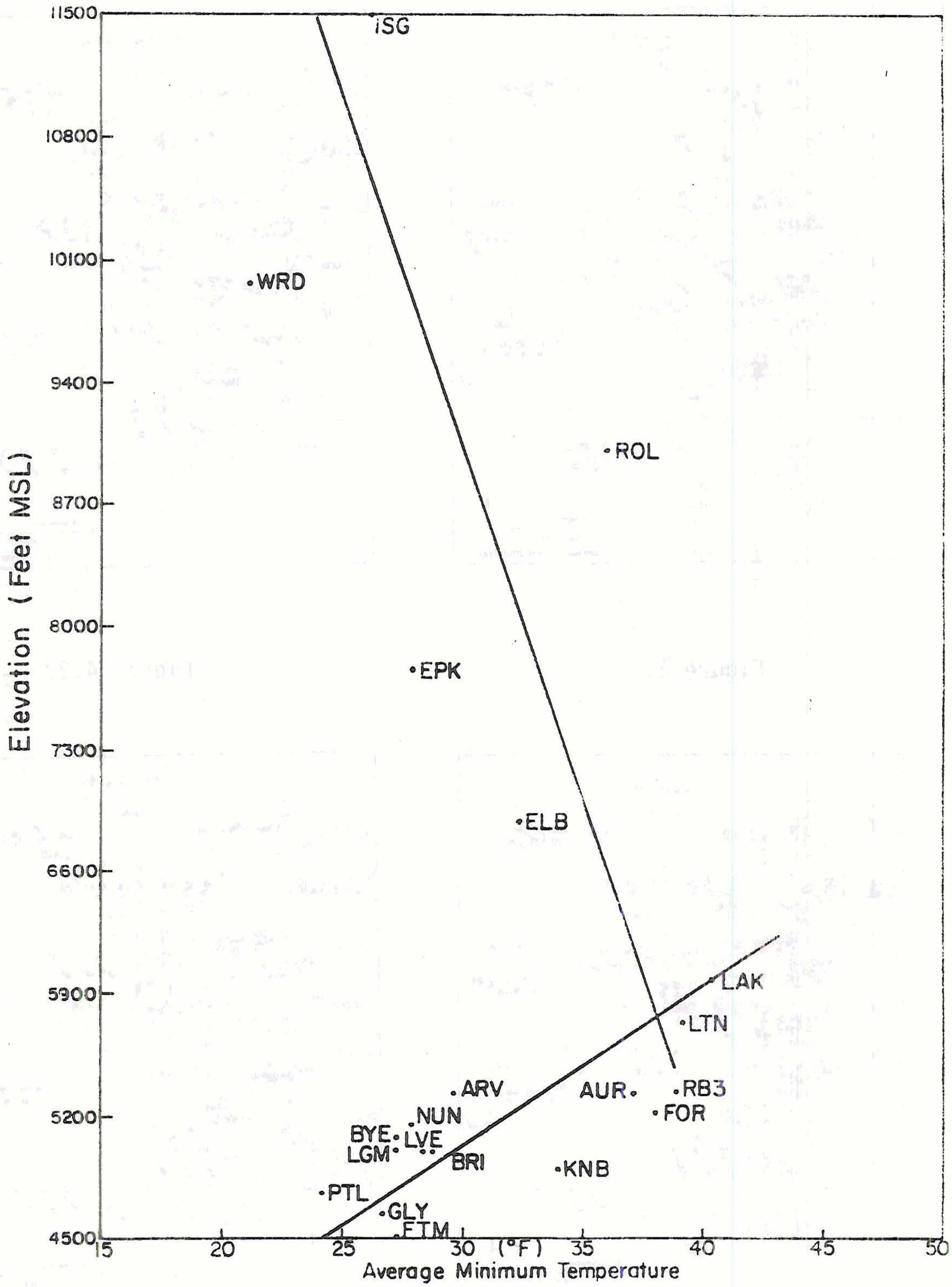


Figure 4.25. Average minimum temperature versus elevation.

elevation within the inversion is around 10°F/1000 feet (calculated from a least squares regression using MINITAB), though local conditions cause some variation from this rate at individual stations. The two regression lines intersect at around 5800 feet. The inversion top heights were around 6400 feet in the October 7 and November 12 Denver 12Z soundings (the sounding for the morning of November 11 contained only the mandatory levels and did not show an inversion).

Figures 4.26 to 4.28 show the comparison between the 12Z temperatures and the 12Z Denver soundings for the three mornings. On all three mornings, the temperature plot has roughly the same shape as the sounding. The sounding is, of course, warmer than the temperature trace due to the radiational cooling of the surface, and it is this temperature difference which creates the pressure gradient that drives the downslope winds. It appears that the temperature difference between sounding and surface is 3 to 5°F, with no substantial change with elevation.

Between one and one and a half hours after sunrise (Figures 4.1-4.2, 4.9-4.10, and 4.18), the downslope winds dissipate along and near the foothills. The wind begins to turn around to upslope. However, the turnaround is not a smooth, quick reversal. A one to three hour transition period, marked by light and variable winds, separates the downslope and upslope winds.

On two of the three mornings there was a similar wind reversal in the mountains simultaneous with the reversal in the foothills. On the third morning, October 7, the day with the highest gradient winds, westerlies were maintained in the mountains throughout the day (Figures 4.10-4.12).

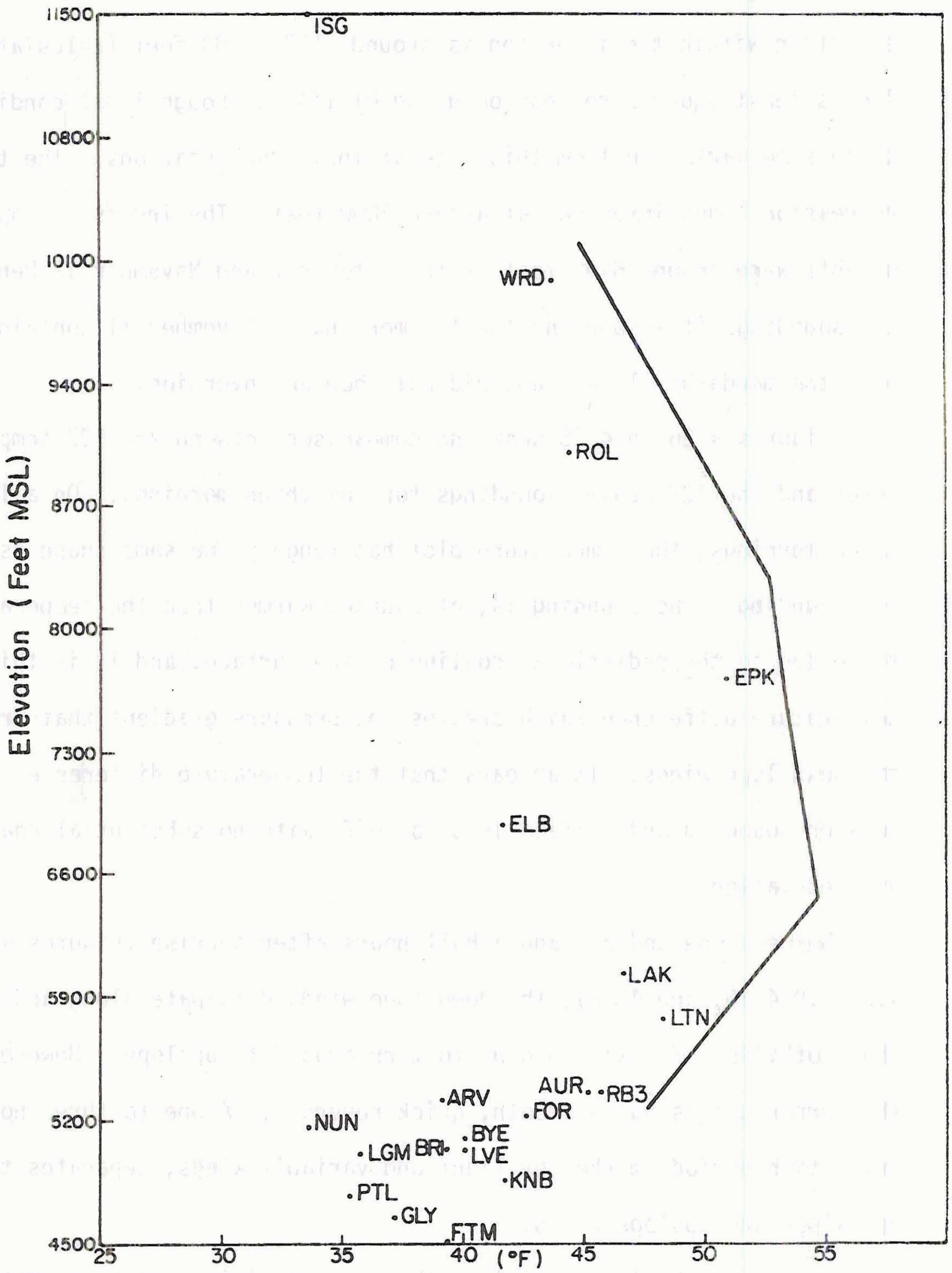


Figure 4.26. Plot of 12Z temperature and Denver rawinsonde sounding (solid line) for October 7.

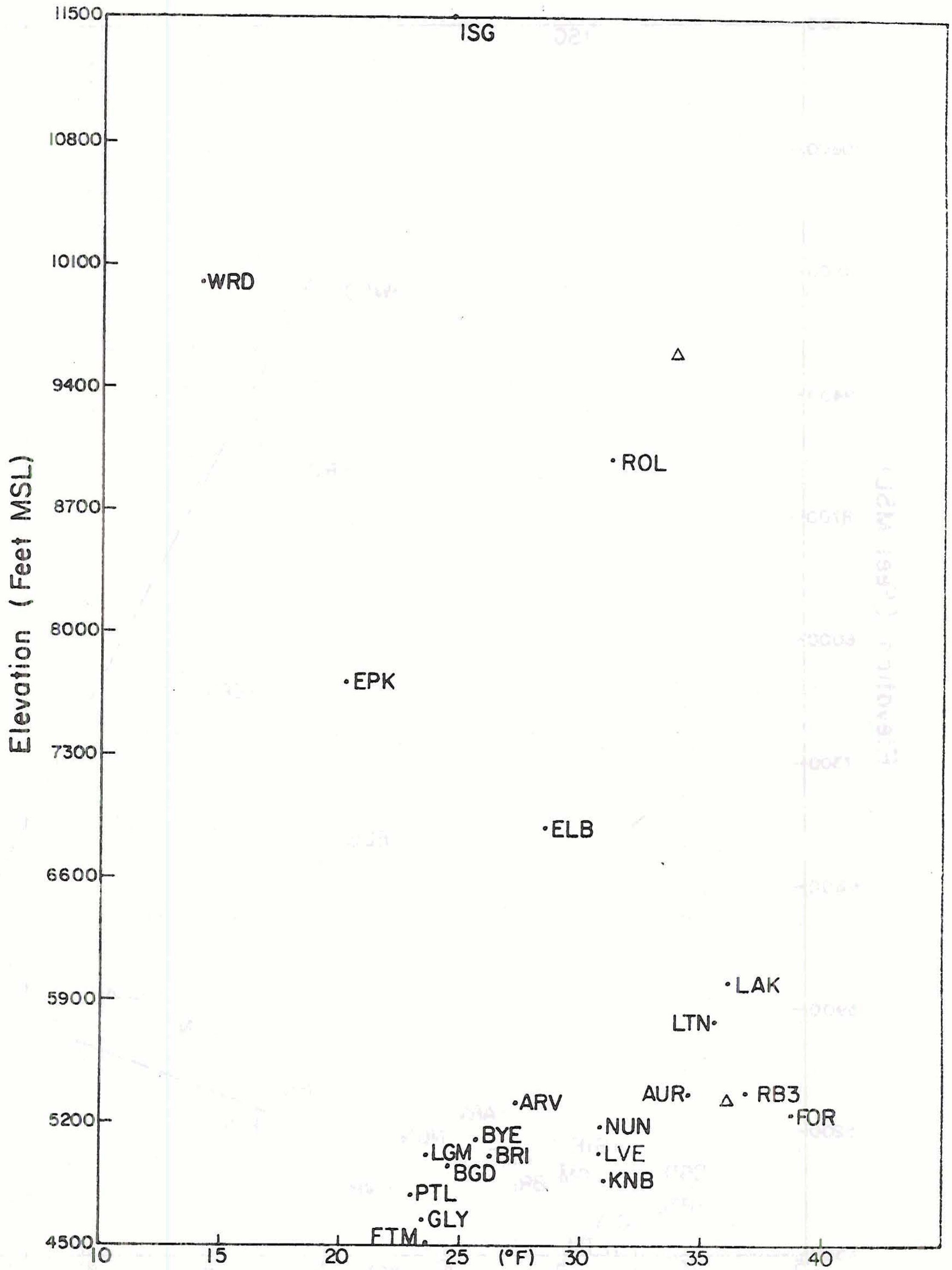


Figure 4.27. Plot of 12Z temperatures and Denver rawinsonde sounding (Δ) for November 11.

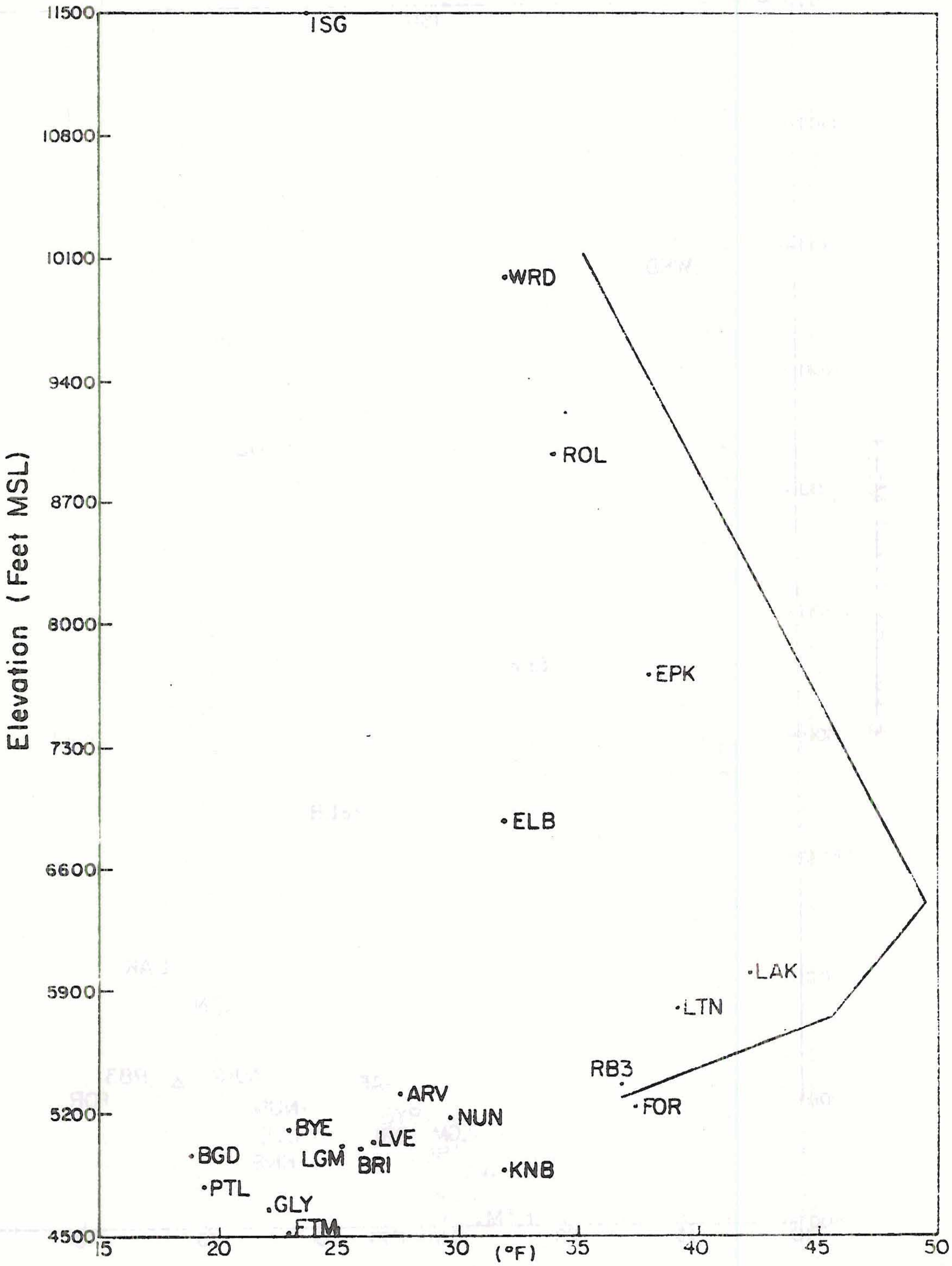


Figure 4.28. Plot of 12Z temperatures and Denver rawinsonde sounding (solid line) for November 12.

By three to four hours after sunrise, upslope winds are established along and near the foothills. Temperatures below 6000 feet have become nearly uniform throughout the region. The downslope winds begin to dissipate out on the plains, first at the more western and further upriver locations (Figures 4.2-4.3, 4.10-4.11, and 4.19). The same type of transition period separates the downslope and upslope winds as in the foothills. No change in wind direction was recorded at the Elbert and Byers stations, and on only one day (November 11) was there a shift to upslope wind flow at Fort Morgan. Strong southerly winds were maintained throughout the day. The transition to upslope winds is completed by six hours after sunrise.

The upslope winds speeds remain steady throughout the day. As Figure 4.12 shows, the strongest speeds are in the extreme eastern portion of the region where there is no diurnal direction shift. Here, the speeds are around 10 knots. Speeds in excess of 5 knots occur in the northern portion of the region where the wind blows toward the Cheyenne Ridge and also south of Denver. Speeds are only 2 to 3 knots in the rest of the plains area. Mountain wind speeds vary greatly between the individual stations, ranging from 3 to 7 knots.

The maximum temperatures on the plains and foothills generally occur between 1330 and 1500 LST, as shown in Table 4.4. The exception is Aravada, which has earlier maximum temperatures. This may be due to the afternoon shade from the line of trees to the west of the station. The two mountain peak stations, Idaho Springs and Rollinsville, have maximum temperatures close to noon.

Table 4.4. Time of maximum temperature.

Date	Time (LST)					
	1100-1200	1205-1300	1305-1400	1405-1500	1505-1600	1605-1700
10/6	ISG	ROL	ARV BRI BYE EPK WRD	AUR ELB FTM GLY KNB LAK LTN NUN PTL	FOR LGM RB3	LVE
10/7	ISG	ARV ELB	BYE FTM NUN ROL WRD	AUR BRI FOR GLY KNB LAK LGM LTN LVE PTL	EPK RB3	
11/11	ARV AUR ISG ROL	ELB FOR	BGD EPK LGM	RB3 BRI FTM GLY KNB LAK LTN LVE NUN PTL WRD	BYE	

Figure 4.29 contains a graph of the average maximum temperature versus elevation. It appears that maximum temperatures are not correlated with elevation below 6000 feet MSL. To test this hypothesis the F-value was computed. With a variance of $7.0°F^2$ and a residual sum of squares of $97.5°F^2$, with 15 stations, $F = [(14 \cdot 7.0) - 97.5]/[97.5 \div 13] = 0.07$, which is easily less than the tabulated 5 percent value of 4.67. Therefore, it can be concluded that there was no correlation of maximum temperature with elevation below 6000 feet on the study days. Local controls play the dominant role in determining the maximum temperature. The least squares fit (from MINITAB) is plotted for stations from Littleton (5740 feet MSL) up. There is an almost linear decrease of maximum temperature with elevation of roughly 4½°F/1000 feet for elevations above this level. The correlation coefficient for the least squares fit is 0.98.

Between one and a half and two hours before sunset, the upslope winds begin to dissipate in the mountains and along the foothills (Figures 4.4-4.5, 4.20-4.21). A one to two hours wind turnaround period follows as downslope winds develop. This turnaround period differs from the morning transition period in that the speeds do not drop so dramatically and the direction shifts smoothly from upslope to downslope.

After sunset, the upslope winds on the plains switch around to downslope, with the same one to two hour turnaround period. As in the morning, the evening turnaround occurs earlier at the further west and further upriver locations. In the first three hours after sunset, temperatures drop nearly twice as rapidly on the plains as in the foothills (Figure 4.5). By five hours after sunset downslope winds are

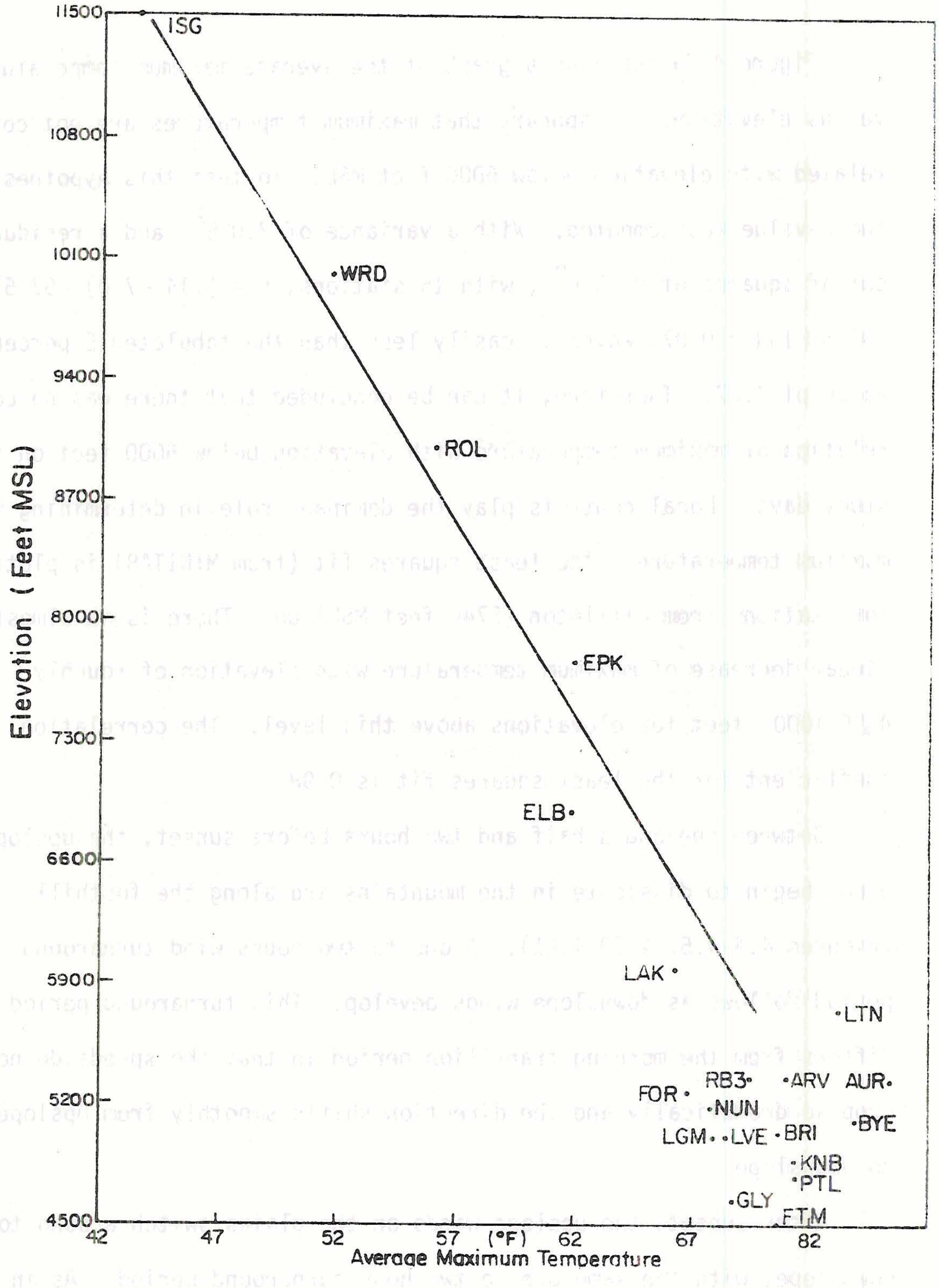


Figure 4.29. Average maximum temperature versus elevation.

established throughout the region. These downslope winds are stronger than the upslope winds, except in the northern part of the region where the wind blows off of the Cheyenne Ridge. Speeds of 8 to 12 knots occur in the foothills and mountains and also in the eastern plains and on the Palmer Ridge. The western plains have speeds of less than 5 knots, while speeds of 5 to 6 knots occur on the Cheyenne Ridge.

After midnight, the downslope winds decrease to only 2 to 3 knots, except in the mountains and on the Palmer Ridge and eastern plains (Figure 4.7). Temperatures remain fairly steady throughout the area. As Table 4.5 shows, minimum temperatures may occur anytime from midnight to an hour after sunrise.

The diurnal temperature ranges for October 7 and November 11 are plotted in Figures 4.30 and 4.31, respectively. The diurnal range decreases with elevation, exceeding 40°F in the South Platte River Valley but less than 20°F in the mountains. The rate at which the diurnal range decreases with elevation appears to be greater below 6000 feet MSL than above 6000 feet MSL. Least squares lines were calculated for above 6000 feet and below 6000 feet for each day using MINITAB and are plotted on the graph.

Table 4.5. Time of minimum temperature.

Date	Time (LST)								
	2300- 0000	0005- 0100	0105- 0200	0205- 0300	0305- 0400	0405- 0500	0505- 0600	0605- 0700	0705- 0800
10/7		ROL ELB EPK WRD			AUR LTN	FOR ISG RB3	BRI BYE FTM GLY KNB LAK LGM NUN PTL	ARV LVE	
11/11				ELB EPK	BGD NUN	WRD	AUR BRI FTM KNB LAK LGM LVE RB3	ARV BYE GLY ISG LTN PTL BYE	FOR
11/12	ARV WRD	ELB EPK		KNB	LAK	BRI NUN ROL	AUR BGD FTM ISG LGM LTN RB3	BYE FOR GLY LVE PTL	

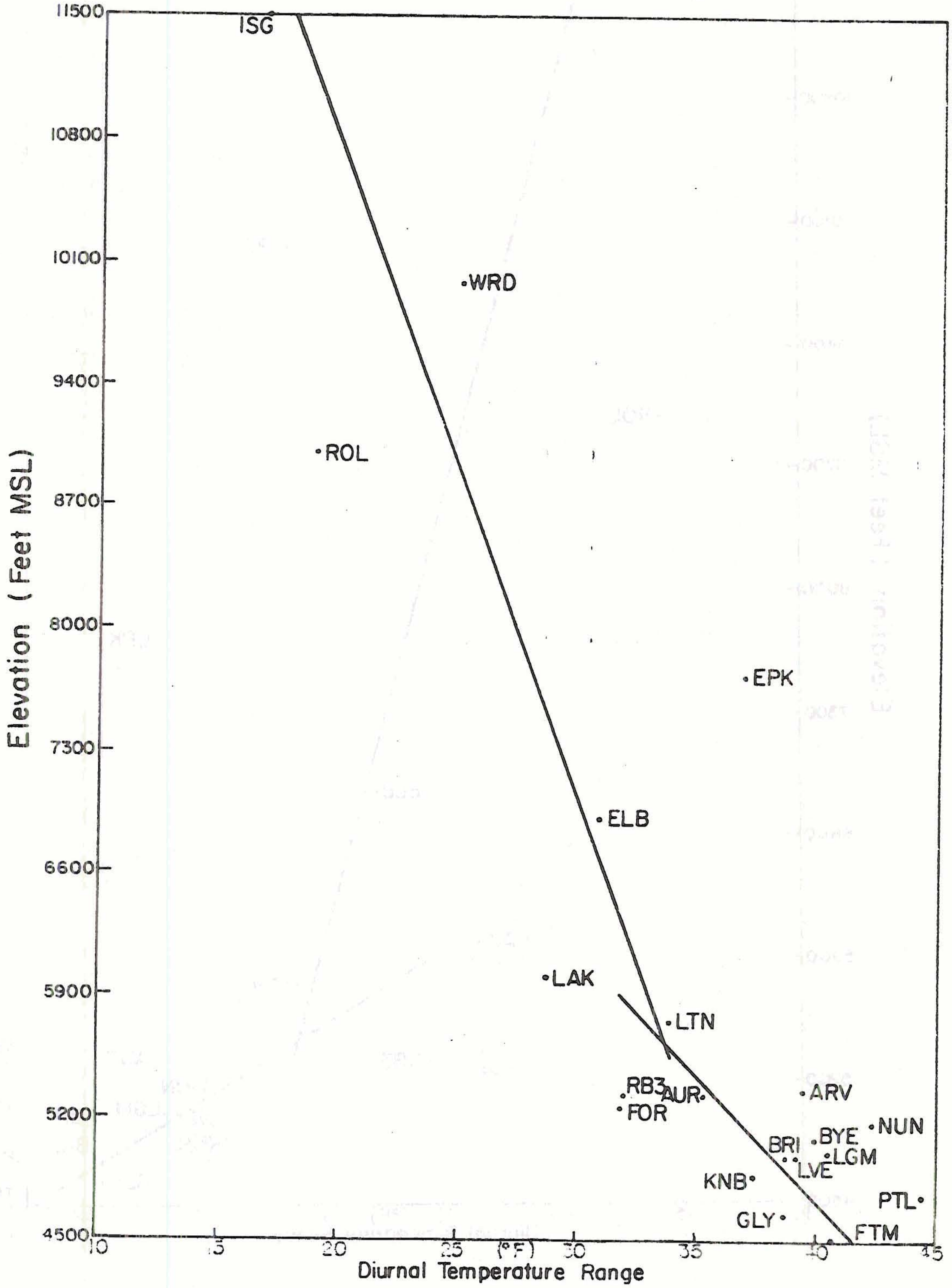


Figure 4.30. Diurnal temperature range versus elevation for October 7.

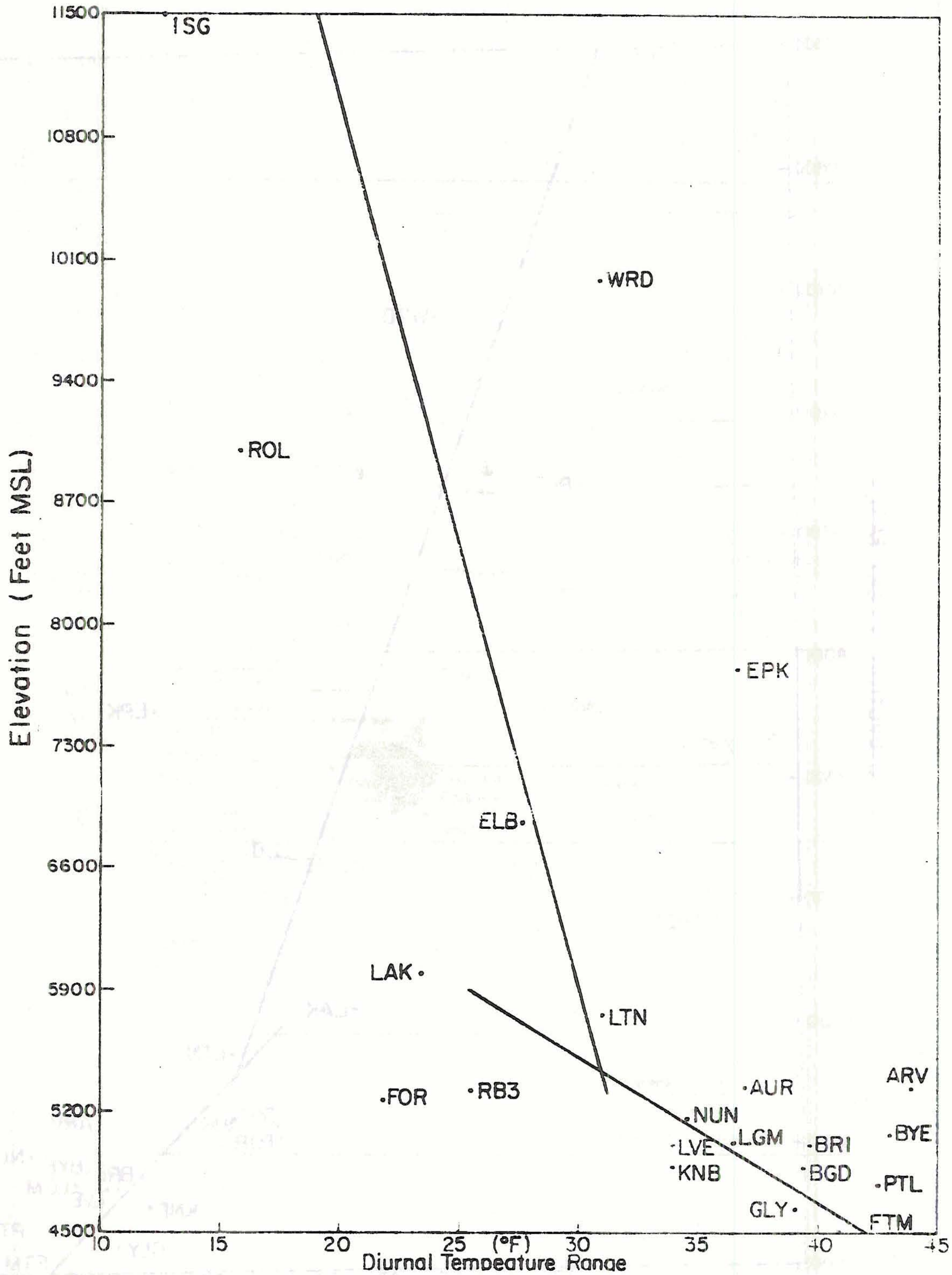


Figure 4.31. Diurnal temperature range versus elevation for November 11.

CHAPTER V

DISCUSSION

A. Discussion of Wind and Temperature Pattern

The role of topography in controlling the regional wind and temperature patterns in northeastern Colorado in the absence of dominant synoptic-scale forcing is apparent. Even with such a limited data set, a consistent diurnal pattern can be seen.

The diurnal wind pattern is illustrated in this section with diagrams of the hypothesized wind flow for the day at one hour before sunrise and two, three, four and six hours after sunrise and for the night at one hour before sunset and one and three hours after sunset, followed by a final diagram representing the early morning wind pattern. Because the wind observations for the period in October and the period in November were similar, no attempt was made to separate out what influence the high pressure center to the east of the study region may have had on the October observations. Some differences might be found in observations with weak pressure gradients oriented differently than the pressure gradients in the days used in this study, particularly in the eastern portion of the region. However, a large scale southerly flow is the climatological norm for the western plains in Autumn (U.S. Department of Commerce, 1968).

Figures 5.1 through 5.5 show the daytime wind evolution. Figure 5.1 shows the wind pattern an hour before sunrise. Downslope winds

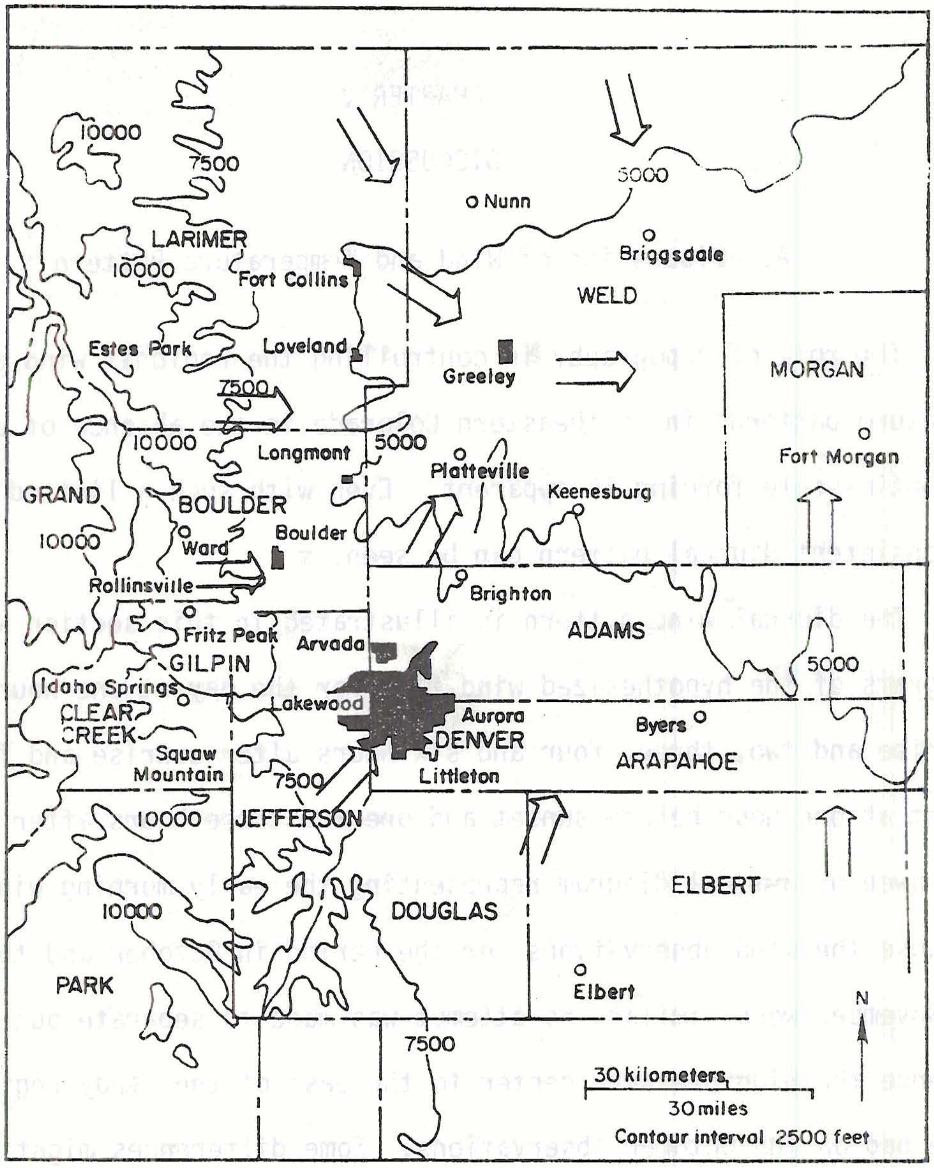


Figure 5.1. Regional wind flow 1 hour before sunrise.

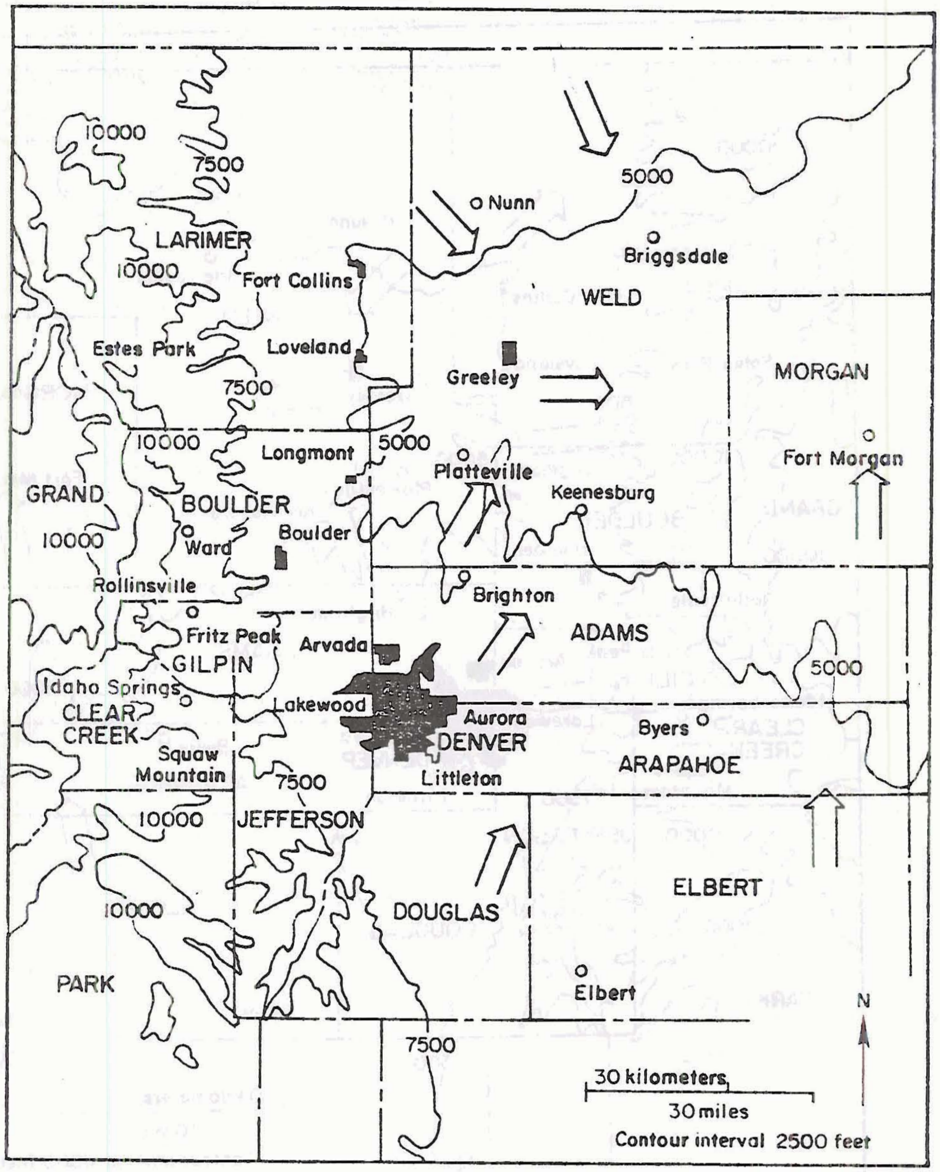


Figure 5.2. Regional wind flow 2 hours after sunrise.

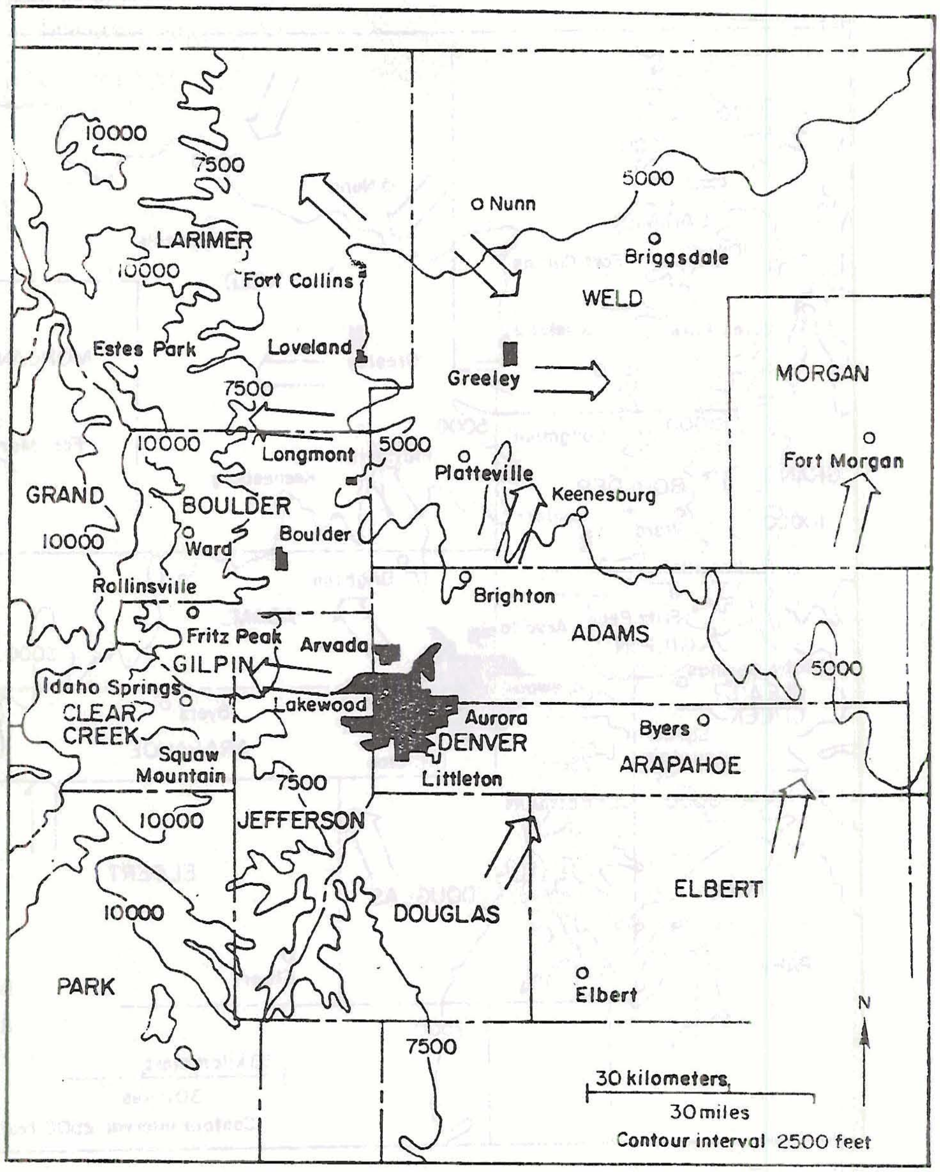


Figure 5.3. Regional wind flow 3 hours after sunrise.

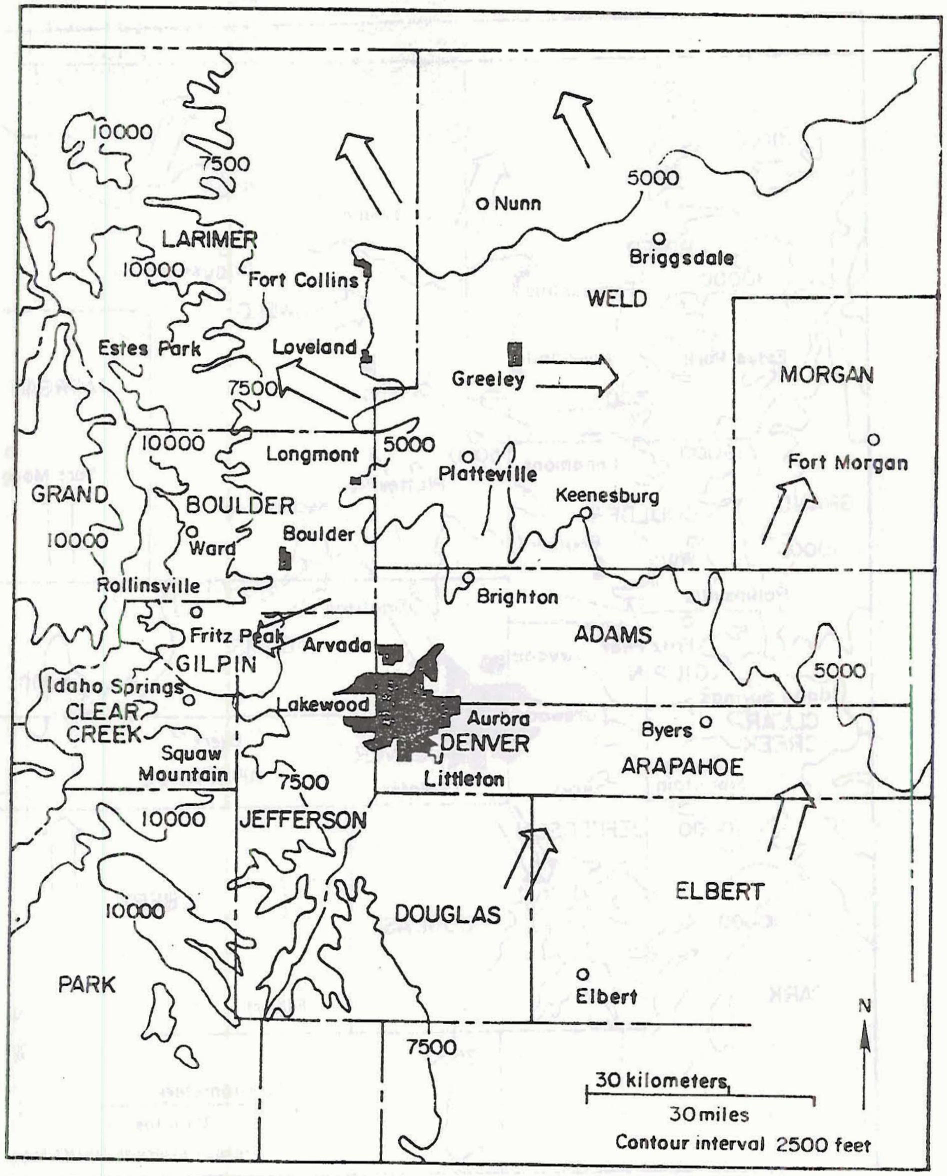


Figure 5.4. Regional wind flow 4 hours after sunrise.

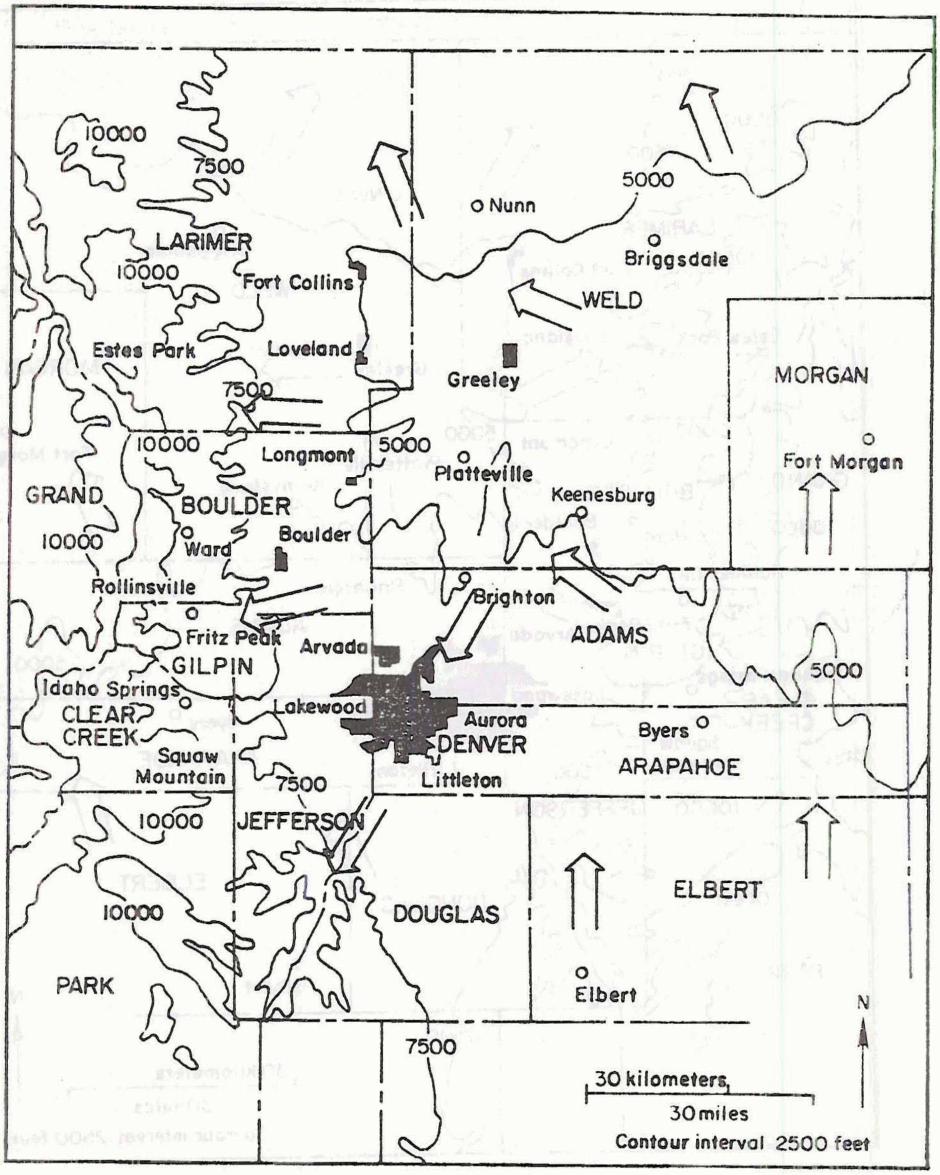


Figure 5.5. Regional wind flow 6 hours after sunrise.

blowing from the Front Range and Cheyenne and Palmer Ridges converge into the South Platte River Valley. Strong southerly winds (10 to 15 knots) blow on the eastern plains.

Two hours after sunrise (Figure 5.2), the transition from downslope to upslope has begun in the foothills and mountains, as evidenced by very light or even calm wind speeds and changes in wind direction from the earlier pattern. On the plains and Cheyenne and Palmer Ridges, however, the downslope winds continue. A region of warm temperatures centered about 5800 feet is still present.

At three hours after sunrise (Figure 5.3), upslope winds have become established along the foothills, and the transition zone has spread onto the plains and the Cheyenne Ridge. Downslope winds are still present on the Palmer Ridge and along the South Platte River. The model results presented by Dirks (1969) show a circulation cell over the slope, with the mass transported upslope by the upslope winds being replaced by a descending column of air.

By four hours after sunrise (Figure 5.4), upslope flow has become established on the south slope of the Cheyenne Ridge but not on the north slope of the Palmer Ridge where upslope winds would have to flow in the opposite direction to the large scale flow. Downslope winds are confined to the Palmer Ridge and the lower elevations along the South Platte River. Temperatures on the plains have caught up with those on the foothills except at the lower elevations along the South Platte River where the inversion was the deepest.

The daytime pattern is firmly established by six hours after sunrise (Figure 5.5). Upslope winds are present everywhere except in the extreme eastern portion of the region where southerly winds from the large scale flow persist throughout the day at speeds in excess of 10 knots. The northern part of the region has a wind component directed toward the Cheyenne Ridge while the southern part has a component directed toward the Palmer Ridge. Coupled with the large scale southerly wind in the eastern part of the region this produces cyclonic curvature in the vicinity of Denver and anticyclonic curvature over the northern part of the region. Speeds of 5 to 8 knots occur in the region with a wind component toward the Cheyenne Ridge, while speeds of only 2 to 3 knots occur in the region with a component toward the Palmer Ridge and against the large scale flow. Mountain wind speeds are site dependent.

Figures 5.6 and 5.9 show the nighttime evolution. An hour before sunset (Figure 5.6), the wind is turning from upslope to downslope in the mountains and foothills and on the Palmer Ridge. Upslope winds continue elsewhere, except in the extreme eastern portion of the region where strong southerly winds persist throughout the night.

An hour after sunset (Figure 5.7), downslope winds are established in the foothills and mountains and on the Palmer Ridge. By three hours after sunset (Figure 5.8), downslope winds occur at all but the lowest elevations along the South Platte River. Plains temperatures have fallen below foothills temperatures by this time. Wind speeds are stronger than in the daytime upslope regime, except in the area having a southerly wind component off of the Cheyenne Ridge. Strongest downslope winds (8 to 12 knots) are along the southern foothills and the Palmer Ridge. Downslope wind speeds are around 5 knots in the rest of the region, though mountain wind speeds may be greater at certain locations.

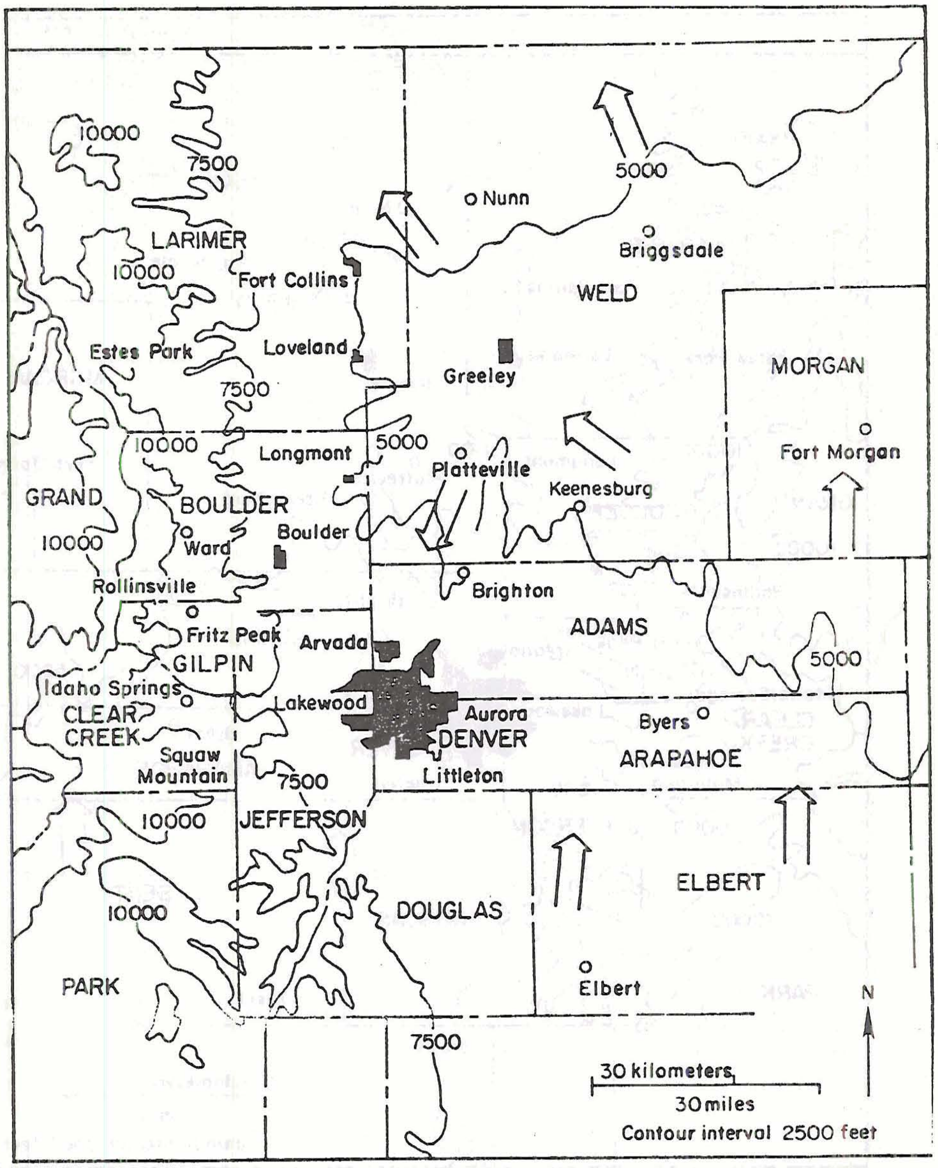


Figure 5.6. Regional wind flow 1 hour before sunset.

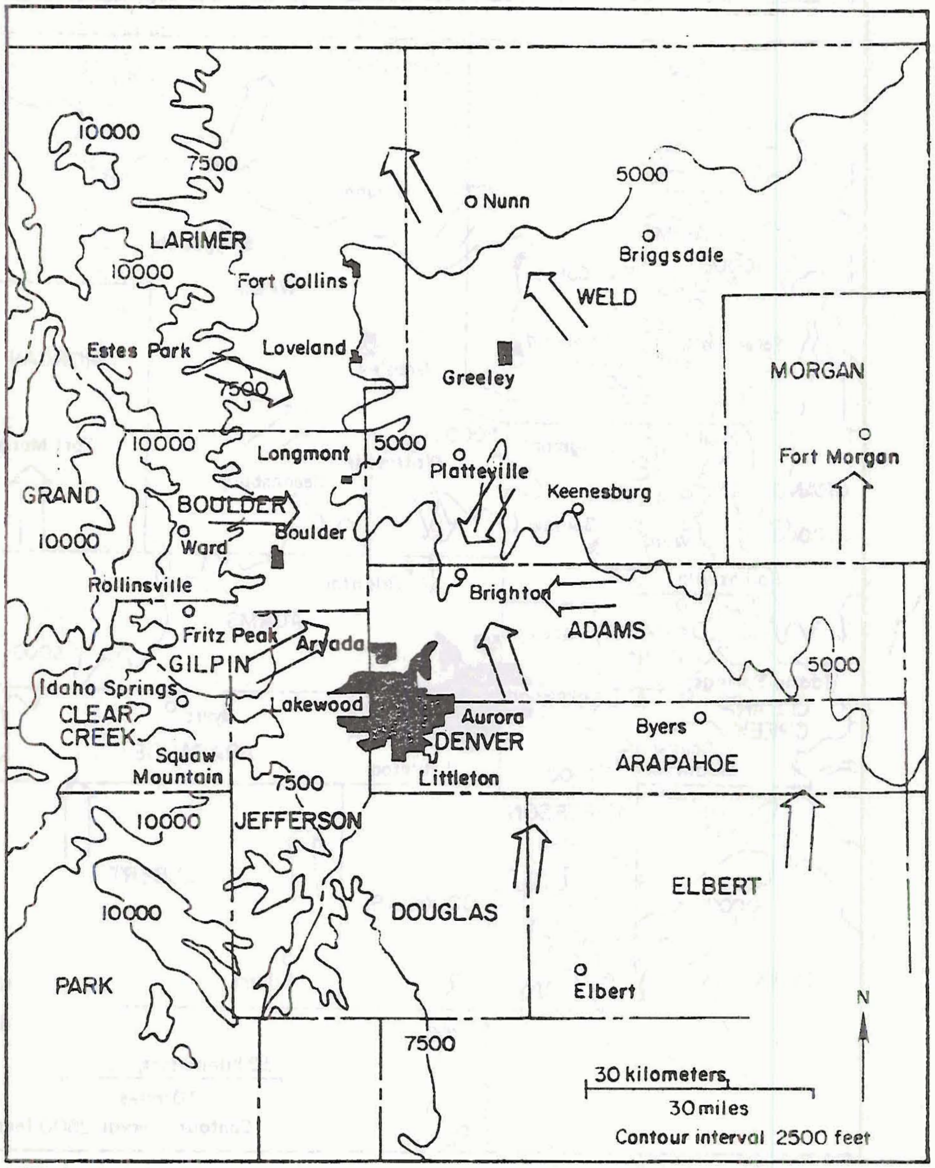


Figure 5.7. Regional wind flow 1 hour after sunset.

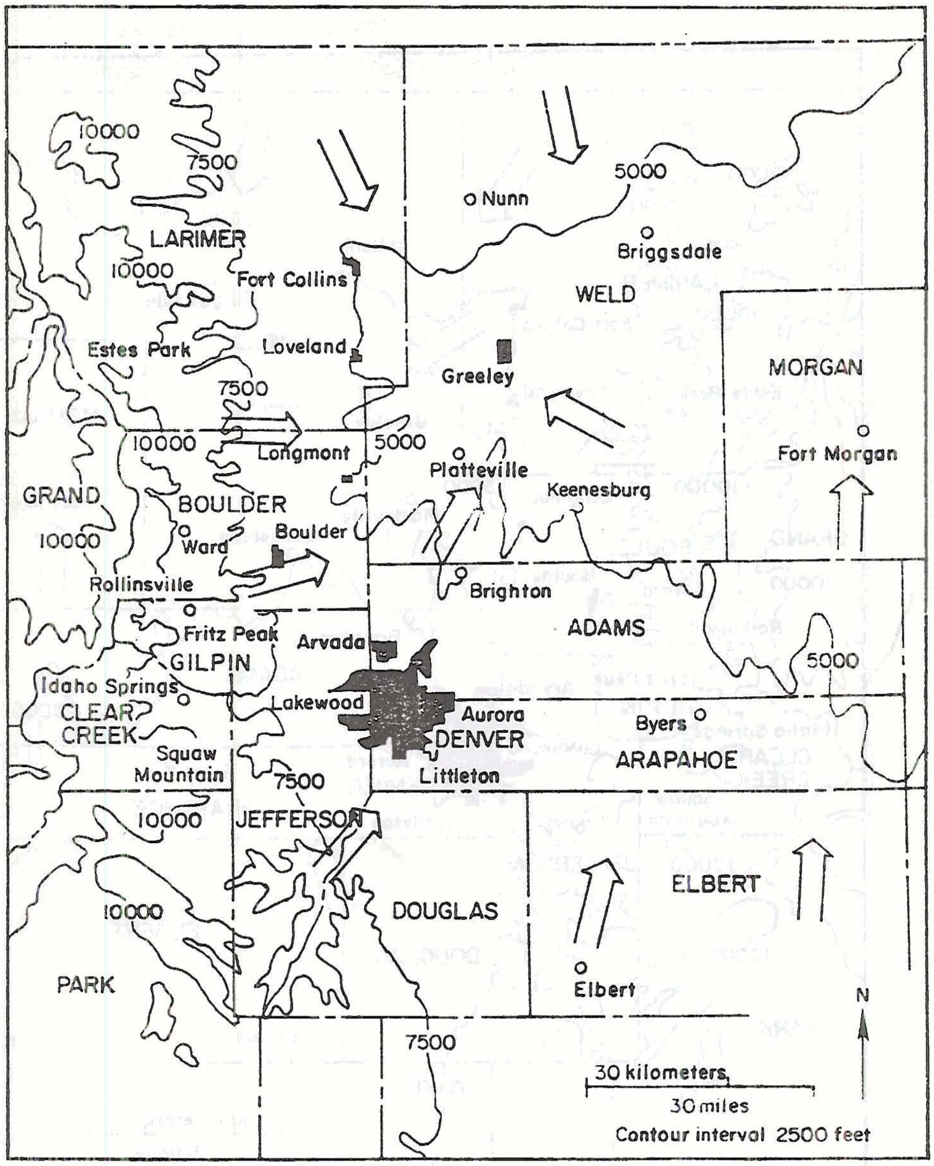


Figure 5.8 Regional wind flow 3 hours after sunset.

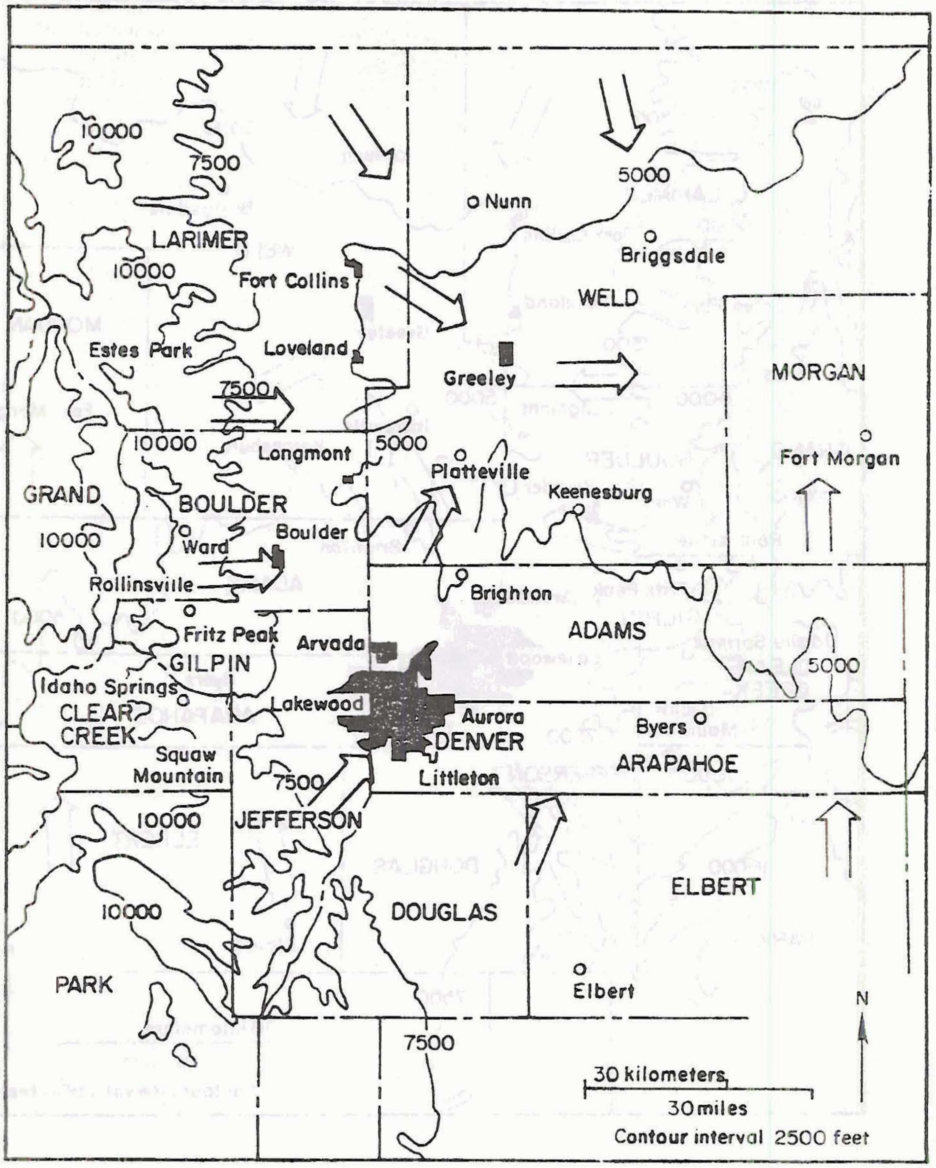


Figure 5.9. Regional wind flow in early morning.

Figure 5.9 shows the early morning wind pattern. Downslope winds off the Front Range and Cheyenne and Palmer Ridges converge into the South Platte River Valley. The strong southerly winds persist in the eastern portion of the region. The downslope winds continue to be strong in the mountains, but foothills and plains wind speeds have decreased to only 2 to 3 knots.

The diurnal wind direction patterns were similar to those observed for July by Johnson and Toth (1982), with upslope winds during the day and downslope winds converging into the South Platte River Valley at night and with the reversal between the two wind regimes occurring first in the foothills and mountains and then spreading eastward. However, there are two differences between their observations and the observations reported in this study. The most important difference is the influence of the Cheyenne and Palmer Ridges on the wind directions on the plains during the day. Johnson and Toth show plains winds that are almost due easterly in the afternoon. The observations presented here show that wind directions on the plains and foothills have significant northerly or southerly components. The stations closest to the Cheyenne Ridge show winds that are more southerly than easterly and the stations closest to the Palmer Ridge show winds that are more northerly than easterly. In addition, unlike their observations, wind direction reversals were observed to occur at the same time in the mountains as along the foothills. These discrepancies are most likely due to the difference in data sets between selecting specific undisturbed days for study and attempting to filter out synoptically disturbed observations by a wind speed criteria.

The extent to which strong gradient-level westerly winds extend down the eastern slope, as they did on October 7, could not be further investigated due to the limited number of mountain stations. The region between 6000 and 9000 feet MSL is represented by only one station, and that station is in a trapping valley.

The observed wind speed pattern contradicted several previous studies. Daytime wind speeds did not have a uniform east-west gradient as Riehl and Herkhof (1970b) observed, but there was also a north-south wind speed variation. Riehl and Crow (1962) observed an increase in wind speeds along the foothills and on the plains in the early morning, following light and variable winds in the evening, but observations presented here show that moderate to strong downslope winds occur throughout the region in the evening, and are followed by a decrease of wind speeds along the foothills and in the South Platte River Valley after midnight. Wind speeds in the mountains and Palmer Ridge and in the eastern part of the region were high throughout the night.

The daytime temperature pattern shows complete independence of maximum temperature and elevation below 6000 feet MSL. Above 6000 feet MSL, the decrease of temperature with height was nearly linear.

At night, an inversion was observed with the top at the level of the foothills and Palmer Ridge stations and with a stable lapse rate above the inversion. The intersection of the lease squares regression lines for stations in the inversion and stations above the inversion is around 5800 feet MSL (Figure 4.25). However, because there are only 2 stations between 6000 feet and 9000 feet MSL, it can not be definitely concluded that the inversion top was at 5800 feet MSL. On the two nights that inversions were shown in the Denver soundings, the inversion top over Denver was around 6400 feet MSL. The morning soundings showed that the free air temperatures were 3 to 5°F warmer than the surface temperatures.

B. Suggestions for Future Research

There is a need for an increase in the number of stations in the foothills. With only one station between 6000 and 9000 feet MSL, it is difficult to determine whether the inversion top increases or decreases close to the foothills and to find the level to which westerly winds mask the upslope winds on days with strong upper level westerlies.

There is also a need for uniform anemometer heights. The current range of anemometer heights, from 20 feet to 210 feet, hinders comparisons between stations.

Several of the stations need to be modified or moved. The Arvada and Byers stations should be moved away from the trees so that they may record representative wind speeds. The Boulder station should be moved from the roof of the NOAA building and placed in a location that is more representative of surface conditions. The towers at the Lakewood, Longmont, and Greeley stations should be lengthened to avoid turbulence from the buildings that they are mounted on.

There is a need to repeat this study with a larger data set so that the timing of the wind reversals can be quantified and the amount of solar heating needed to drive the upslope winds can be determined.

CHAPTER VI

CONCLUSIONS

Data collected by the PROFS mesometeorological network was used to study the undisturbed clear day wind and temperature pattern along the Front Range in northeastern Colorado in Autumn. Three days and three nights were available for study.

A diurnal wind regime was observed which consisted of daytime upslope and nighttime downslope winds with components directed toward both the Front Range and the Cheyenne and Palmer Ridges.

The transition from downslope to upslope in the morning takes one to three hours at each station and involves a distinct break between the wind systems. The transition begins in the foothills and mountains and spreads eastward, taking four to five hours to spread through the entire region. Because the large scale flow over the western plains was southerly during the study, the upslope winds were observed earlier on the south slope of the Cheyenne Ridge than on the north slope of the Palmer Ridge. The strongest upslope winds occur in the northern part of the region, where there is a strong up-Cheyenne Ridge wind component. Speeds there are 5 to 8 knots. Upslope speeds elsewhere are 3 to 4 knots. Mountain wind speeds are site dependent.

The downslope winds also begin in the foothills and mountains and spread eastward, taking four to five hours to spread throughout the region. However, the transition at each individual station only takes half as long as the morning transition. The evening wind speeds are stronger than the upslope wind speeds, except in the northern part of the region where there is a strong down-Cheyenne Ridge component. Speeds of 8 to 12 knots occurred in the foothills and on the Palmer Ridge, with downslope speeds of 5 knots or less elsewhere. As in the daytime, mountain speeds are site dependent. Between the foothills and South Platte River, the winds diminish in the early morning, but maintain their strength elsewhere.

The diurnal wind regime did not reach the eastern fringe of the PROFS study region. Here, strong southerly winds of 10 to 15 knots persisted throughout both day and night.

Maximum temperatures were found to be independent of height at elevations below 6000 feet MSL and strongly dependent on elevation above 6000 feet. At night, there is an inversion that extends as high as the foothills with minimum temperatures decreasing at 10°F/1000 feet, while minimum temperatures decrease with elevation above the inversion at 2½°F/1000 feet. The morning sounding from Denver shows that the surface temperature is 3 to 5°F cooler than the free air with no variation with elevation.

Maximum temperatures generally occur in the small range of 1330 LST to 1500 LST. Minimum temperatures may occur anytime between midnight and 1 hour after sunrise.

The diurnal temperature range was observed to decrease with elevation and ranged from 40°F along the South Platte River to 20°F in the high mountains.

REFERENCES

Banta, R., and W. R. Cotton, 1981: An analysis of the structure of local wind systems in a broad mountain basin. Journal of Applied Meteorology, 20(11), pp. 1255-1266.

Braham, R. R., and M. Draginis, 1960: Roots or orographic cumuli. Journal of Meteorology, 17(2), pp. 214-226.

Conley, J. R., 1982: An analysis of solar radiation data for Fort Collins, Colorado. Master's Thesis, Colorado State University, 37 p.

Crow, L. W., 1976: Airflow study related to EPA Field Monitoring Program, Denver Metropolitan Area, November 1973. In Proceedings of the Symposium on Denver Air Pollution Study -- 1973, Volume I. Edited by P. A. Russell. U.S. Environmental Protection Agency EOA-600/9-76-007a, Research Triangle Park, North Carolina, pp. 3-30.

Davidson, B., and P. K. Rao, 1963: Experimental studies of the valley-plain wind. Int. J. Air Wat. Poll., 7, pp. 907-923.

Defant, F., 1951: Local winds. Compendium of Meteorology. Edited by T. M. Malone. Boston, American Meteorological Society, pp. 665-672.

Dirks, R. A., 1969: A theoretical investigation of convective patterns in the lee of the Colorado Rockies. Atmospheric Science Paper No. 154, Colorado State University, 122 p.

Djordjevic, N., W. Ehrman, and G. Swanson, 1966: Further studies of Denver air pollution. Atmospheric Science Paper No. 105, Colorado State University, 146 p.

Fleagle, R. G., 1950: A theory of air drainage. Journal of Meteorology, 7(3), pp. 227-232.

Flohn, H., 1968: Contribution to a meteorology of the Tibetan highlands. Atmospheric Science Paper No. 130, Colorado State University, 170 p.

Haagenson, P. L., 1979: Meteorological and climatological factors affecting Denver air quality. Atmospheric Environment, 13(1), pp. 79-86.

Johnson, R. H., and J. J. Toth, 1982: Topographic effects and weather forecasting in the Colorado PROFS mesonetwork area. Preprint Volume, Ninth Conference on Weather Forecasting and Analysis, June 28-July 1, 1982. Seattle, Washington, pp. 440-445.

Manins, P. C., and B. L. Sawford, 1979: Katabatic winds: a field case study. Quarterly Journal of the Royal Meteorological Society, 105, pp. 1011-1025.

Orville, H. D., 1964: On mountain upslope winds. Journal of Atmospheric Sciences, 22(6), pp. 622-633.

Pratte, J. F., and L. Kaimal, 1981: Prototype Regional Observing and Forecasting Service surface mesonetwork operator's manual. PROFS-SURFNET-80-001, NOAA/ERL, 112 p.

Riehl, H., and L. W. Crow, 1962: A study of Denver air pollution. Atmospheric Science Paper No. 33, Colorado State University, 15 p.

Riehl, H., and D. Herkhof, 1970a: Meteorological aspects of Denver air pollution. Atmospheric Science Paper No. 158, Colorado State University, 41 p.

Riehl, H., and D. Herkhof, 1970b: Larimer County, Colorado, Air Pollution and Outlook. Colorado State University, 42 p.

Staley, D. O., 1959: Some observations of surface-wind oscillations in a heated basin. Journal of Meteorology, 16(4), pp. 364-370.

Thyer, N. H., 1966: A theoretical explanation of mountain and valley winds by a numerical method. Archiv für Meteorologie, Geophysik und Bioklimatologie, Ser. A, 15(3-4), pp. 318-348.

U.S. Department of Commerce, 1968: Climatic Atlas of the United States. ESSA, Environmental Data Service, U.S. Government Printing Office, Washington, DC.

Whiteman, C. D., 1980: Breakup of temperature inversion in Colorado mountain valleys. Atmospheric Science Paper No. 328, Colorado State University, 250 p.

APPENDIX A

Weather Maps

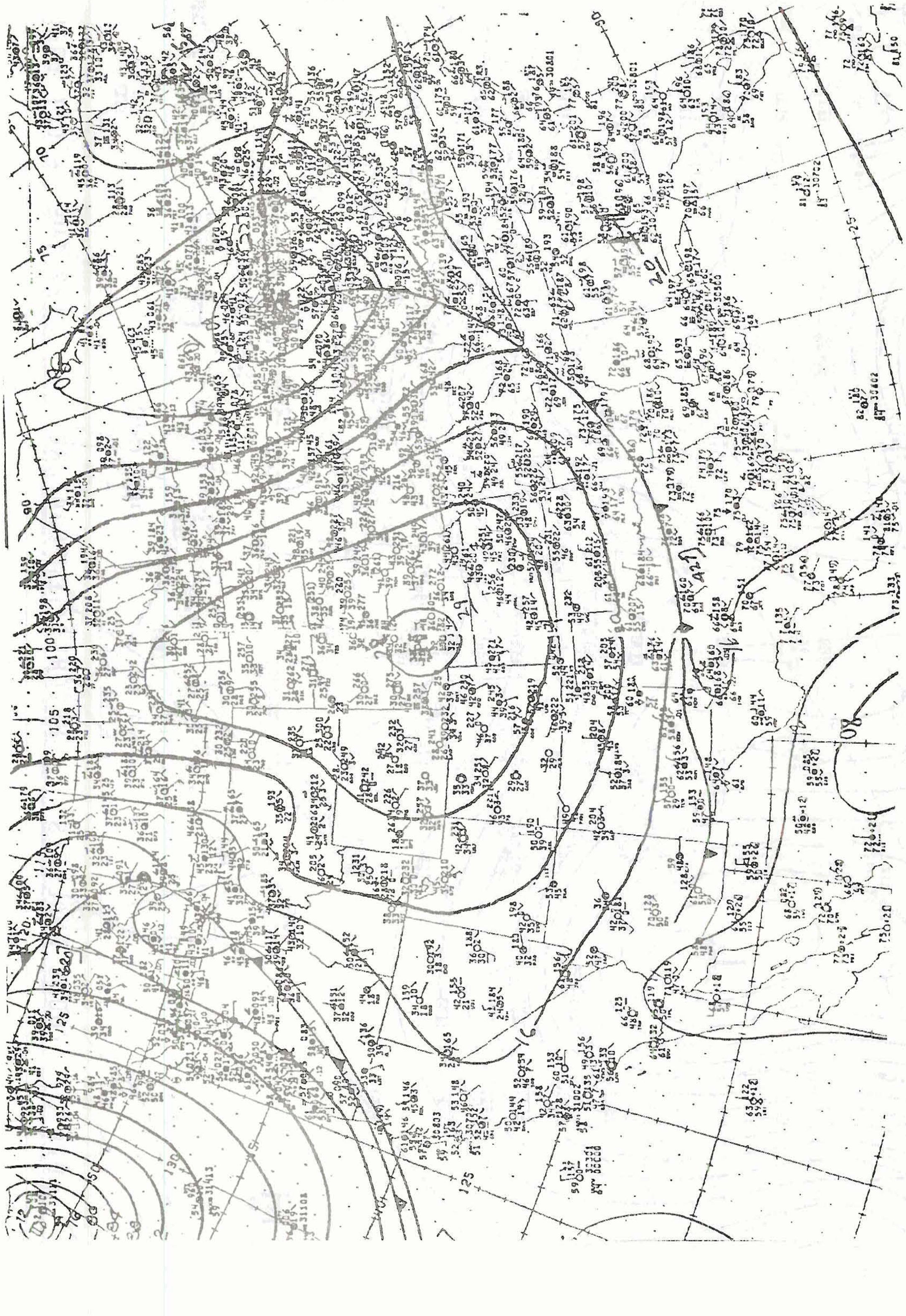


Figure A.1. Surface analysis for October 6, 1981 12Z.

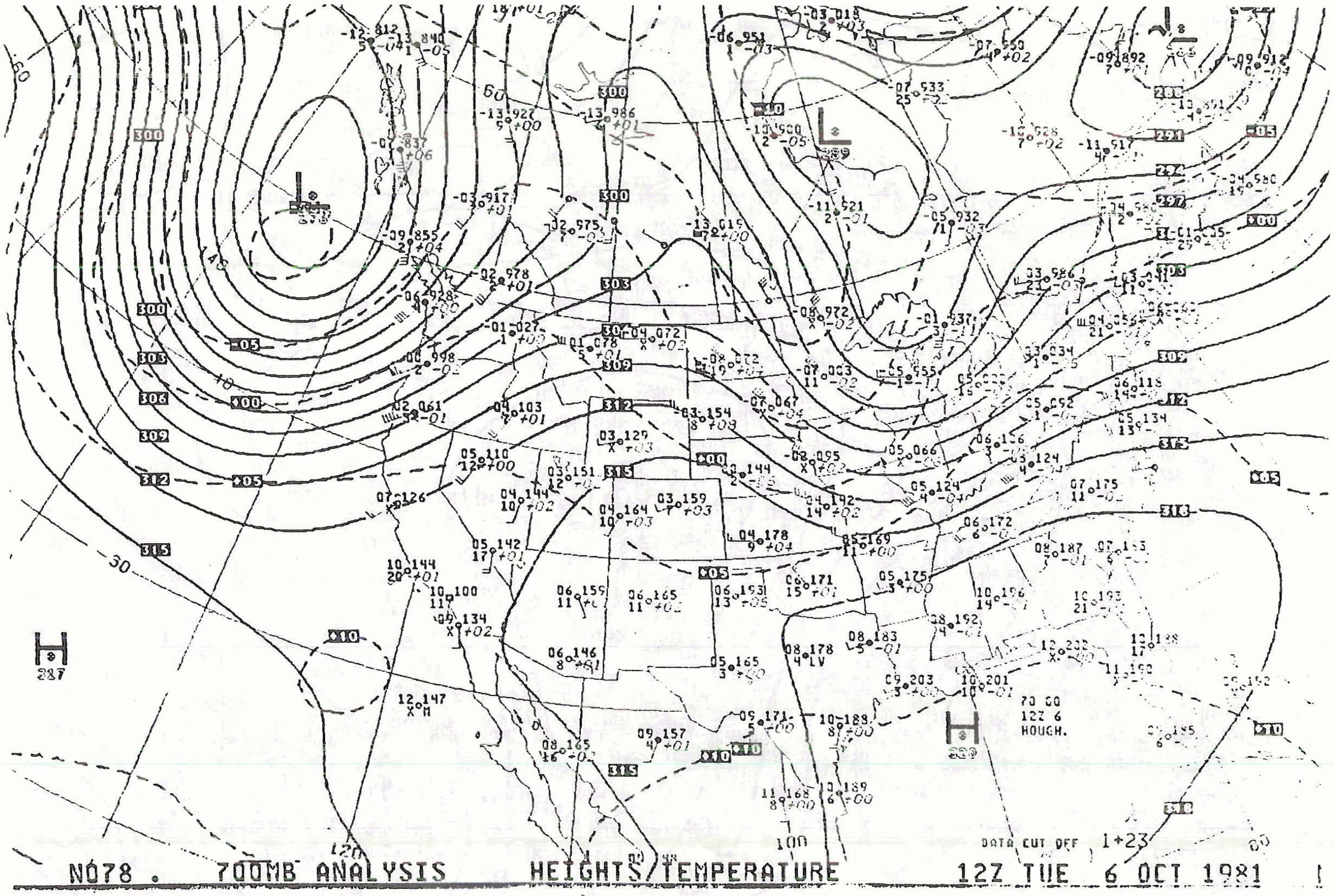


Figure A.2. 700 mb analysis for October 6 12Z.

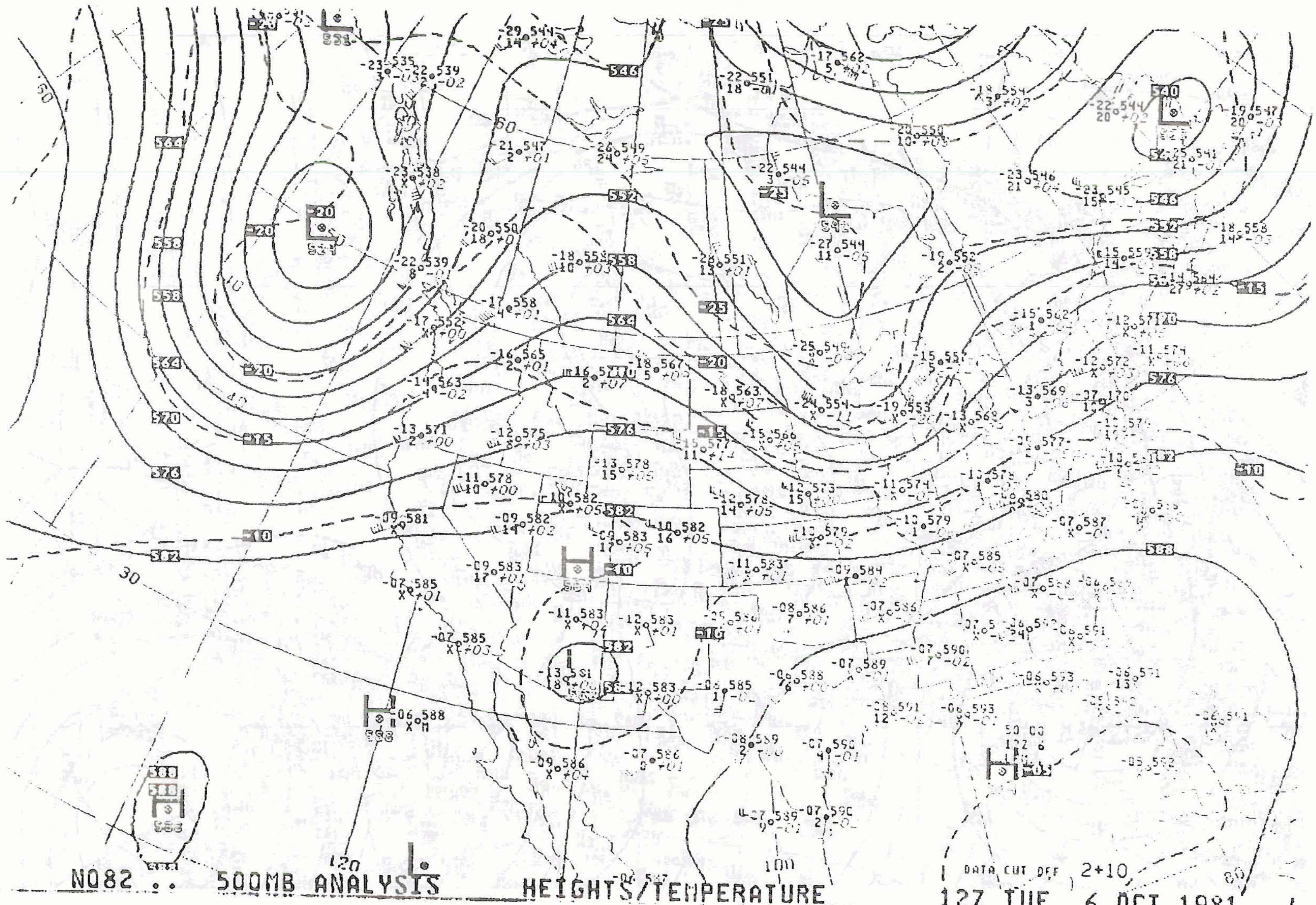


Figure A.3. 500 mb analysis for October 6 12Z.

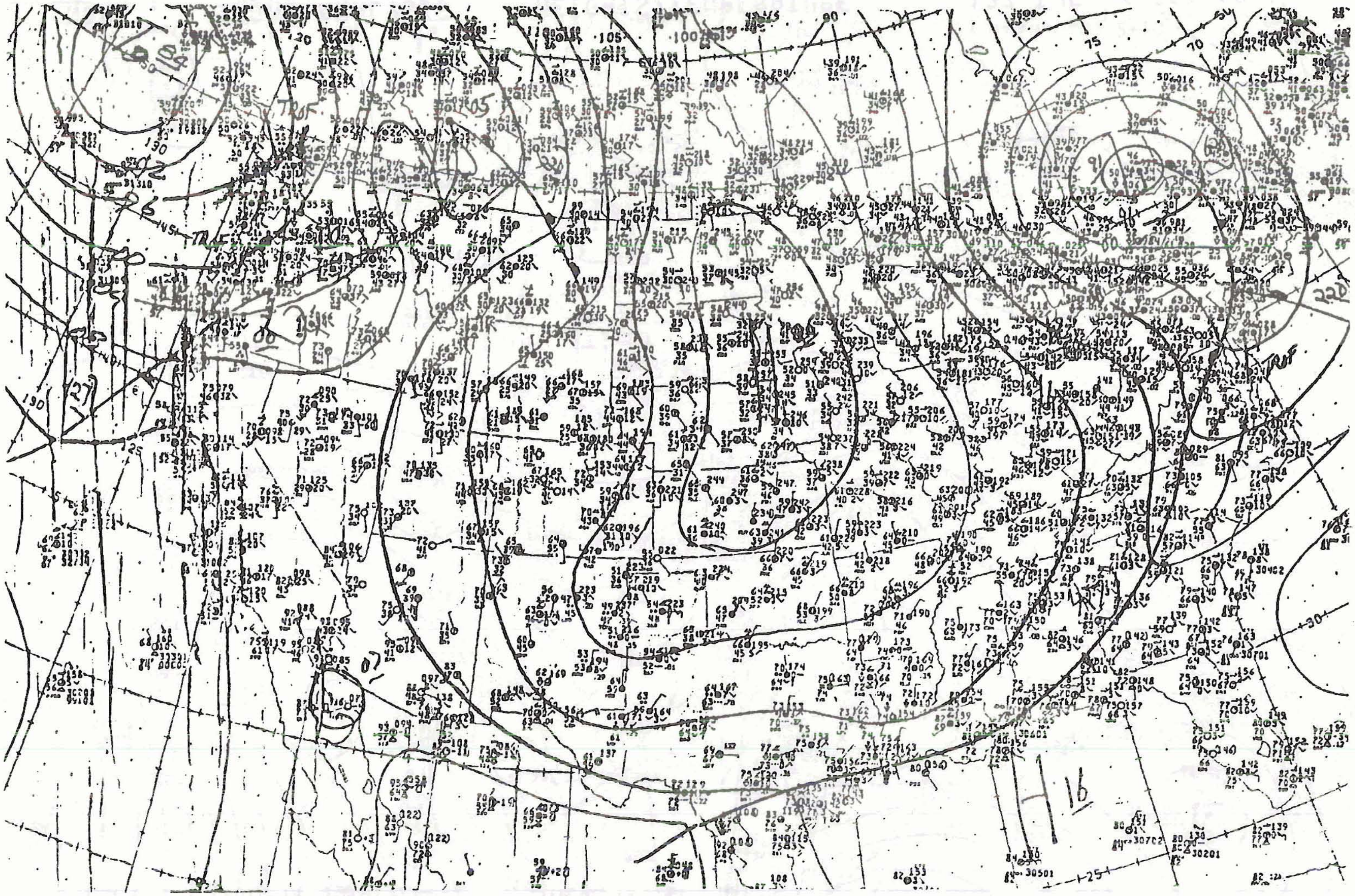


Figure A.4. Surface analysis for October 7, 1981 0Z.

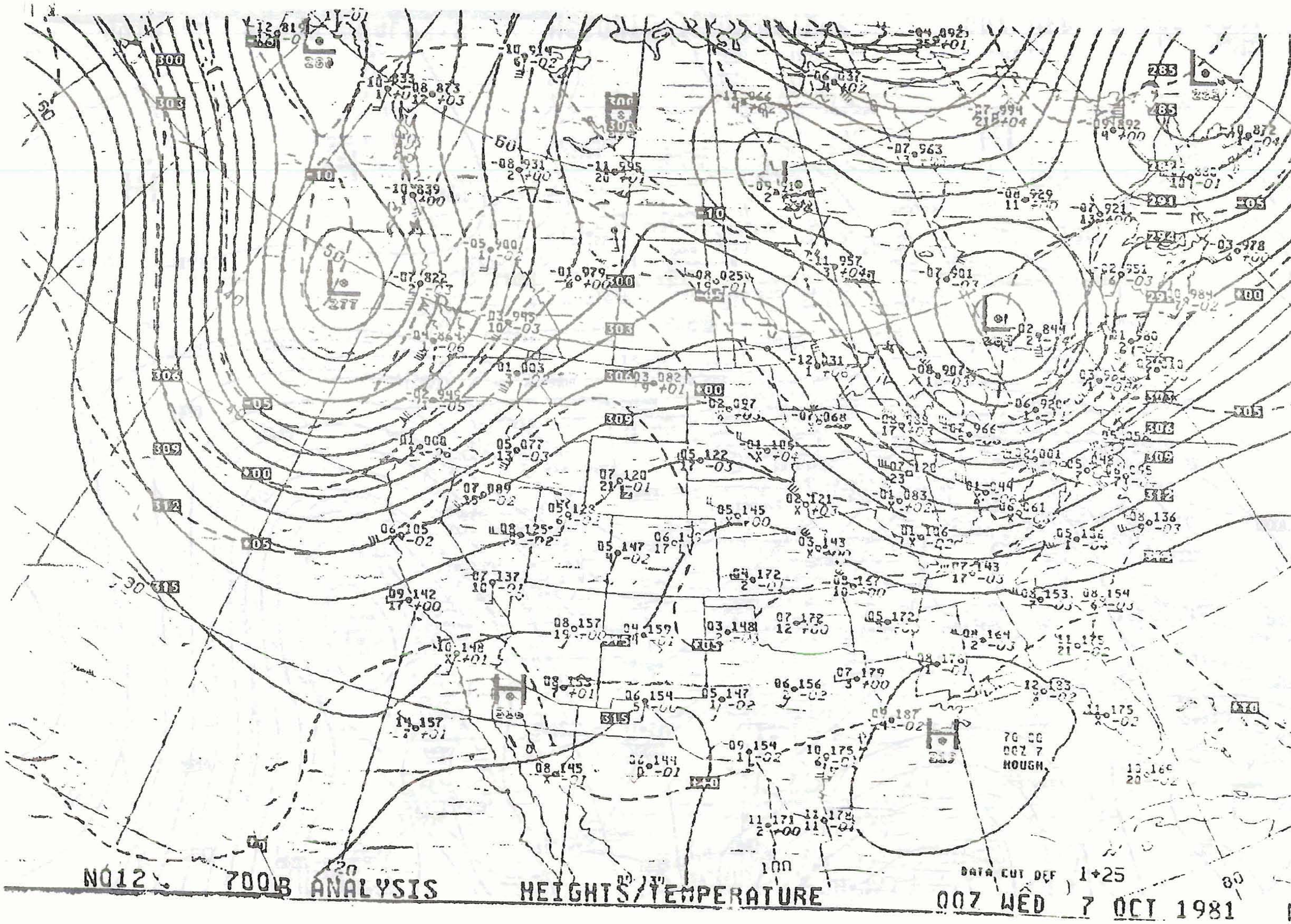


Figure A.5. 700 mb analysis for October 7 0Z.

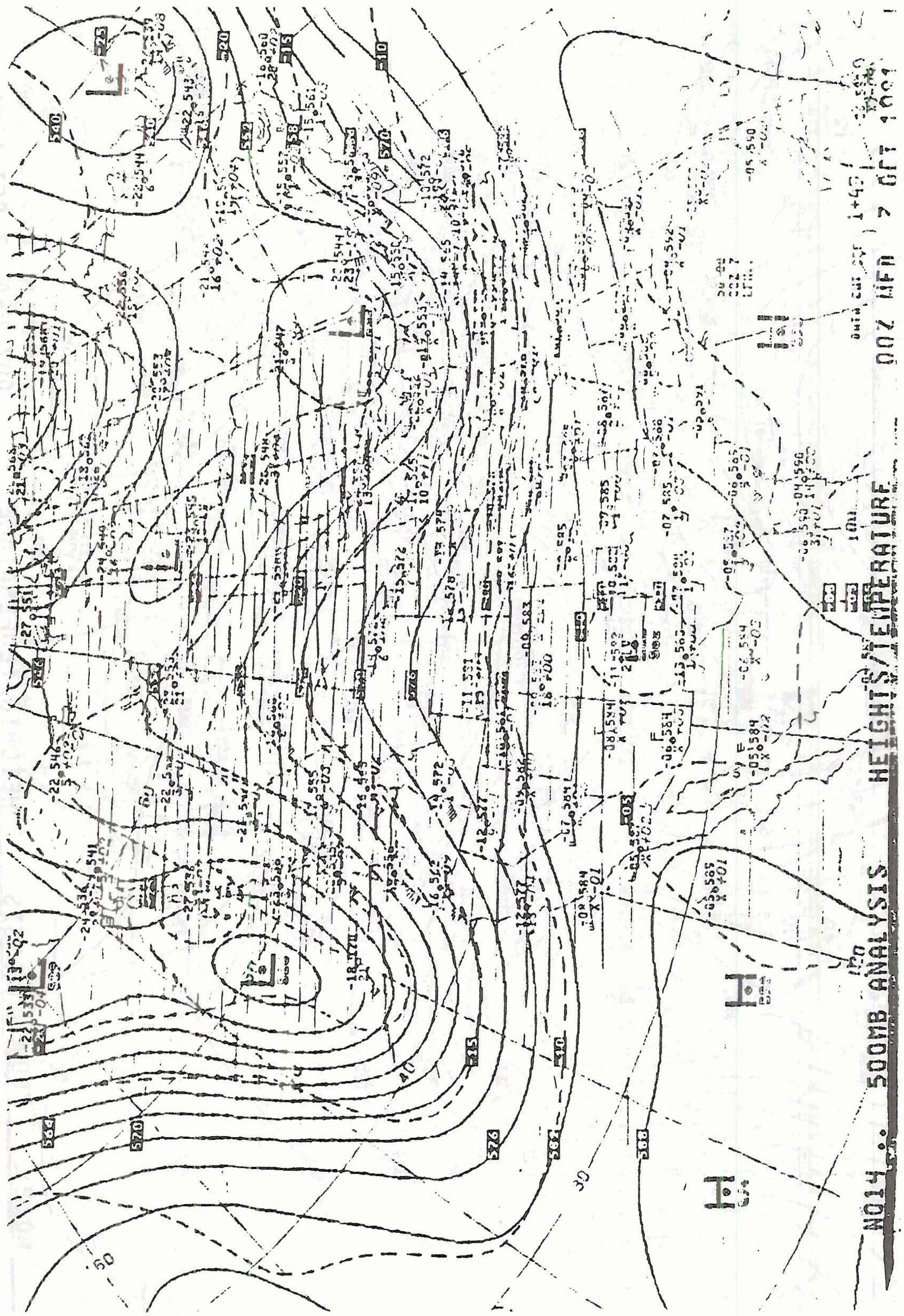
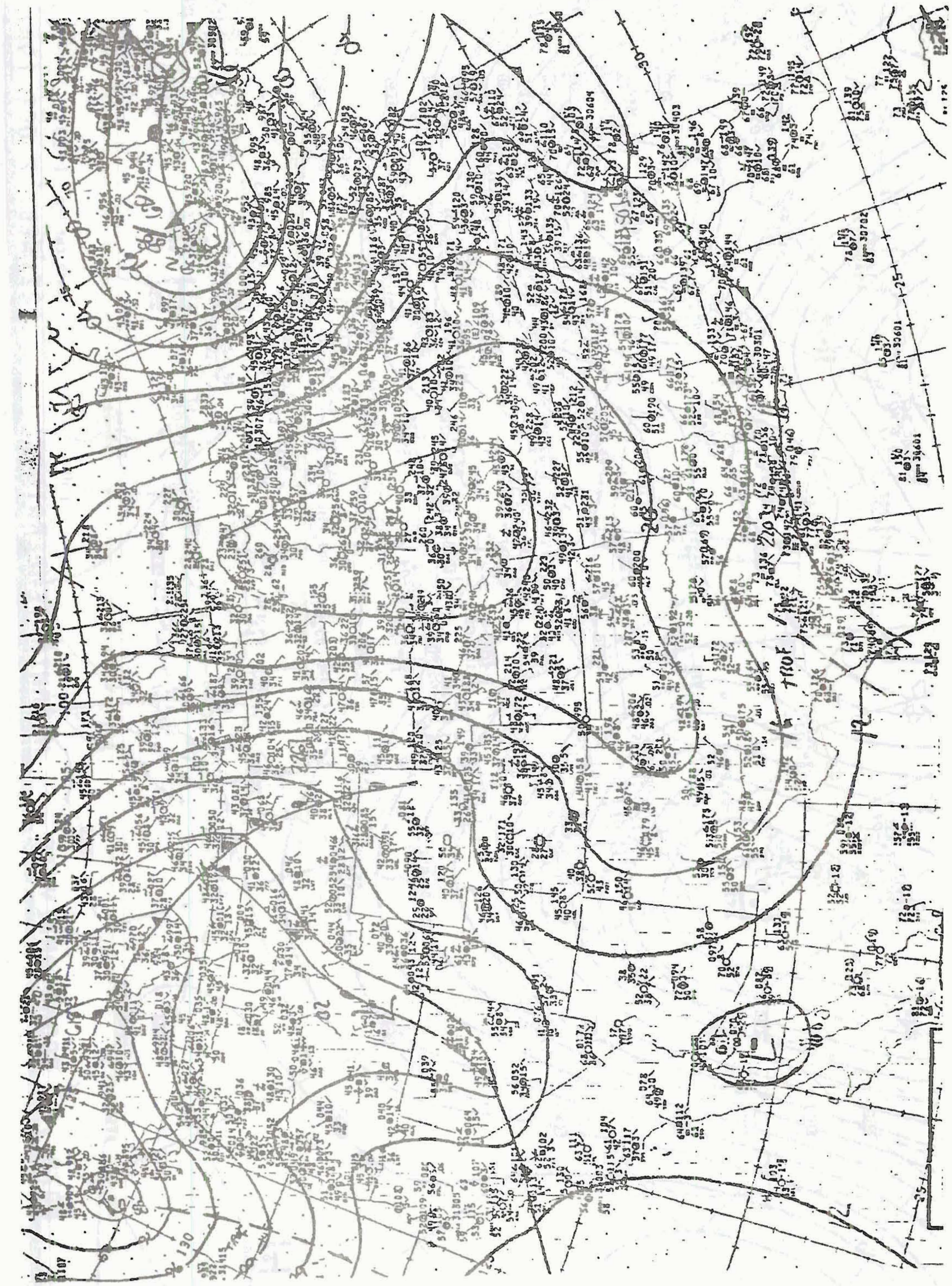


Figure A.6. 500 mb analysis for October 7 0Z.



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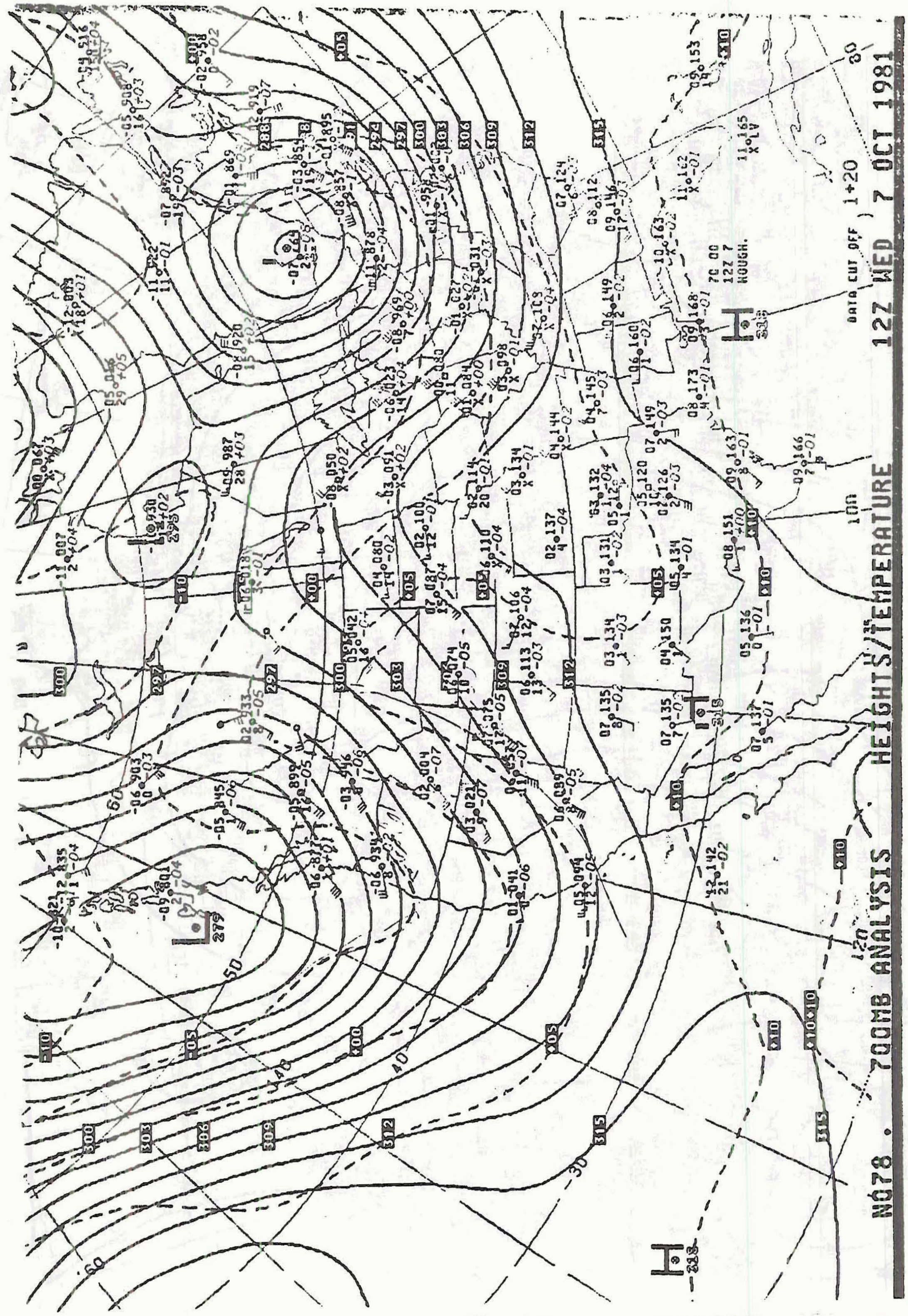


Figure A.8. 700 mb analysis for October 7 12Z.

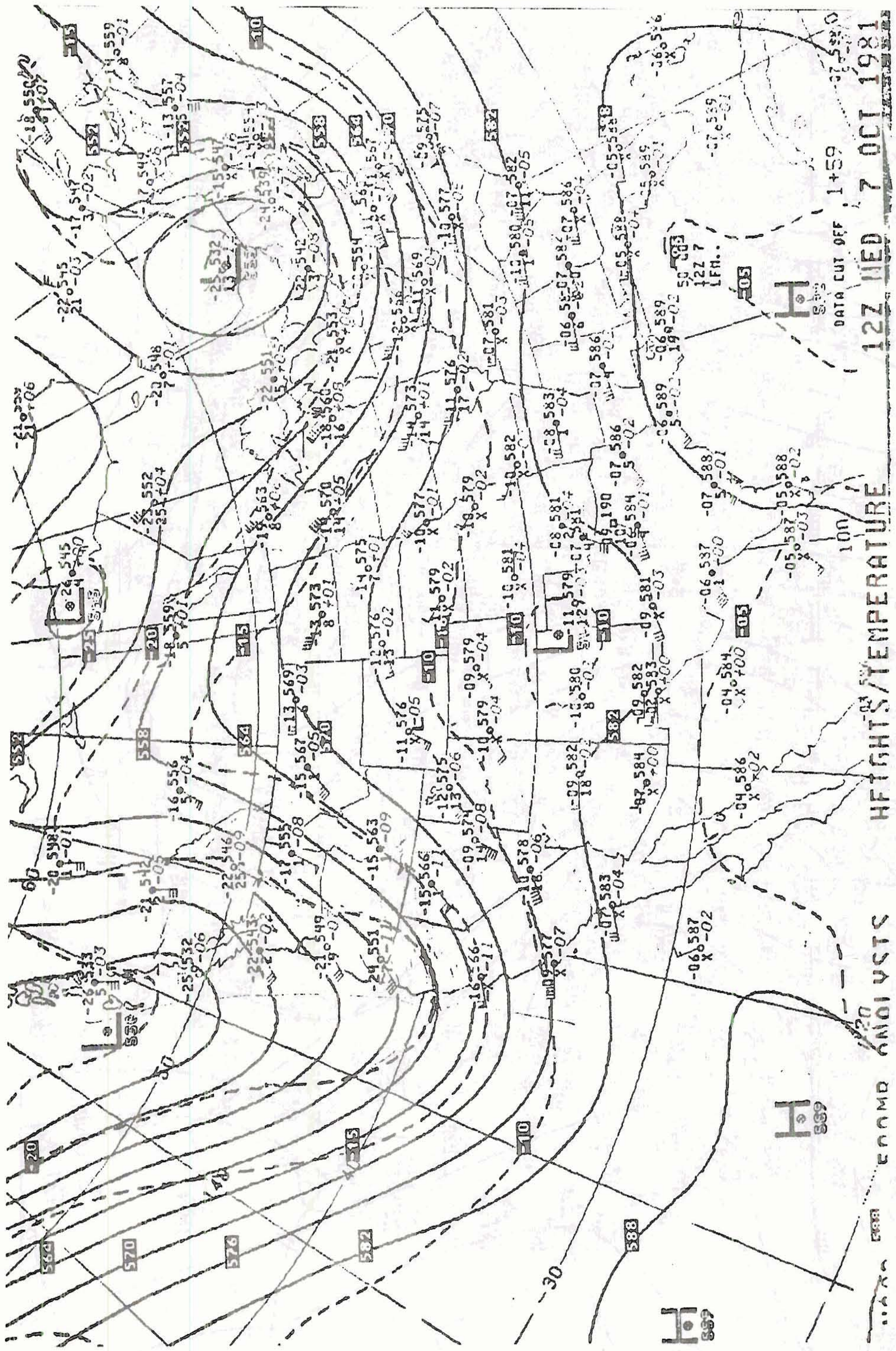


Figure A.9. 500 mb analysis for October 7 12Z.

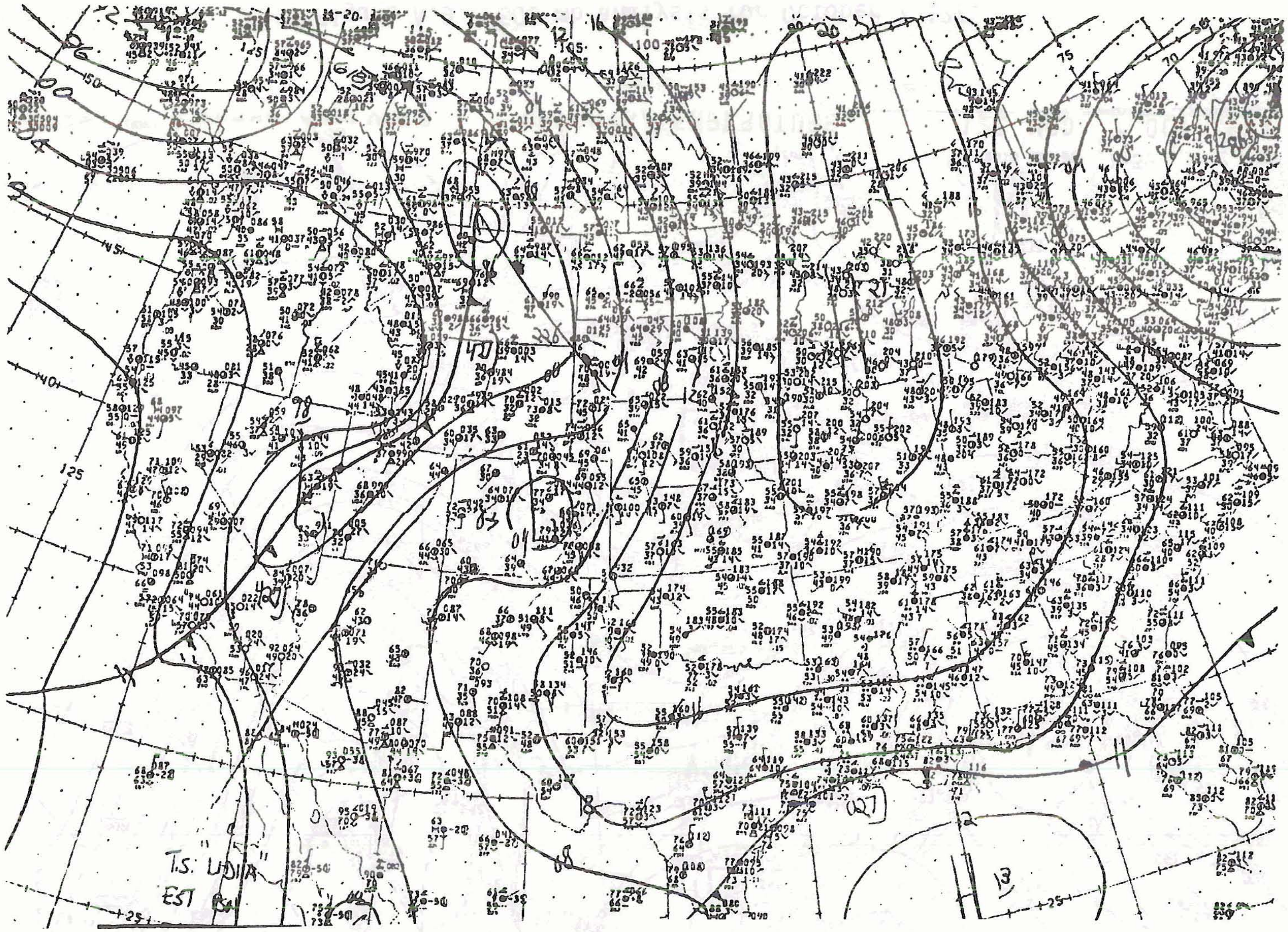


Figure A.10. Surface analysis for October 8, 1981 0Z.

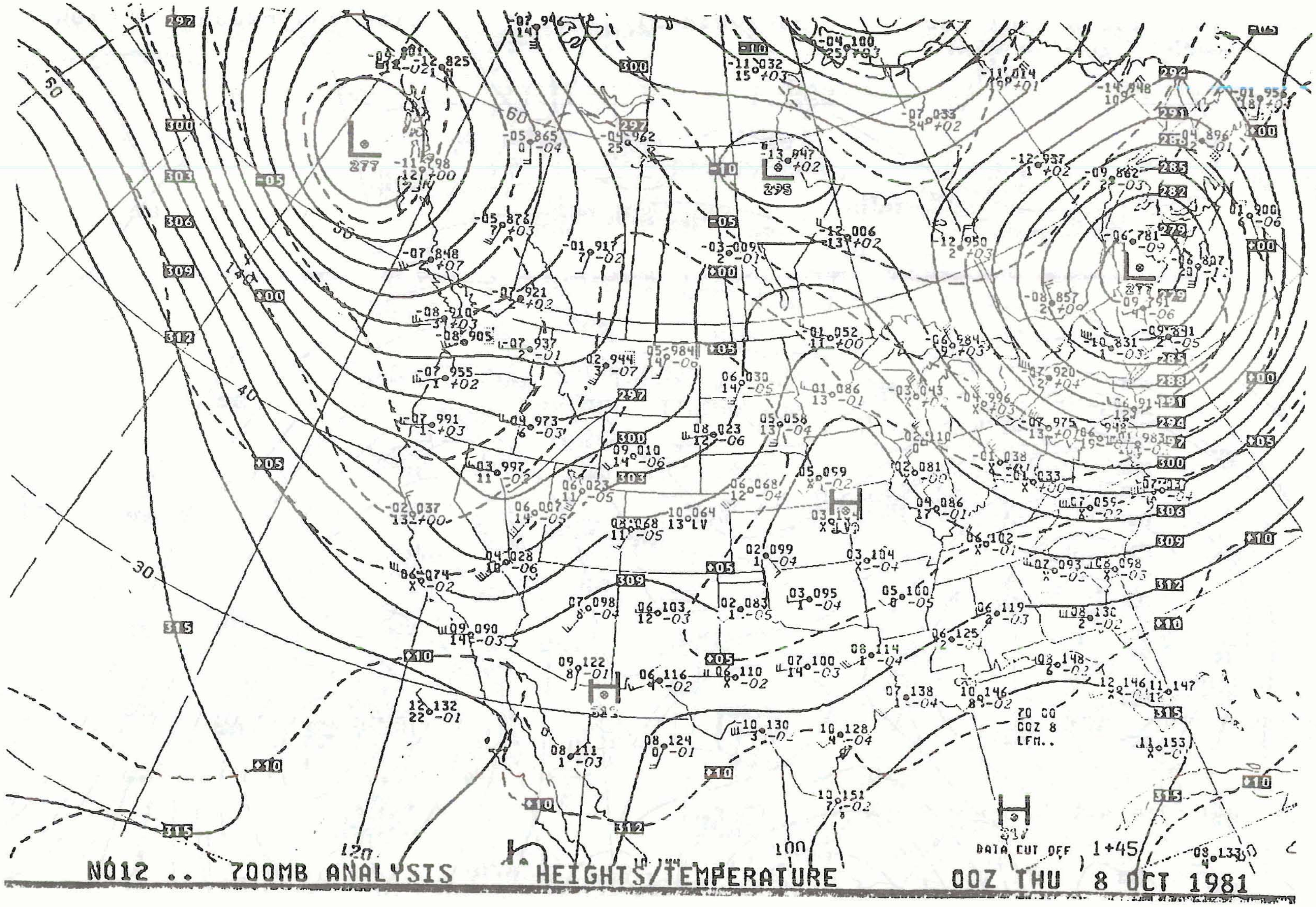


Figure A.11. 700 mb analysis for October 8 OZ.

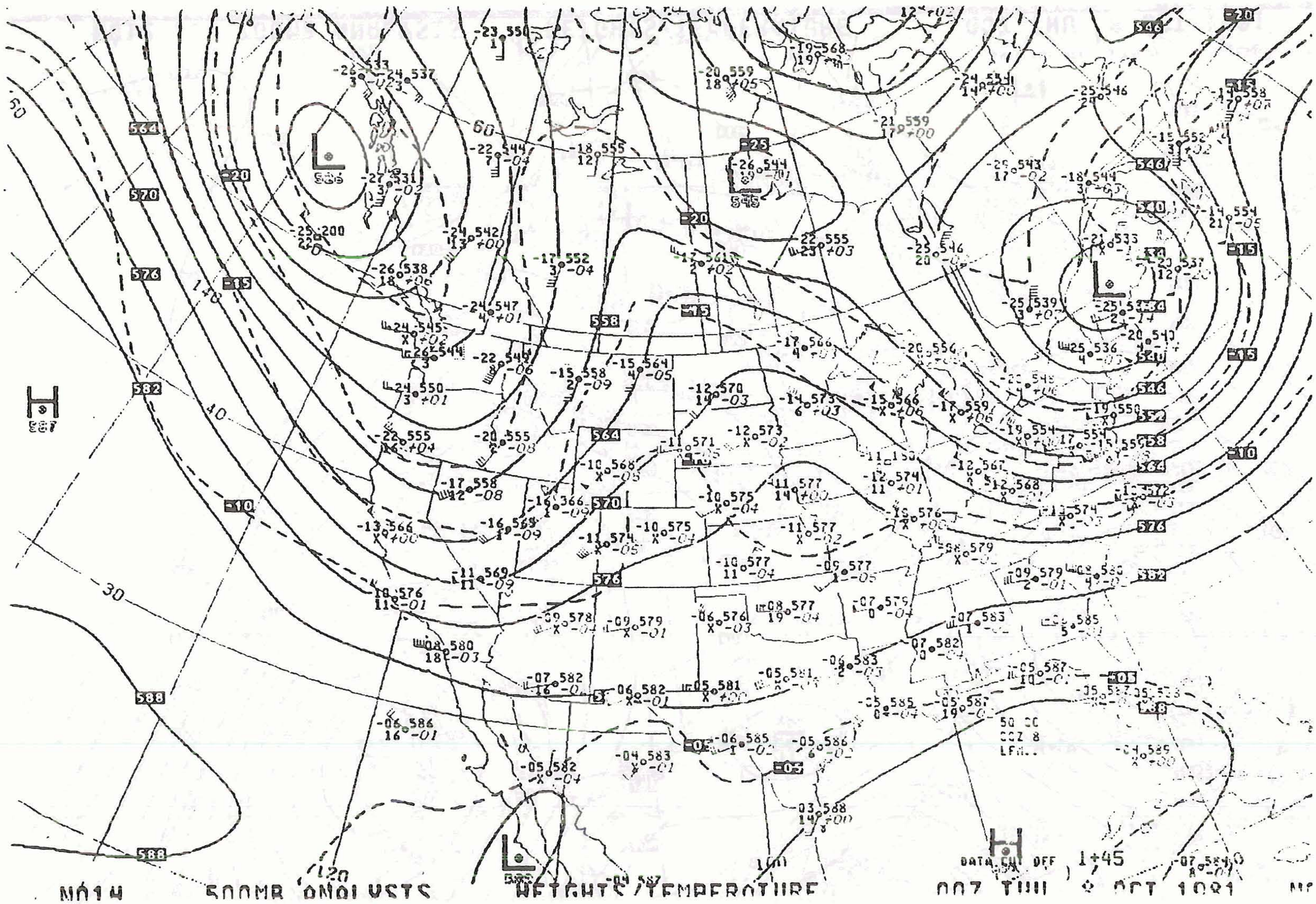


Figure A.12. 500 mb analysis for October 8 0Z.

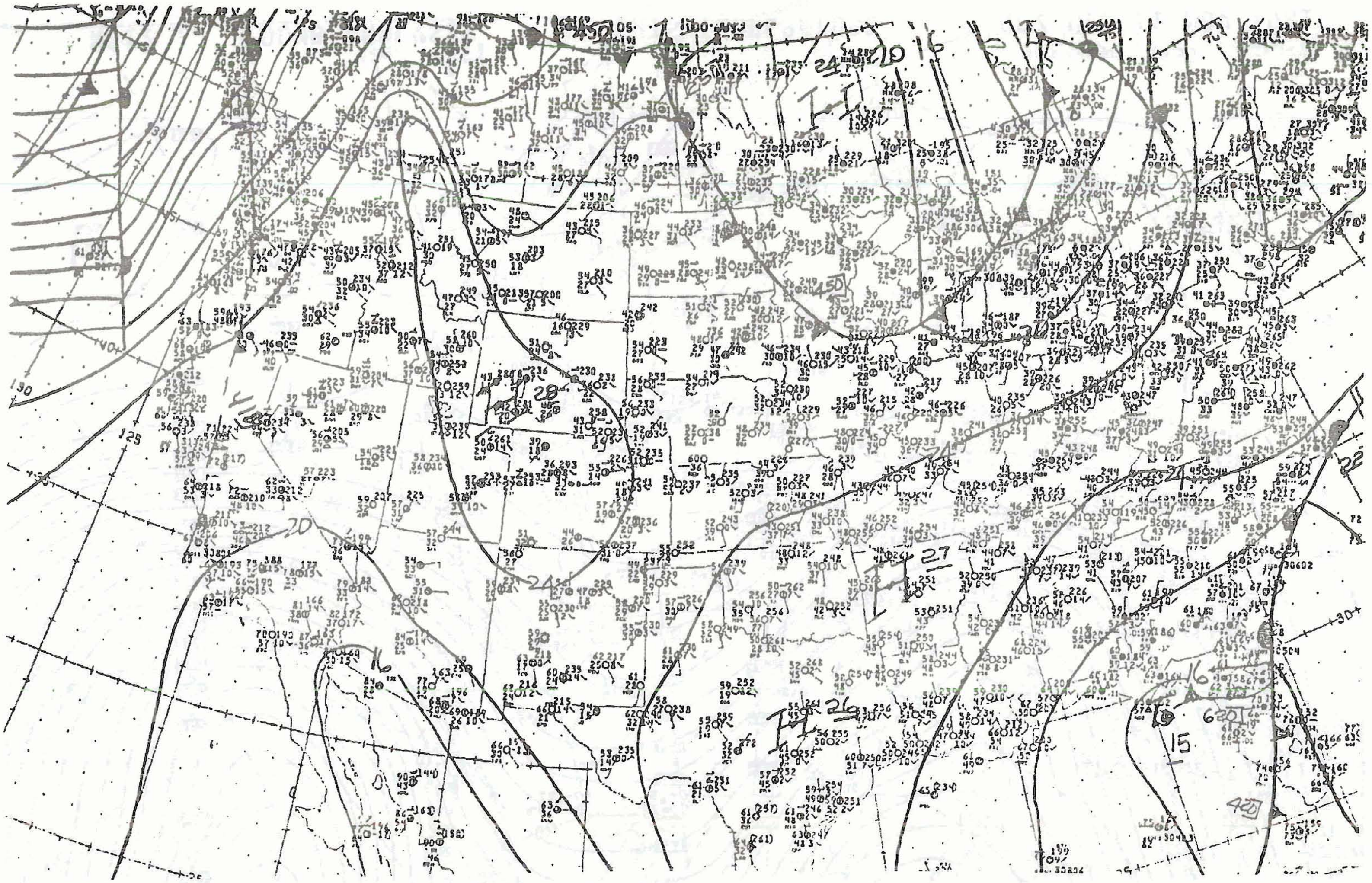


Figure A.13. Surface analysis for November 11, 1981 0Z.

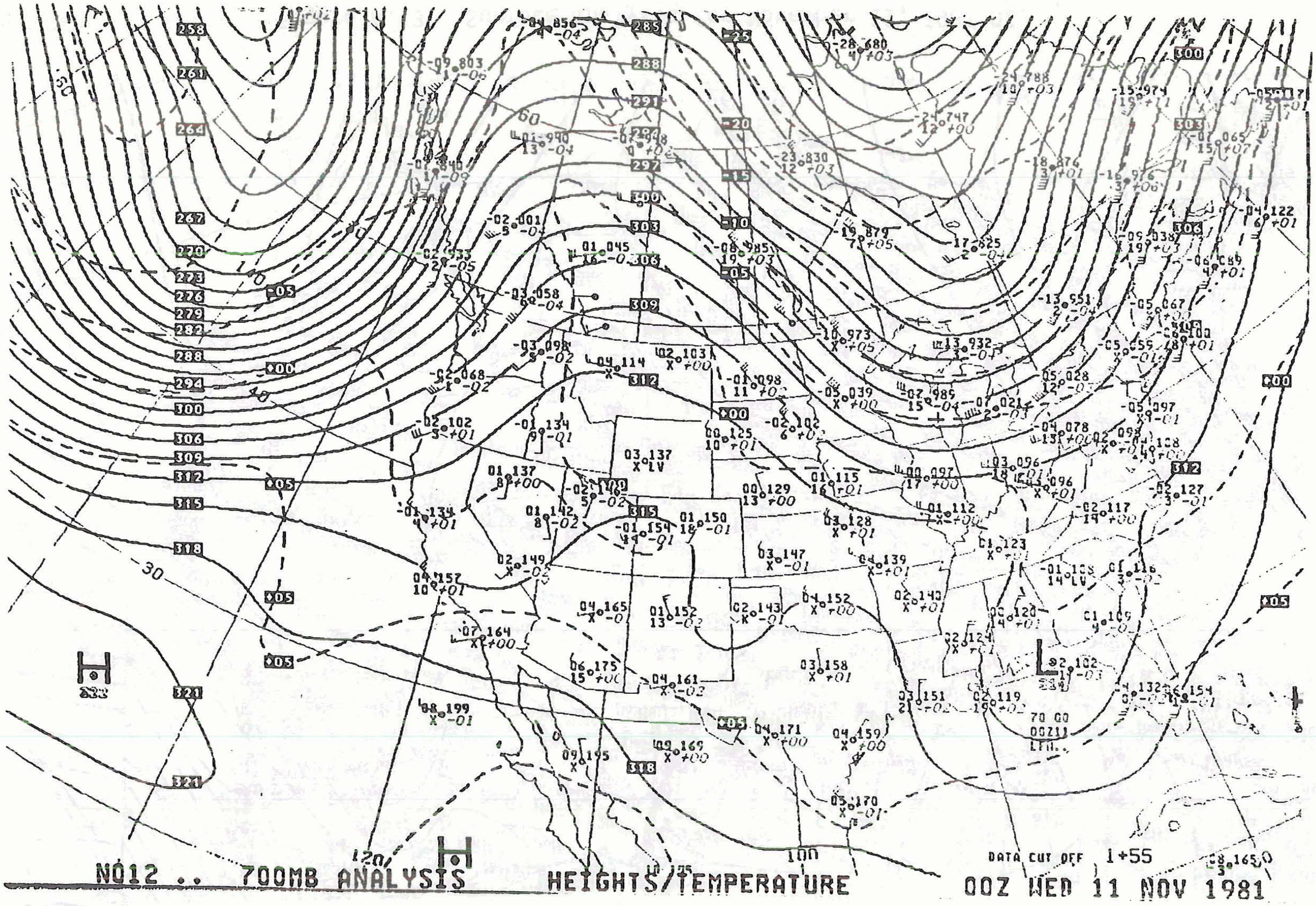
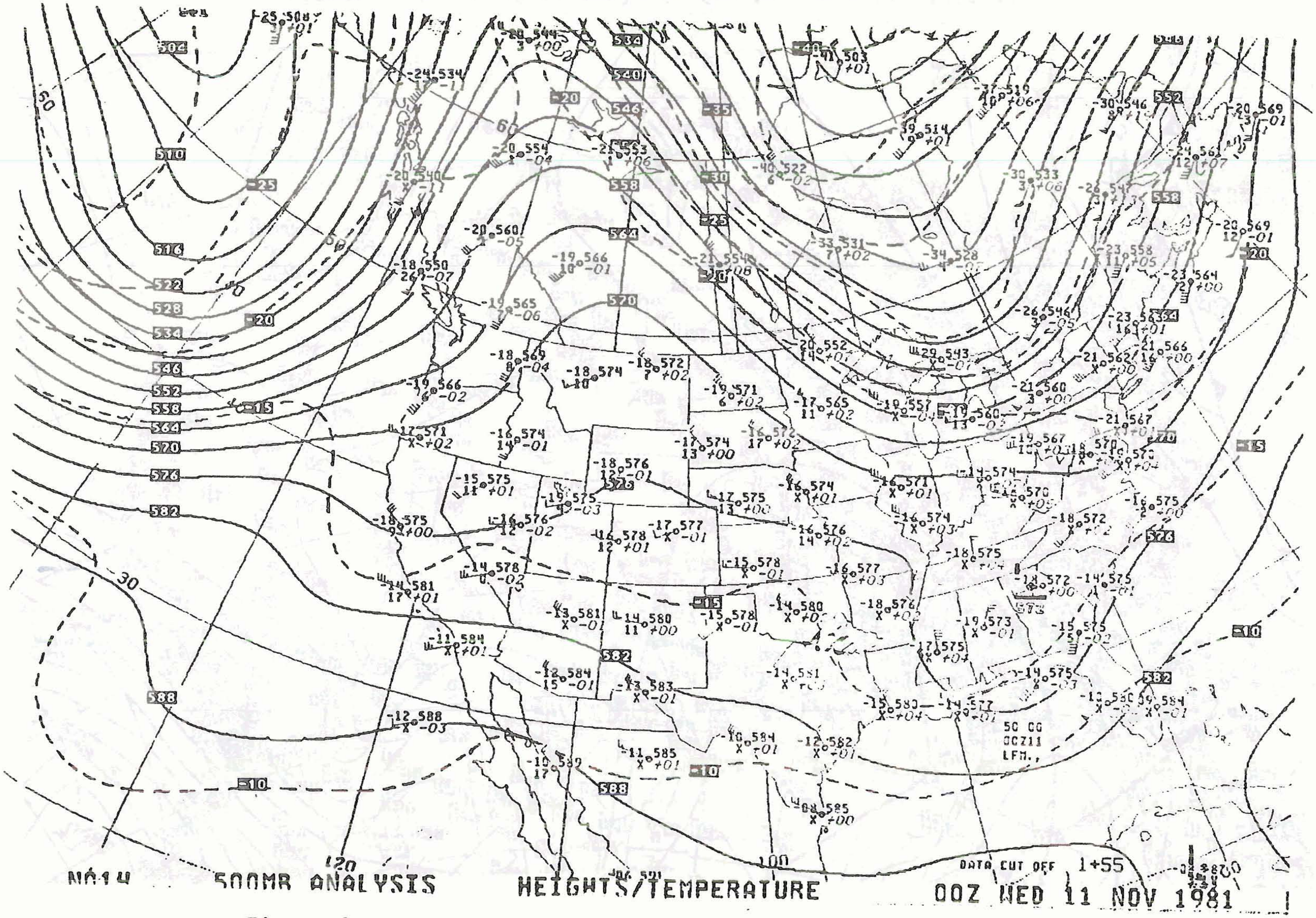


Figure A.14. 700 mb analysis for November 11 0Z.



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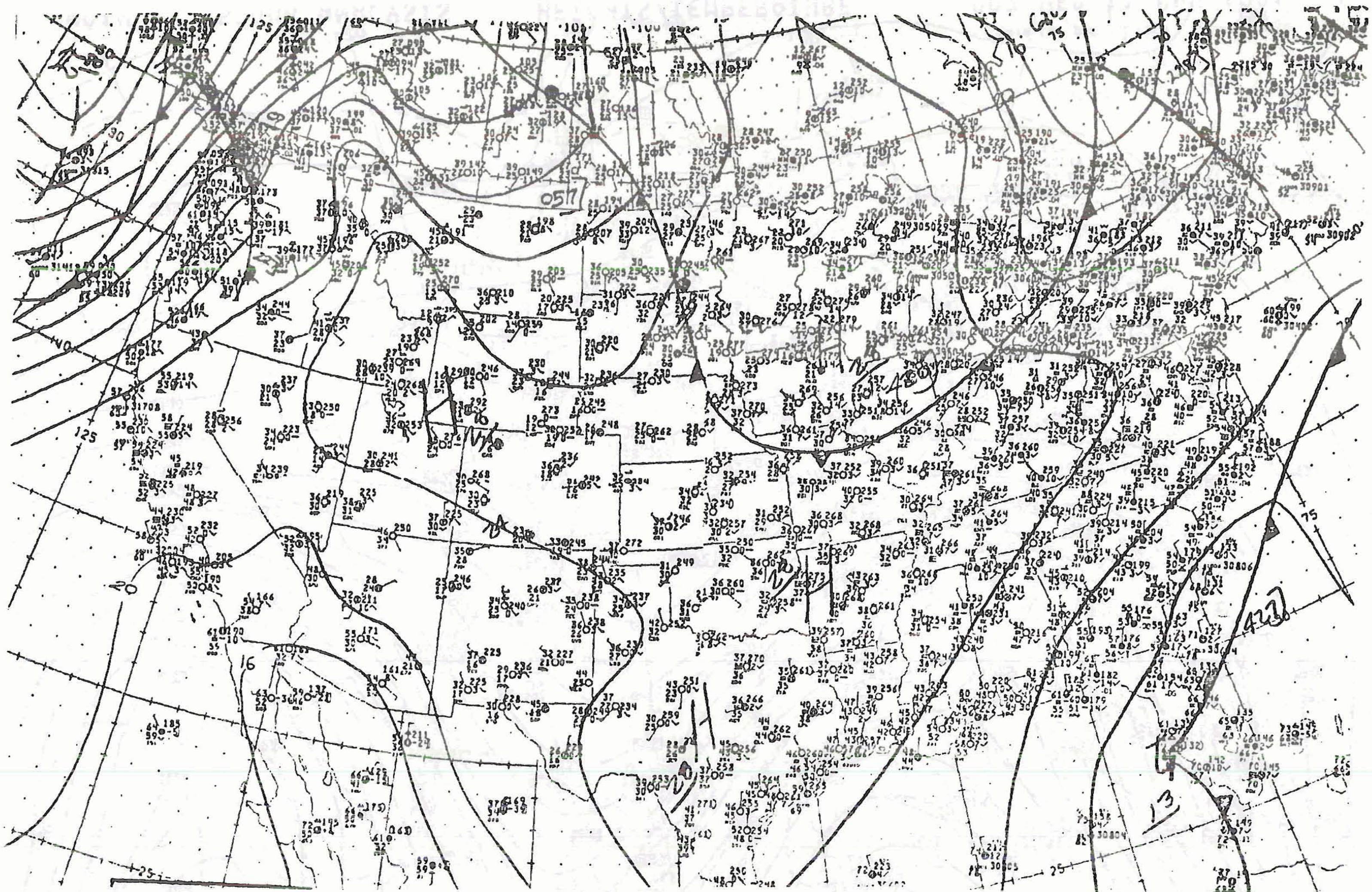

Figure A.16. Surface analysis for November 11, 1981 12Z.

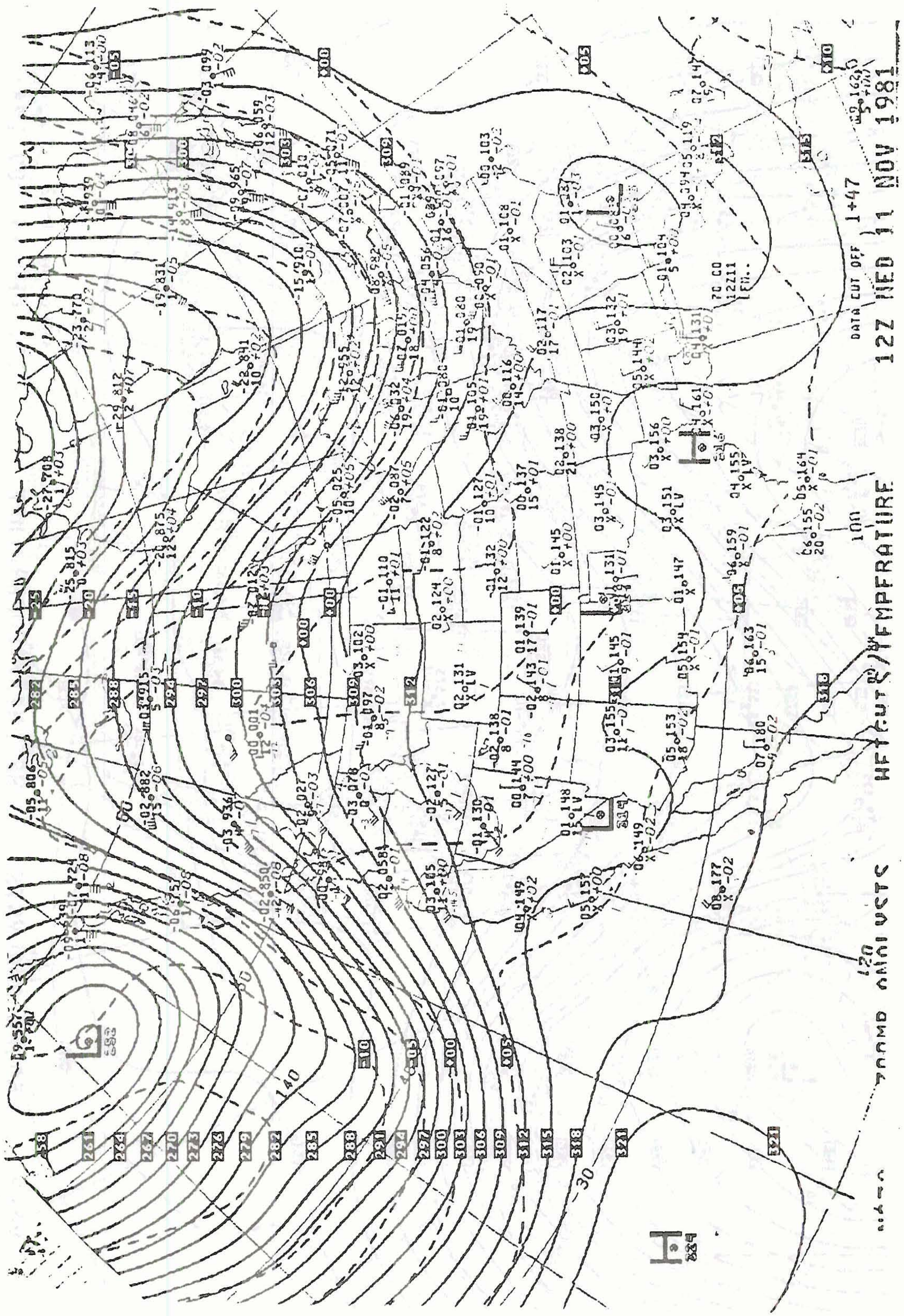

Figure A.17. 700 mb analysis for November 11 12Z.

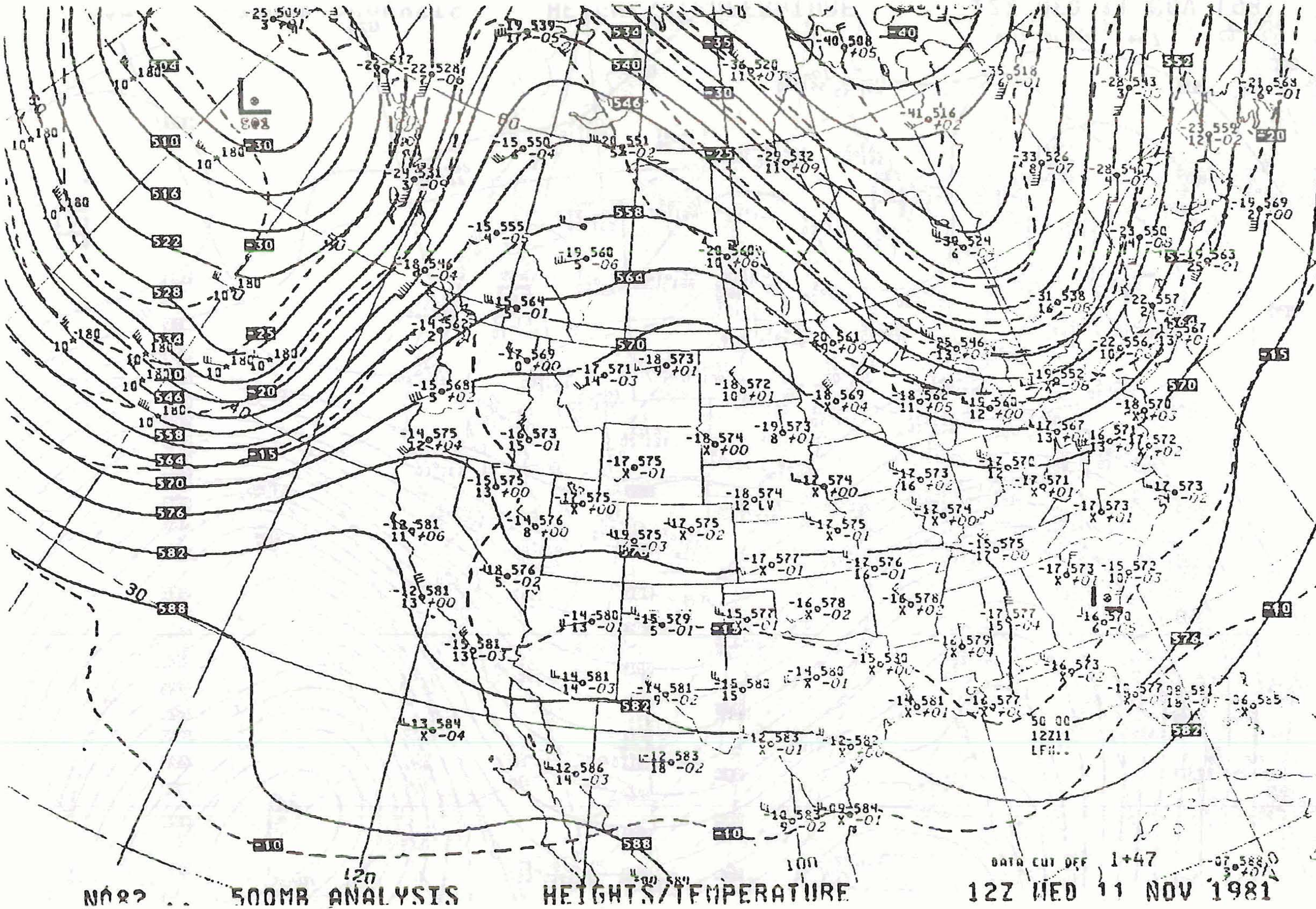

Figure A.18. 500 mb analysis for November 11 12Z.

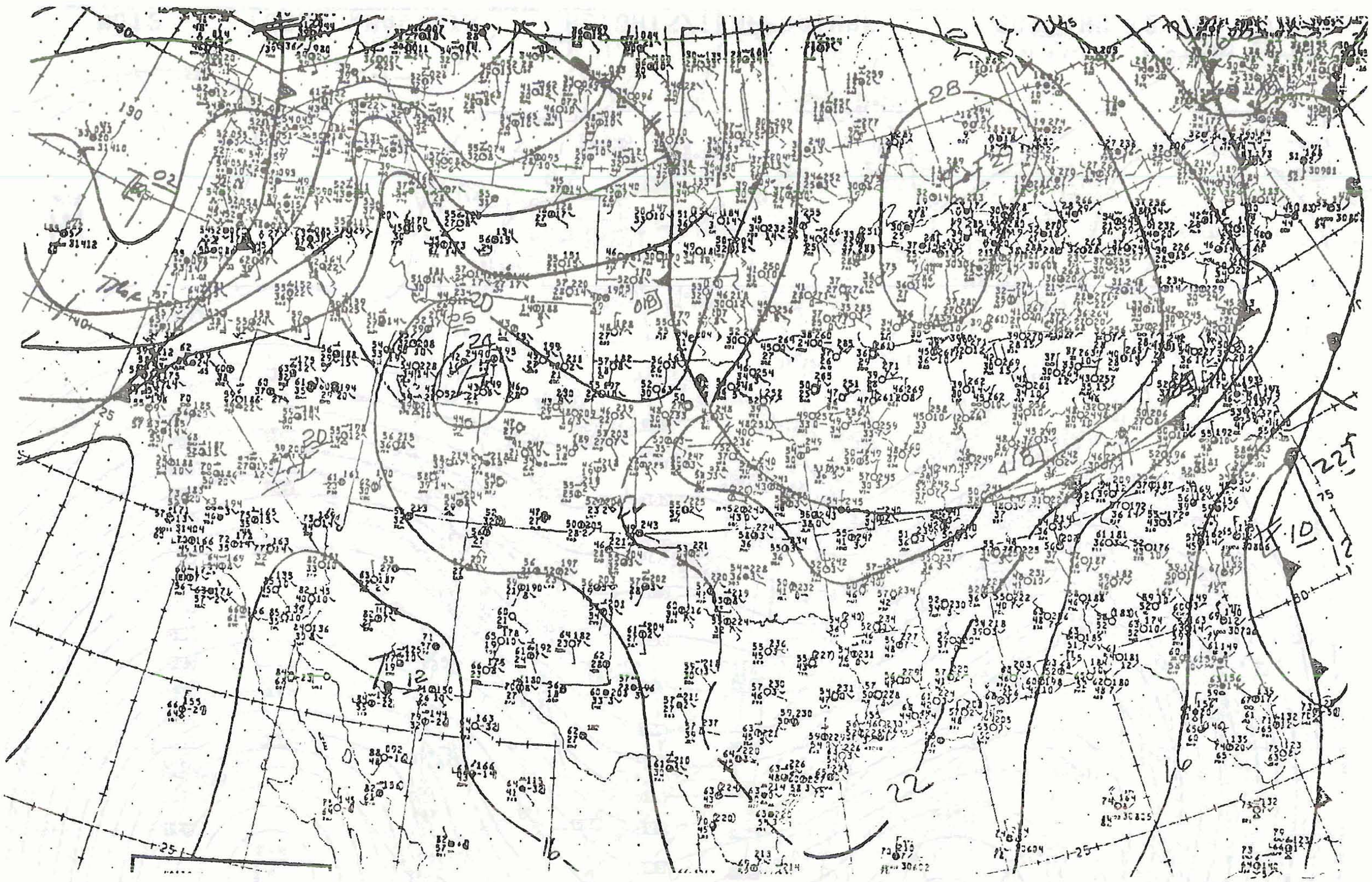

Figure A.19. Surface analysis for November 12, 1982 0Z.

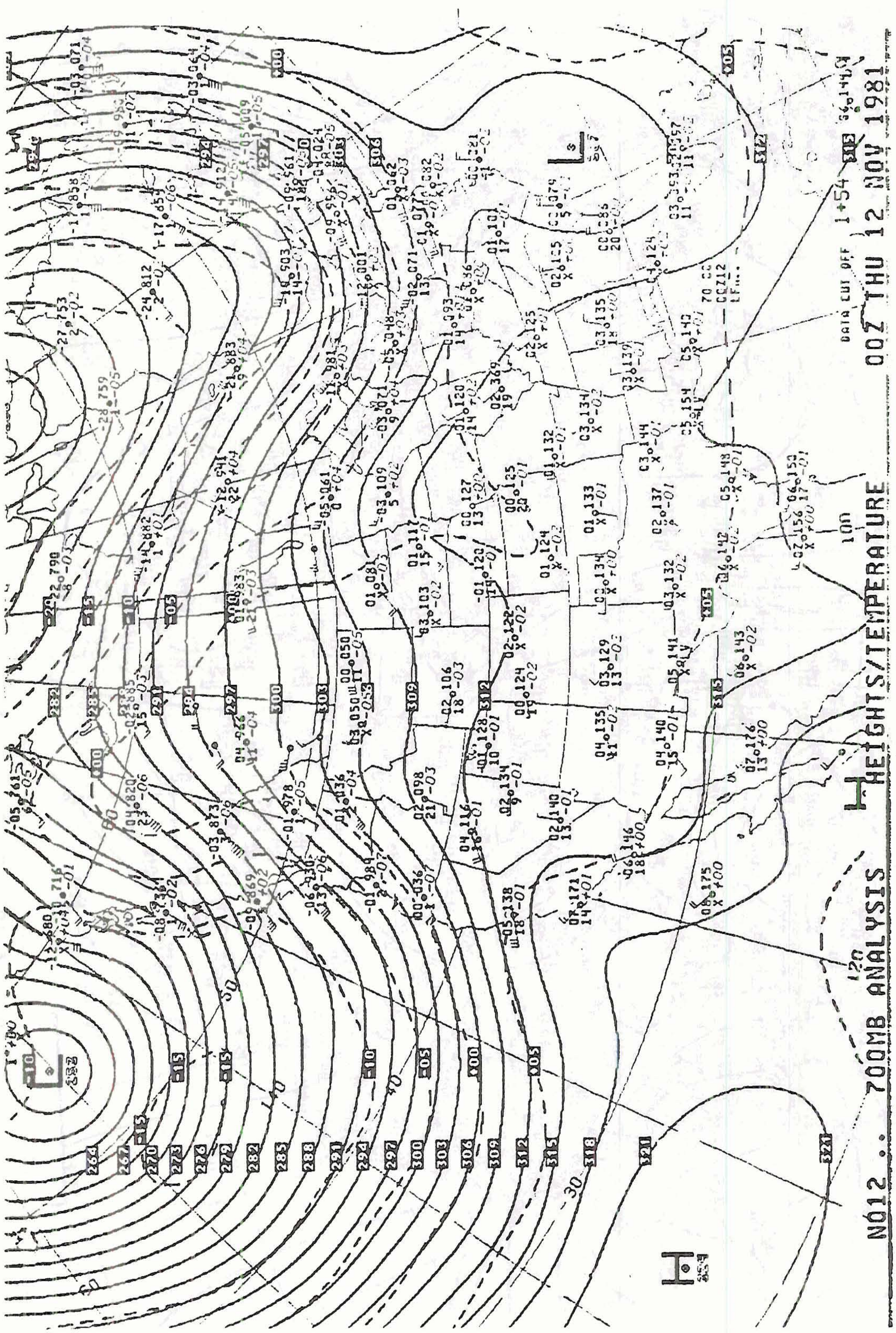

Figure A.20. 700 mb analysis for November 12 0Z.

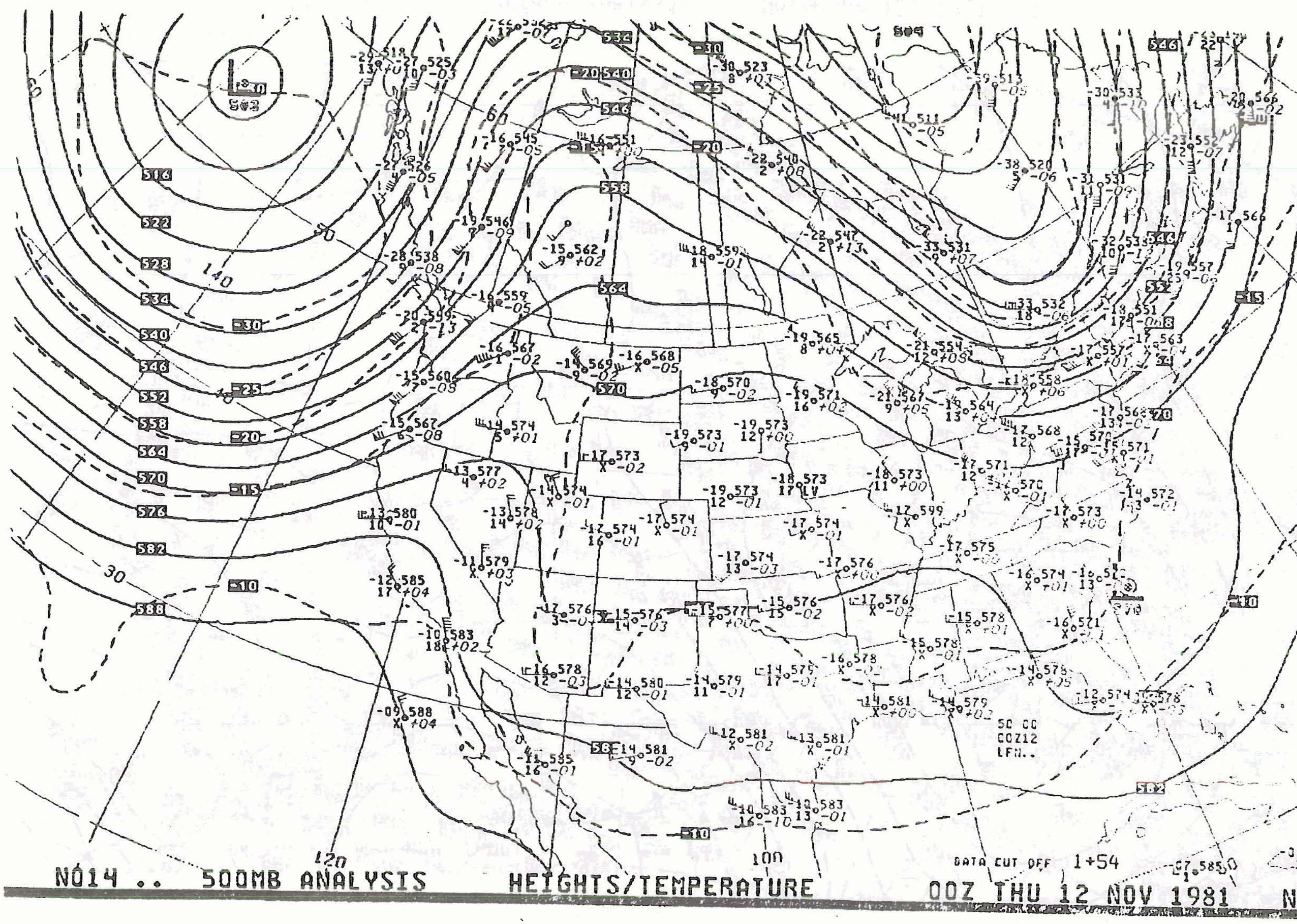

Figure A.21. 500 mb analysis for November 12 OZ.

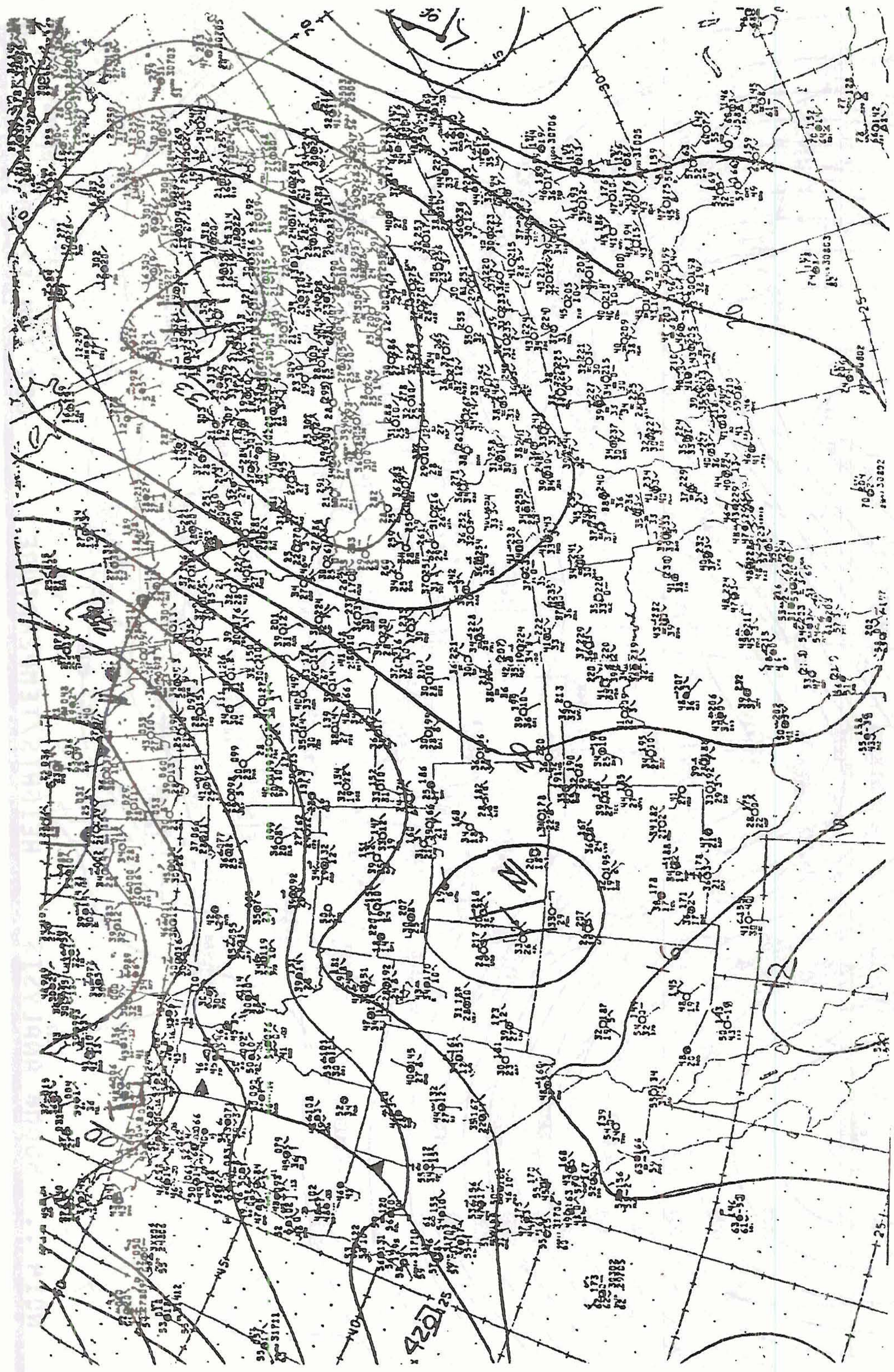

Figure A.22. Surface analysis for November 12, 1981 12Z.

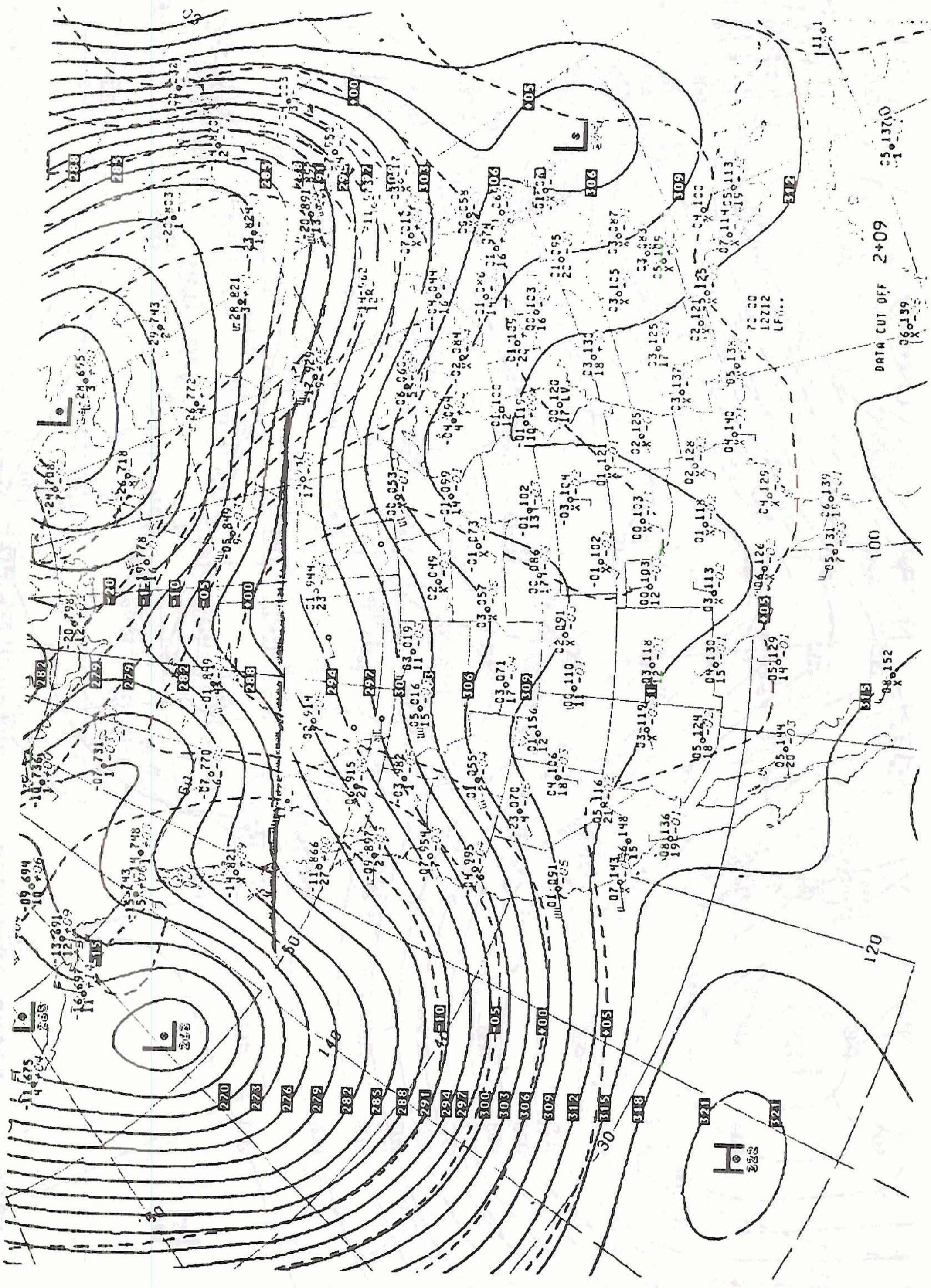

Figure A.23. 700 mb analysis for November 12 12Z.

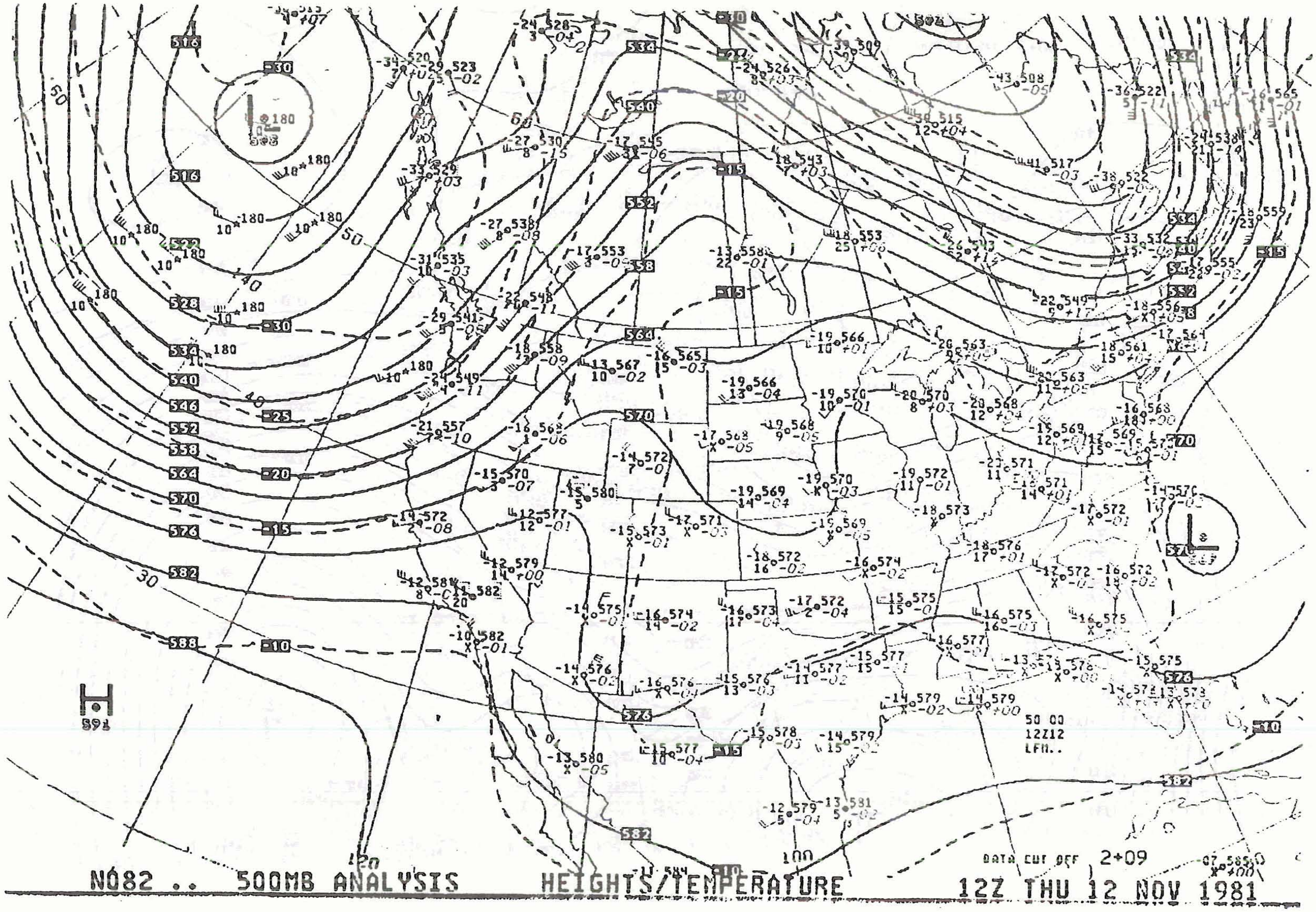

Figure A.24. 500 mb analysis for November 12 12Z.

APPENDIX B

Denver Soundings

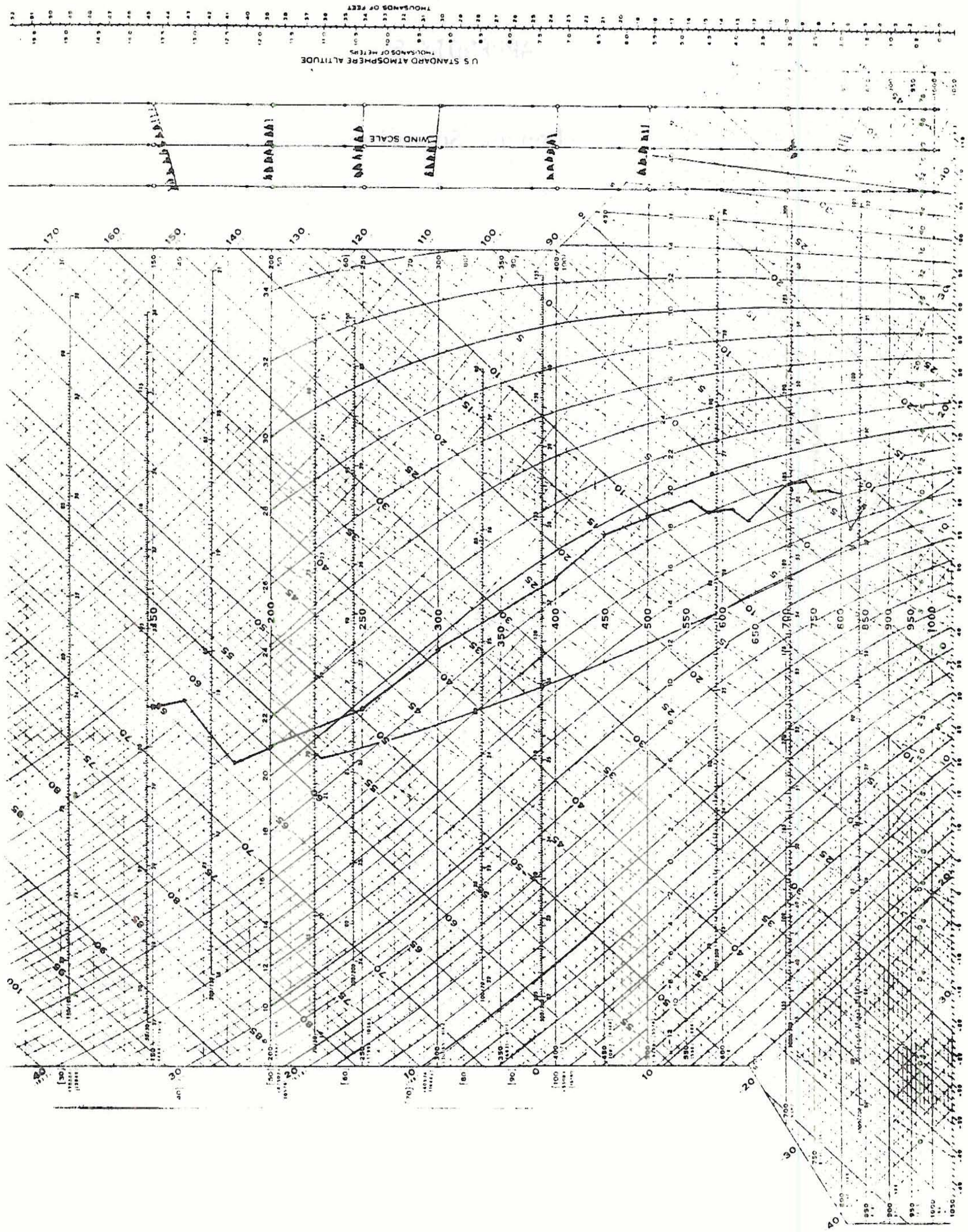

Figure B.1. Denver sounding for October 6 12Z.

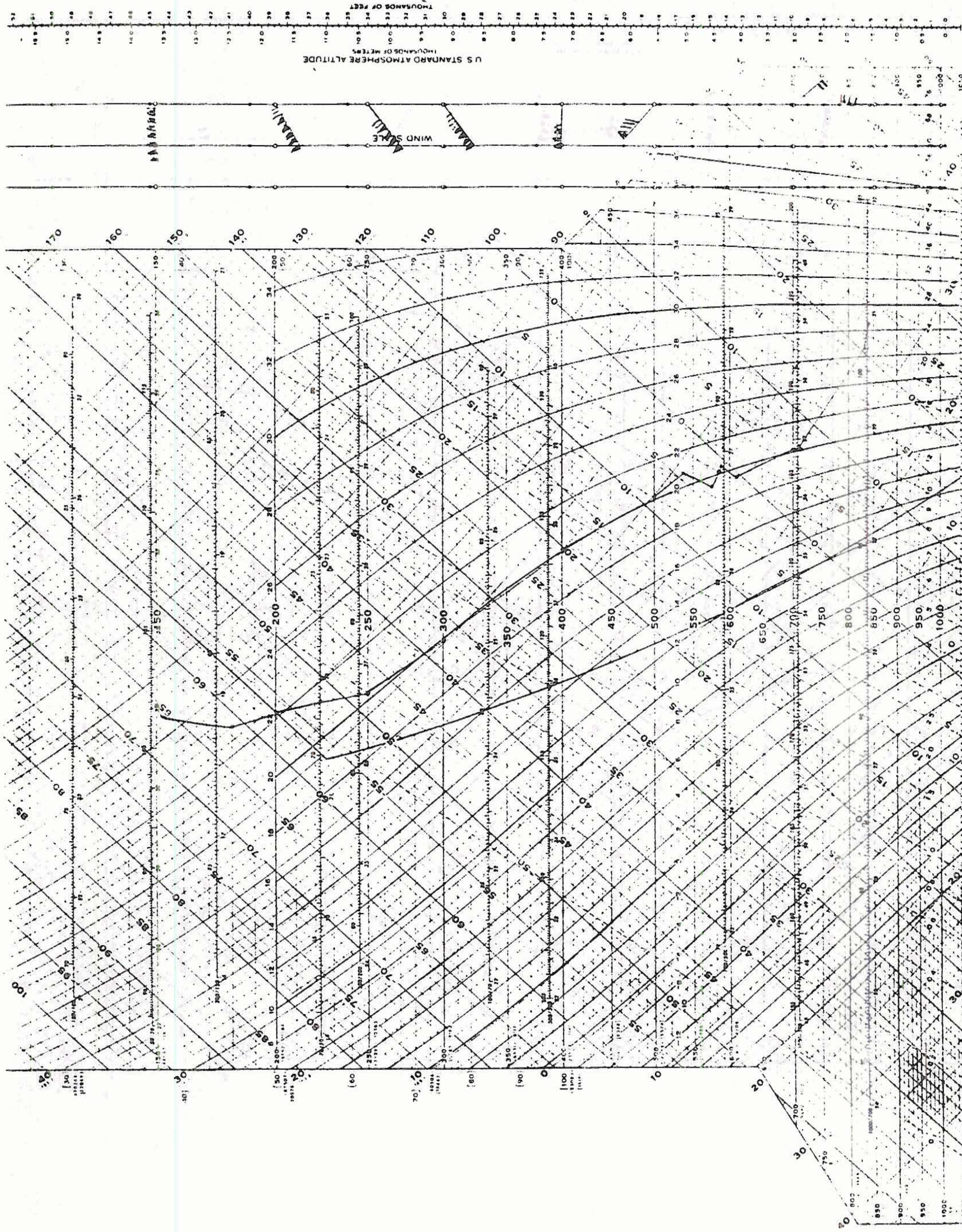

Figure B.2. Denver sounding for October 7 0Z.

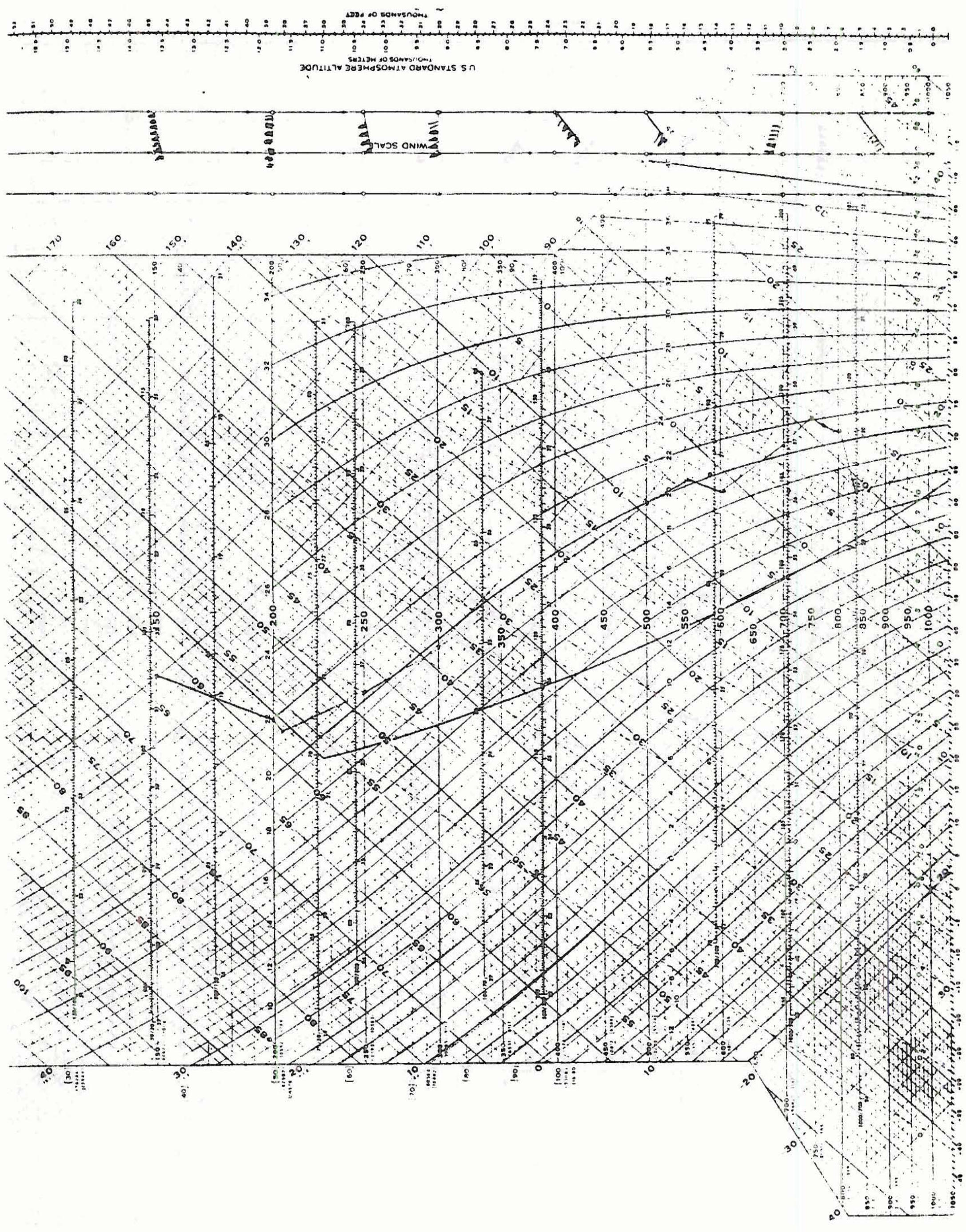

Figure B.3. Denver sounding for October 7 12Z.

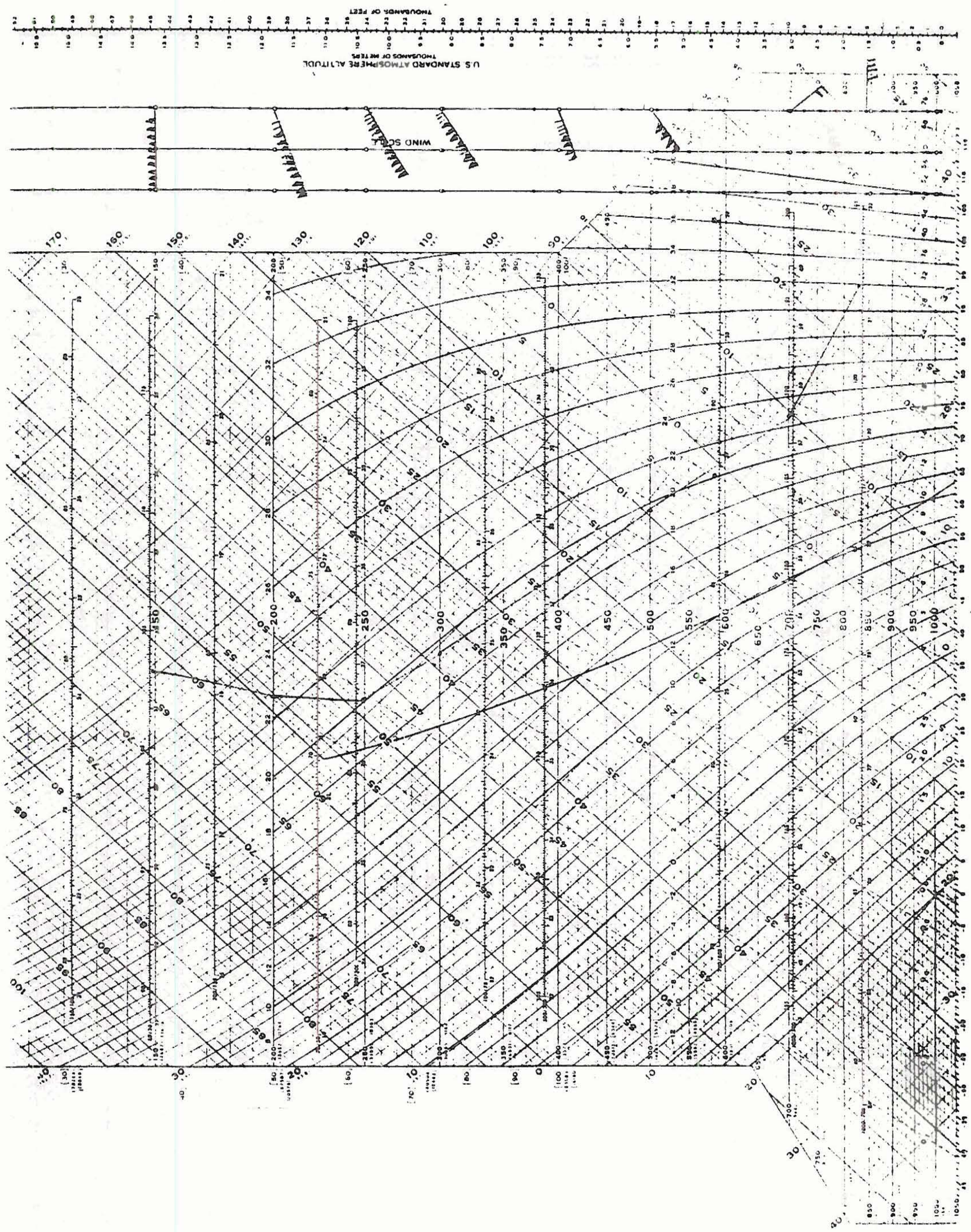

Figure B.4. Denver sounding for October 8 0Z.

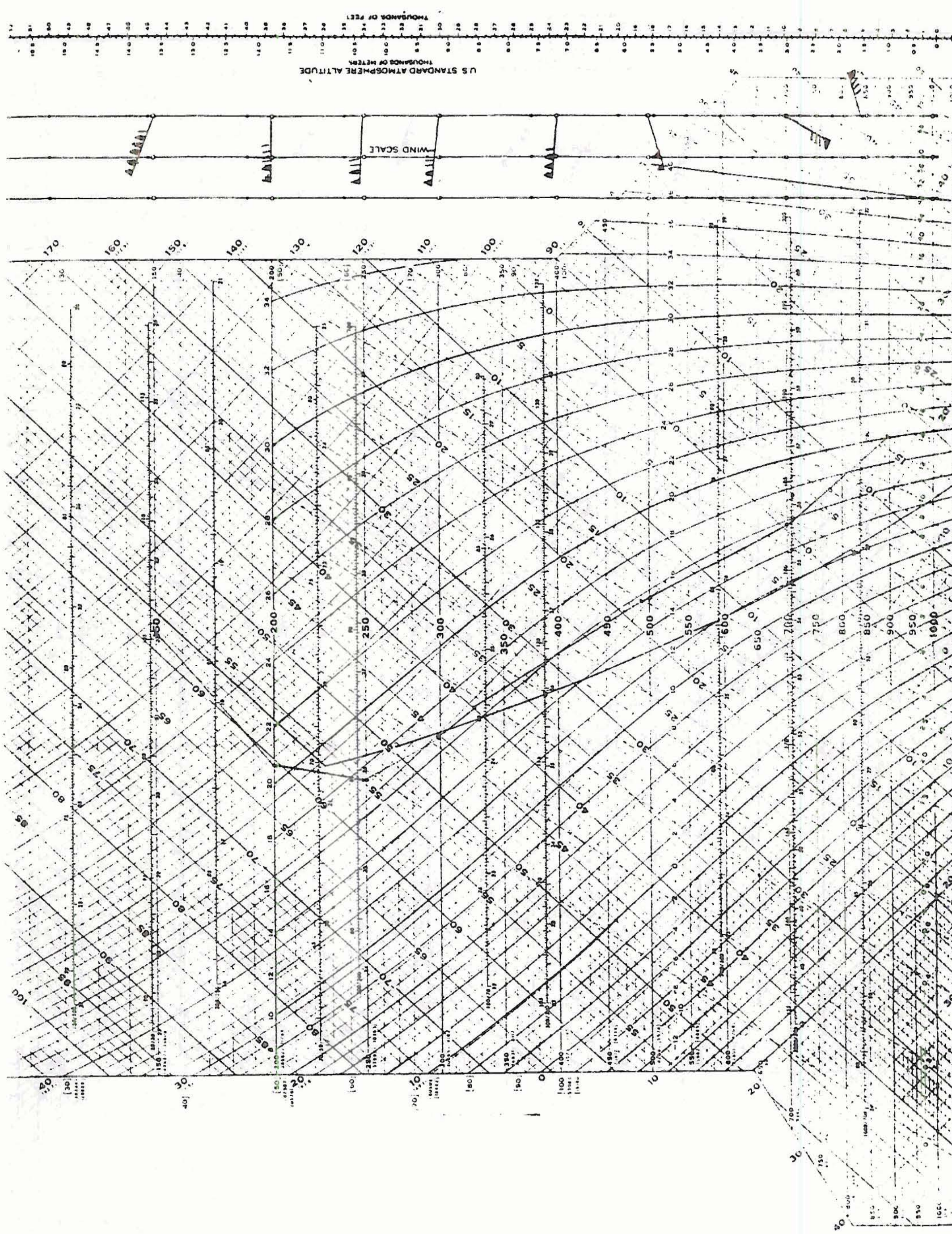

Figure B.5. Denver sounding for November 11 0Z.

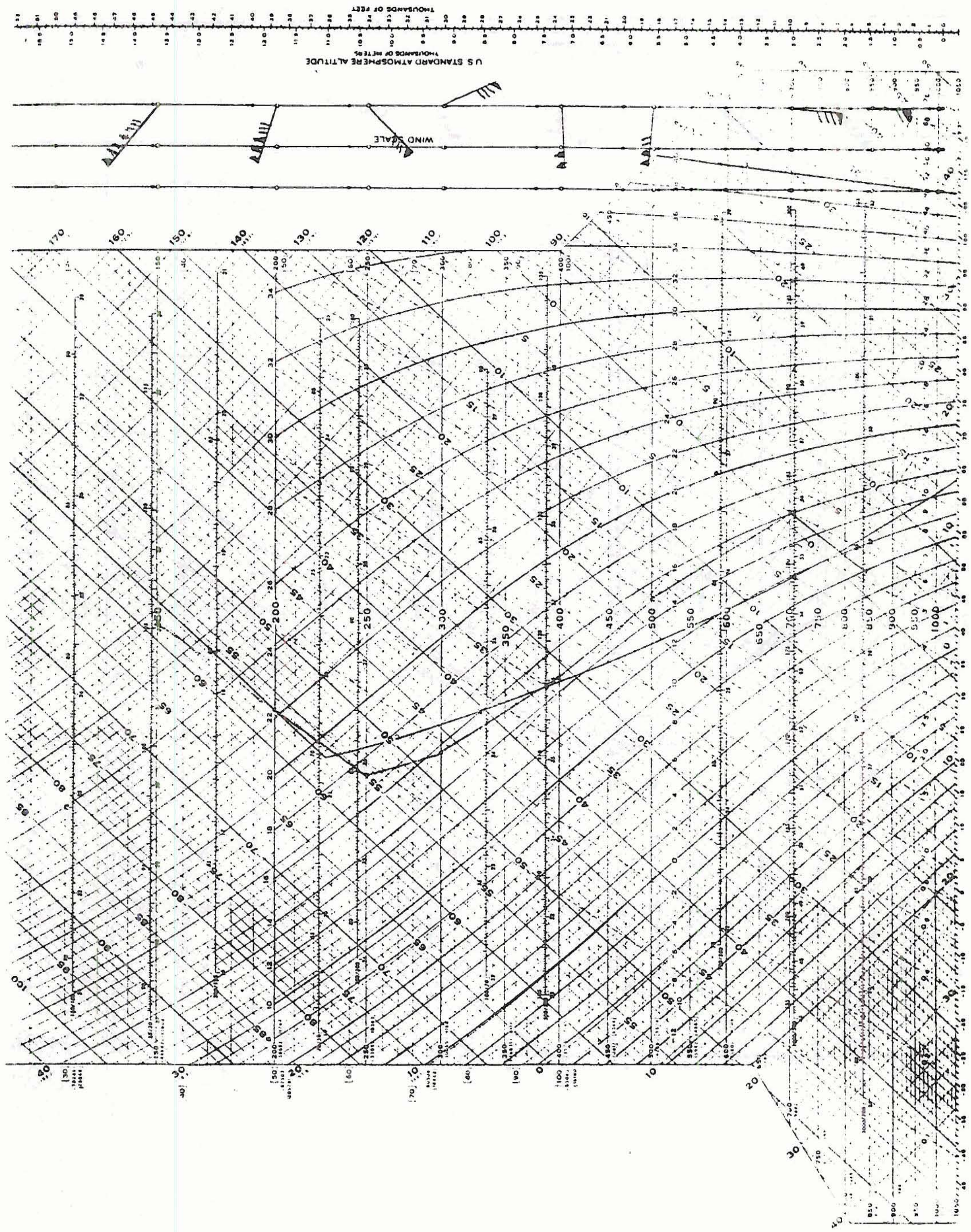

Figure B.6. Denver sounding for November 11 12Z.

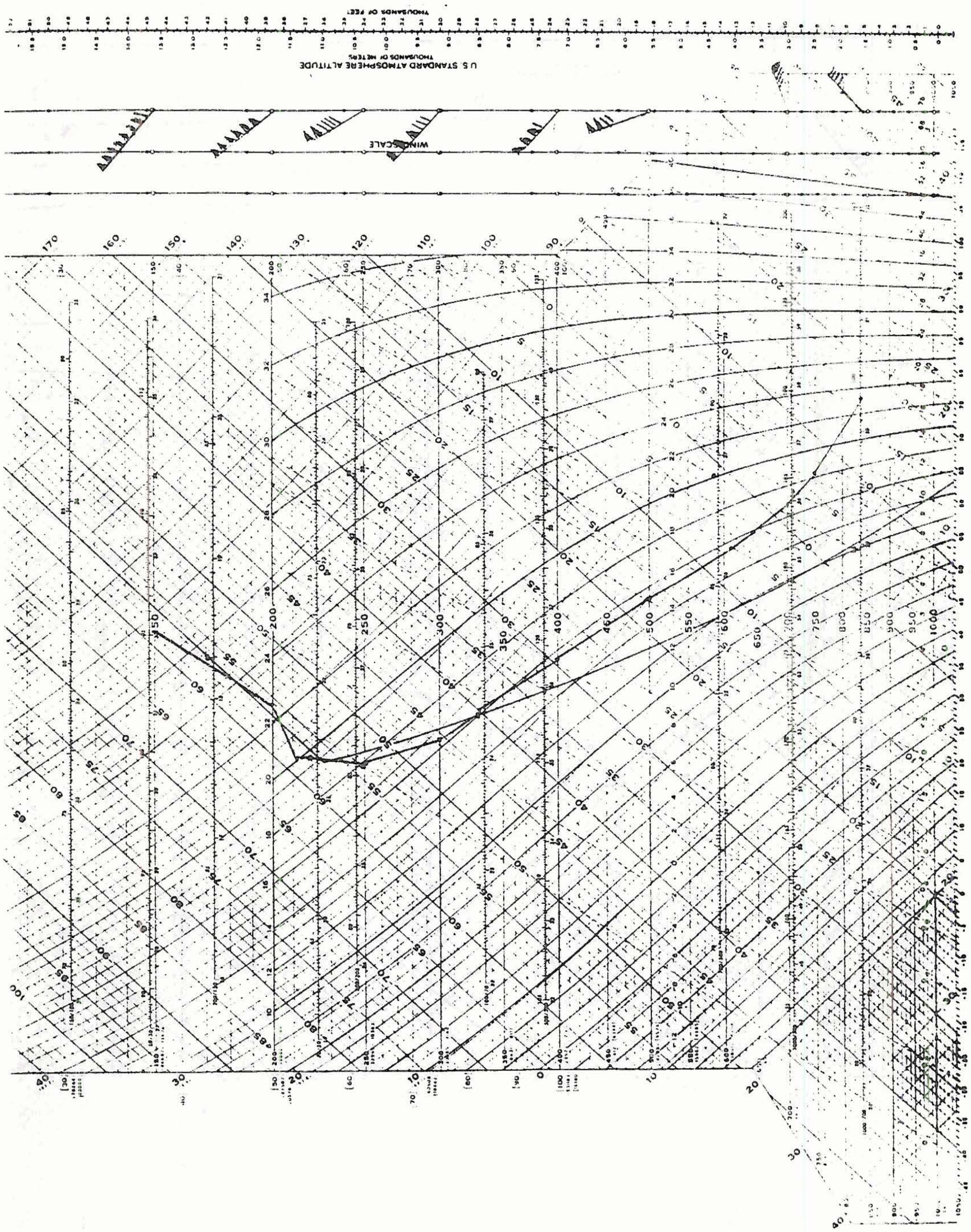

Figure B.7. Denver sounding for November 12 0Z.

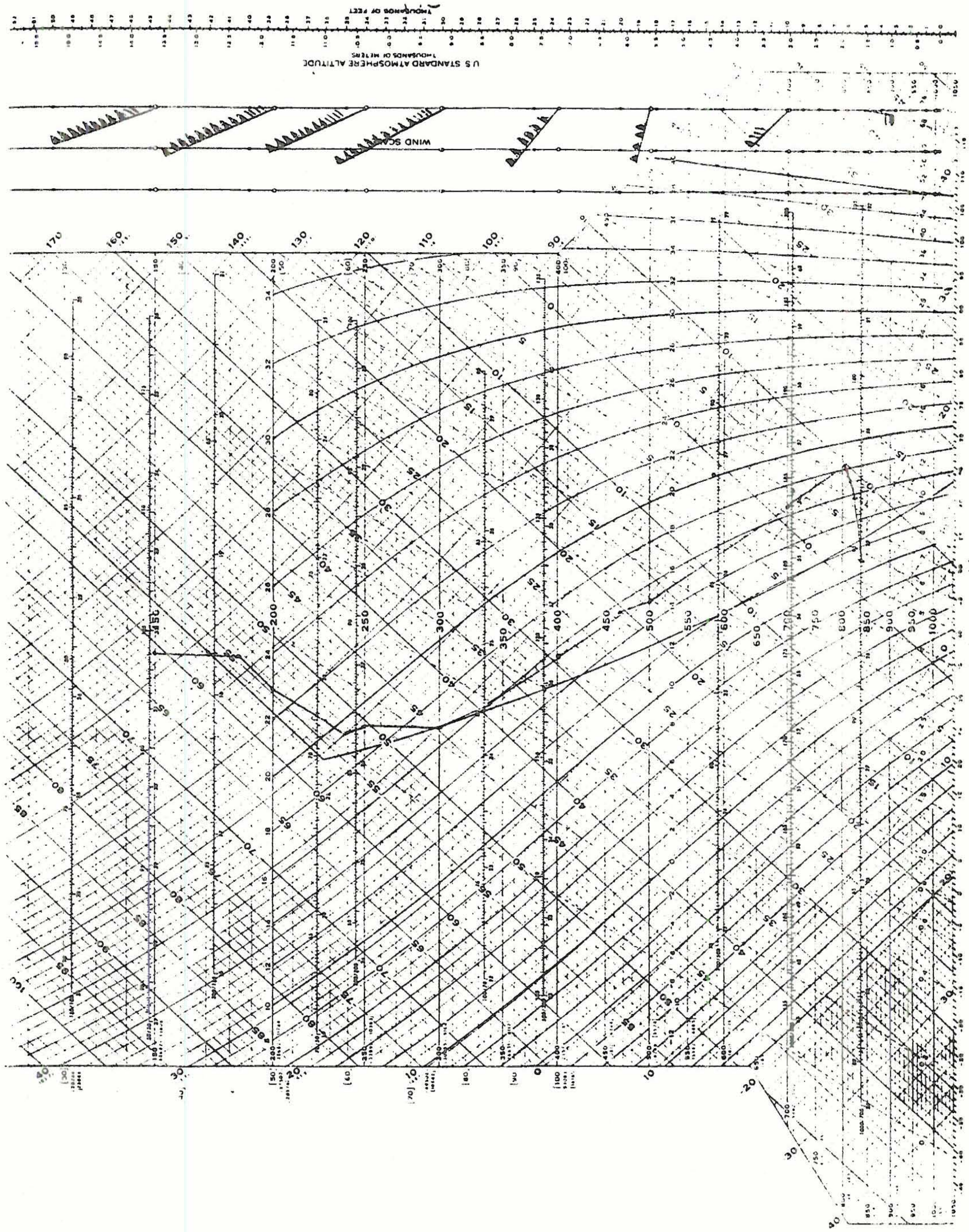

Figure B.8. Denver sounding for November 12 12Z.

Bibliographic Data Sheet.

"Undisturbed Clear Day Diurnal Wind and Temperature Pattern in NOrtheastern Colorado"

by J. K. Smith and T. B. McKee

16. Abstract (continued).

The downslope winds also begin in the foothills and mountains and spread eastward, taking four to five hours to spread throughout the region. However, the transition at each individual station only takes half as long as the morning transition. The evening wind speeds are stronger than the upslope wind speeds, except in the northern part of the region where there is a strong down-Cheyenne Ridge component. Speeds of 8 to 12 knots occurred in the foothills and on the Palmer Ridge, with downslope speeds of 5 knots or less elsewhere. As in the daytime, mountain speeds are site dependent. Between the foothills and South Platte River, the winds diminish in the early morning, but maintain their strength elsewhere.

The diurnal wind regime did not reach the eastern fringe of the PROFS study region. Here, strong southerly winds of 10 to 15 knots persisted throughout both day and night.

Maximum temperatures were found to be independent of height at elevations below 6000 feet MSL and strongly dependent on elevation above 6000 feet. At night, there is an inversion below around 5800 feet MSL with minimum temperatures strength of about 10^{o}F/1000 feet, while minimum temperatures decrease with elevation above the inversion at 2½^{o}F/1000 feet. The morning sounding from Denver shows that the surface temperature is 3 to 5^{o}F cooler than thr free air, with no variation with elevation.

Maximum temperatures generally occur in the small range of 1330 LST to 1500 LST. Minimum temperatures may occur anytime between midnight and 1 hour after sunrise.

The diurnal temperature range was observed to decrease with elevation and ranged from 40^{o}F along the South Platte River to 20^{o}F in the high mountains.

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16. Abstracts

Data collected by the PROFS mesometeorological network was used to study the undisturbed clear day wind and temperature pattern along the Front Range in northeastern Colorado in Autumn. Three days and three nights were available for study.

A diurnal wind regime was observed which consisted of daytime upslope and nighttime downslope winds with components directed toward both the Front Range and the Cheyenne and Palmer Ridges.

The transition from downslope to upslope in the morning takes one to three hours at each station and involves a distinct break between the wind systems. The transition begins in the foothills and mountains and spreads eastward, taking four to five hours to spread through the entire region. The strongest upslope winds occur in the northern part of the region, where there is a strong up-Cheyenne Ridge wind component. Speeds there are 5 to 8 knots. Upslope speeds elsewhere are 3 to 4 knots. Mountain wind speeds are site dependent. (continued)

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