NOAA TECHNICAL MEMORANDUM NWS CR-66

THE EFFECT OF DIURNAL HEATING ON THE MOVEMENT OF COLD FRONTS THROUGH EASTERN COLORADO

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August 1982

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Weather Service

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ABSTRACT

A frequently observed phenomenon unique to the Rocky Mountain region is the apparent effect of diurnal heating on the movement of cold fronts southward through the High Plains. Fronts may stall or slow across Montana and Wyoming during greatest surface heating, with a marked acceleration southward after sunset. Because of this, cold frontal passages seem to occur significantly more often during the nighttime hours in eastern Colorado, especially during the warm season. The propensity toward nighttime frontal passages has been recognized among forecasters, and is considered a general rule of thumb. Whether or not this generalization is founded in fact will be confirmed through statistical means and illustrated by case study. For this purpose, the cold frontal passage of October 20-21, 1981 will be examined briefly. Later it will be shown that for all identifiable cold frontal passages at Denver since 1960, more than two-thirds (69 percent) occurred between the hours of 6 p.m. and 6 a.m.*. Moreover, this figure rises to 80 percent when considering only the warmest months of the year. A few other common characteristics of High Plains cold fronts in Colorado will also be pointed out during the course of this paper.

INTRODUCTION

Cold fronts along the eastern slopes and High Plains of the central Rocky Mountain region exhibit a definite tendency to pass through the region with greater frequency and speed at night than during the day. Since dynamic influences such as upper troughs may pass through the area randomly at anytime, consideration must be given, at least in part, to the effects of diurnal heating in explaining this phenomenon. Cold fronts, especially in summer, are unable to overcome the effects of intense surface heating at high altitudes. Furthermore, dynamic or mechanical lee troughs may be enhanced by this thermal influence. The effect is not unlike the thermal low pressure areas often found in the southwest desert regions in summer. However, due to the elevation and low moisture content of the High Plains, diurnal temperature ranges may exceed 30 degrees (F) and these thermal effects are rapidly diminished after sunset. It is at that time a marked acceleration of the front often occurs. Rapid surface pressure rises may be observed along the front as the trough weakens or fills. Fronts that do pass through the region during maximum heating tend to be exceptionally strong and most often during the winter months.

Recognizing this phenomenon is of course critical in timing frontal passage at Denver, Colorado Springs, and other Front Range cities. It is of particular importance to aviation interests since extensive upslope low clouds, fog, and precipitation usually follow behind the front. Of all cold frontal passages at Denver since 1960, 63 percent were accompanied by stratiform clouds of marginal VFR category or lower ($\leq$ 3000 feet AGL), lagging by an average of one and

*all times are Mountain Standard unless otherwise noted three-quarters hours. Since most frontal passages occur at night, and since significant stratiform precipitation is usually associated with post-frontal upslope conditions, it follows that the onset of upslope precipitation in Denver will most often occur at night.

Dynamic effects and the larger-scale flow pattern of course cannot be ignored when considering the movement of surface fronts. However, these influences tend to be very weak during the summer, especially at latitudes south of 40 degrees. Therefore, it is the intent of this paper to focus on diurnal influences which can be subtle and often overlooked, but have dramatic effect. The following is a brief case history of a cold front moving south through Wyoming and eastern Colorado on October 20-21, 1981. The weakening of the surface trough and acceleration after sunset are especially evident.

CASE STUDY

The large-scale flow pattern for the period Tuesday, October 20, and Wednesday, October 21, was rather stable with a long-wave ridge position just off the west coast of the United States extending northward into the Gulf of Alaska. Northwest flow prevailed over the northern and central Rockies. Early Tuesday, a minor short-wave trough was rotating southeast across Montana.

At the surface at 12Z (5 a.m.) Tuesday, October 20, a cold front was located across central Wyoming (Fig. 1a). A weak trough was located along the front. A broad surface high was elongating and building southeast out of western Canada behind the front. The front reached Casper just before 7 a.m. It wasn't until 5 p.m. however, that stratus and light snow finally reached the station. Weather conditions preceding and following the front were typical for such a situation. Over southern Wyoming, clear skies or high thin cirrus clouds were observed most of Tuesday. Temperatures were in the 60's with strong west to southwest winds. In contrast, over northern Wyoming and Montana behind the front, temperatures were in the 20's and 30's with overcast stratus, light snow, and fog. Winds were generally north to northeast.

The front dropped slowly southward during the day, finally reaching Cheyenne at 5 p.m. (Fig. 1b). This was 10½ hours after the front had reached Casper, a distance of only 129 nm. At 2 p.m., the time of warmest surface temperatures, observations showed that the trough had reached its maximum depth, approximately 1011 mb. By 5 p.m. (Fig. 1b), it was beginning to weaken at which time the front was located from Jackson-south of Lander-Cheyenne-Goodland.

During this time of year, sunset occurs in this region at around 5:30 p.m. It is interesting to examine what happened within the period from 5 p.m. to 8 p.m., when surface heating was lost. Shortly after sunset, pressures began rising rapidly throughout Wyoming. Pressure tendencies at observing stations showed four to five millibar rises across much of Wyoming for the three-hour period ending at 8 p.m. (Fig. 1c). The trough had rapidly filled after sunset while the surface high continued to push southward out of Montana. It is also at this time that the cold front began to accelerate.

Frontal passage occurred at Denver at 9:50 p.m., at Colorado Springs at 11:14 p.m. Wednesday (Fig. 1d), and at Trinidad near the southern border at 2 a.m. When considering distances between stations, the front averaged 12 knots between Casper and Cheyenne, 16 knots between Cheyenne and Denver, and 36 knots beteet Denver and Trinidad. On Wednesday, after passage of the front, temperatures were 30 to 40 degrees cooler across eastern Colorado with overcast stratus, light snow, drizzle, and fog. As is often the case, the cold air mass was of insufficient depth to penetrate west of the Continental Divide. The Denver RAOB at 12Z (5 a.m.) Wednesday, October 21, indicated a moisture depth extending to about 10,000 feet ASL, fairly typical for this kind of situation, and is vividly illustrated by the GOES visible satellite imagery for mid-day Wednesday (Fig. 2). In fact mid-day temperatures at many mountain locations were 20 to 30 degrees warmer than on the eastern plains.

The figures and illustrations presented in this case clearly show the acceleration of the cold front after sunset. With the absence of strong dynamic influences, this acceleration was due largely to the loss of surface heating. The following is a statistical study of past cold frontal passages at Denver, and will show that this type of behavior is not an isolated incident.

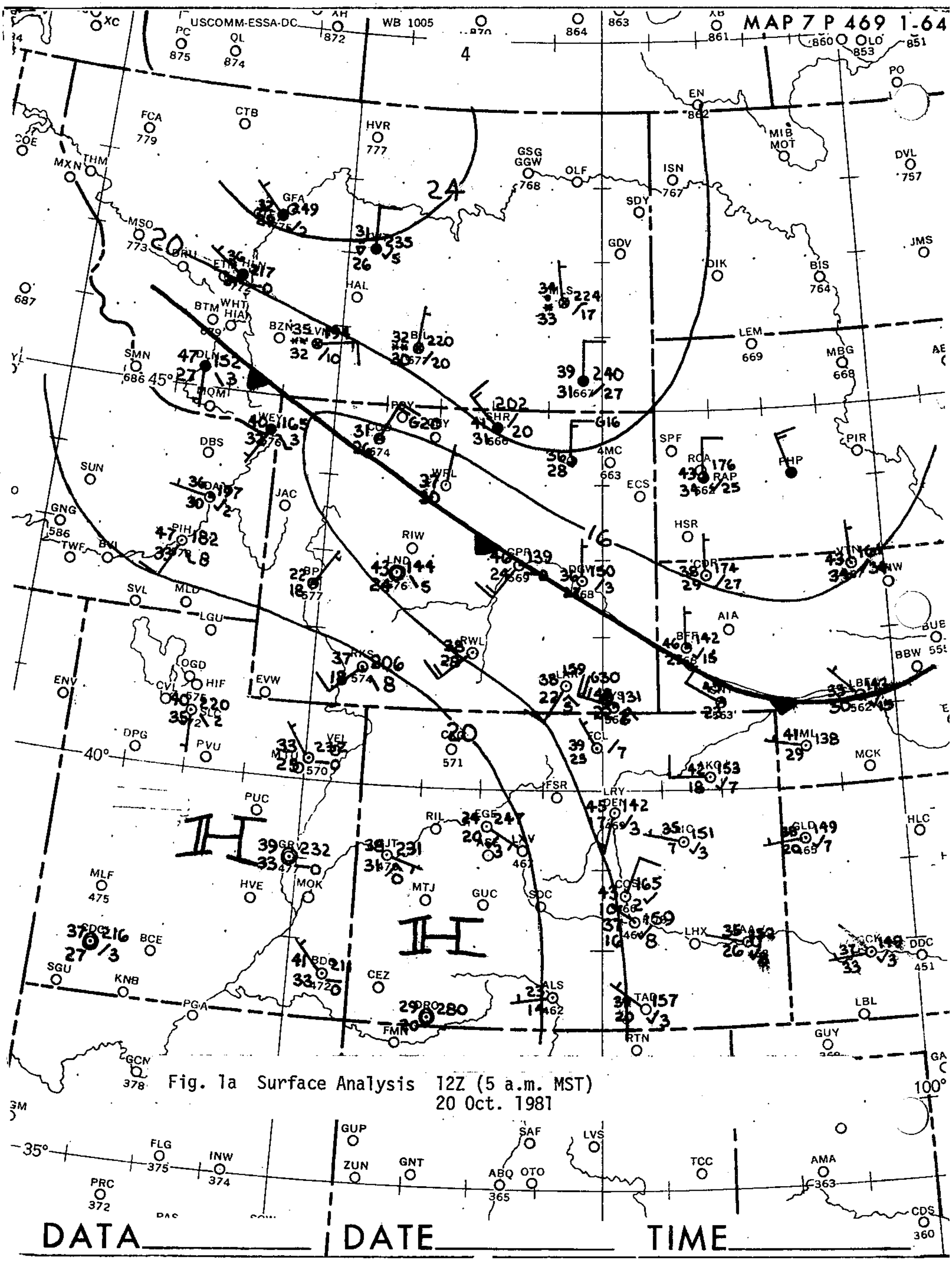


Fig. 1a Surface Analysis 12Z (5 a.m. MST)
20 Oct. 1981

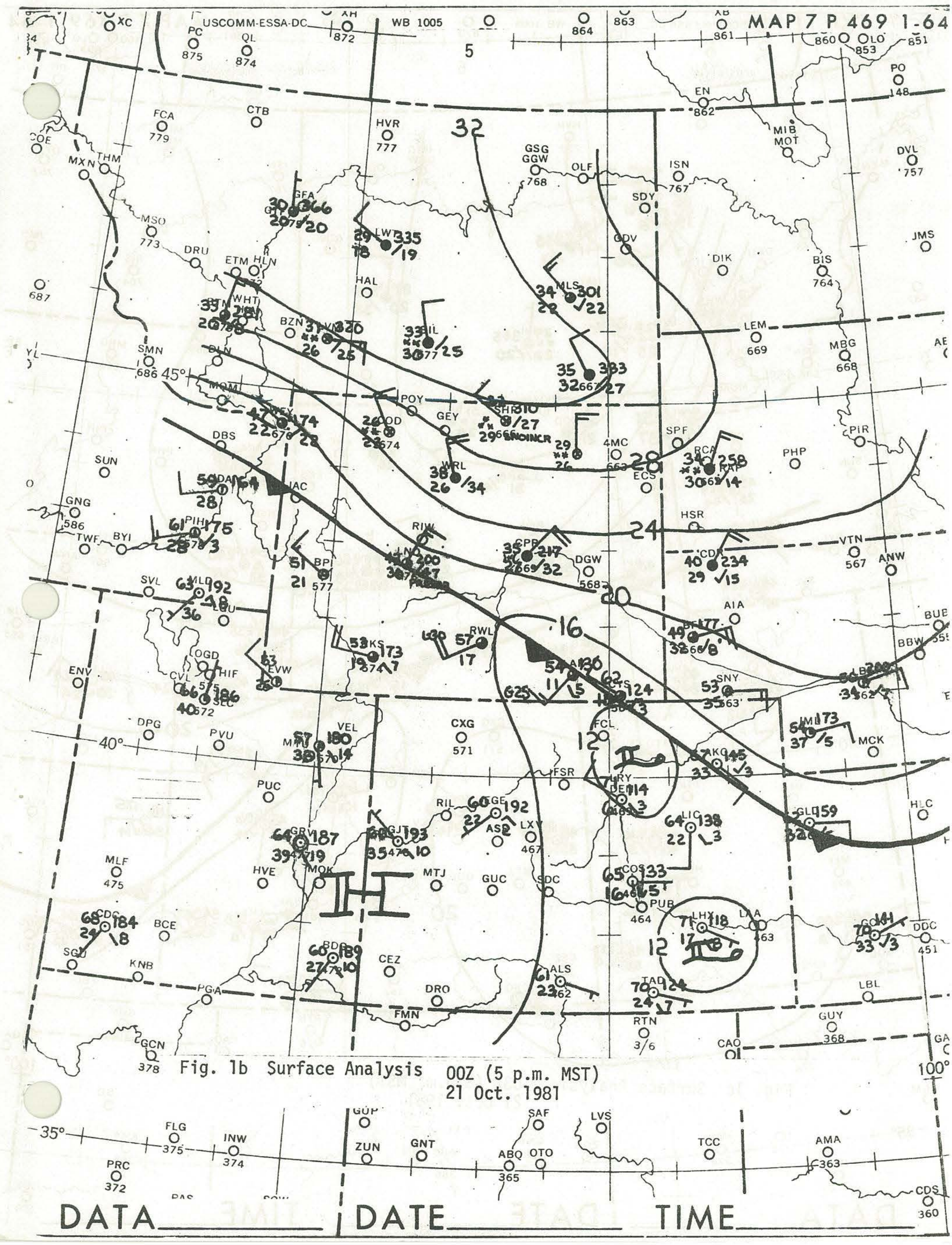


Fig. 1b Surface Analysis 00Z (5 p.m. MST)
21 Oct. 1981

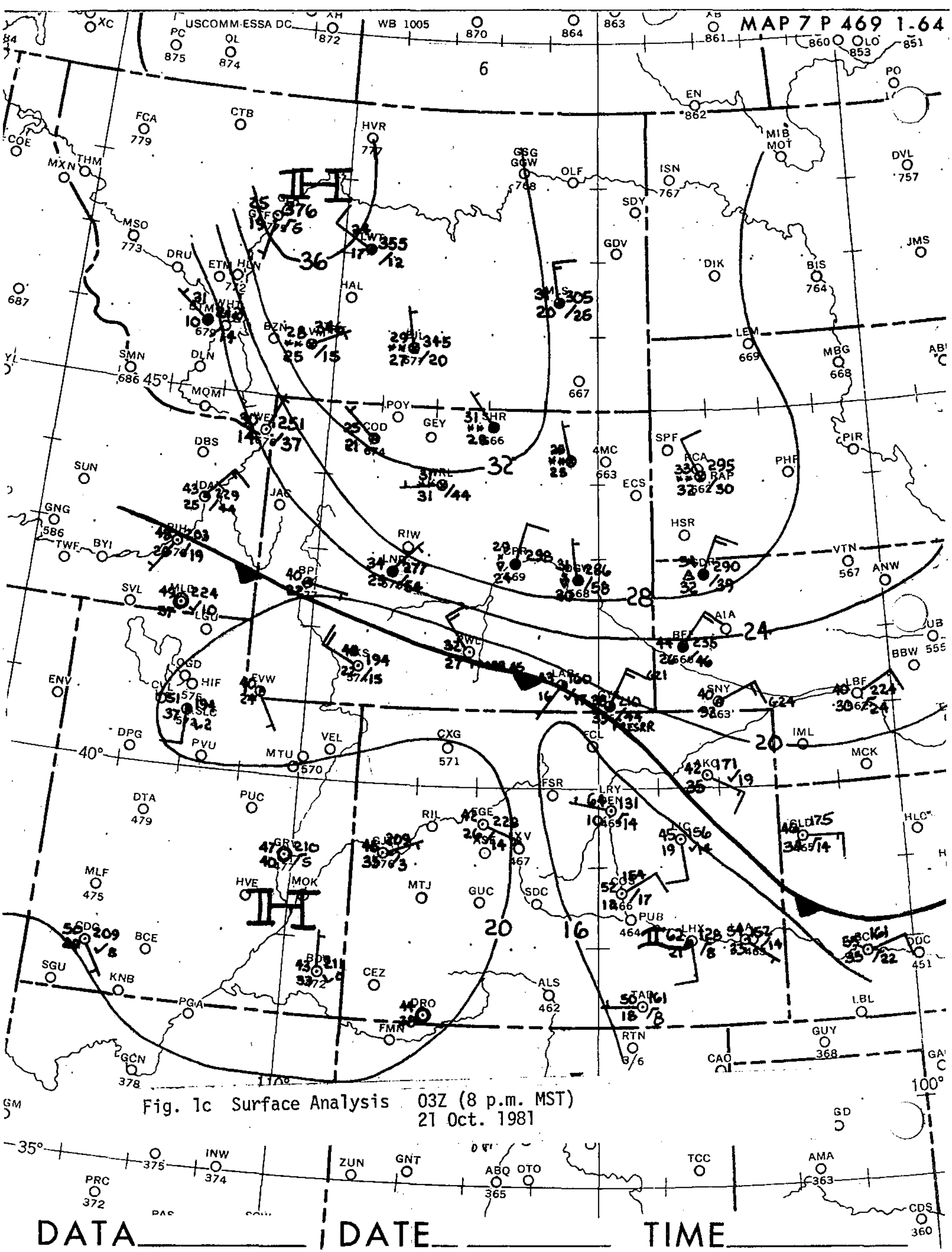


Fig. 1c Surface Analysis 03Z (8 p.m. MST)
21 Oct. 1981

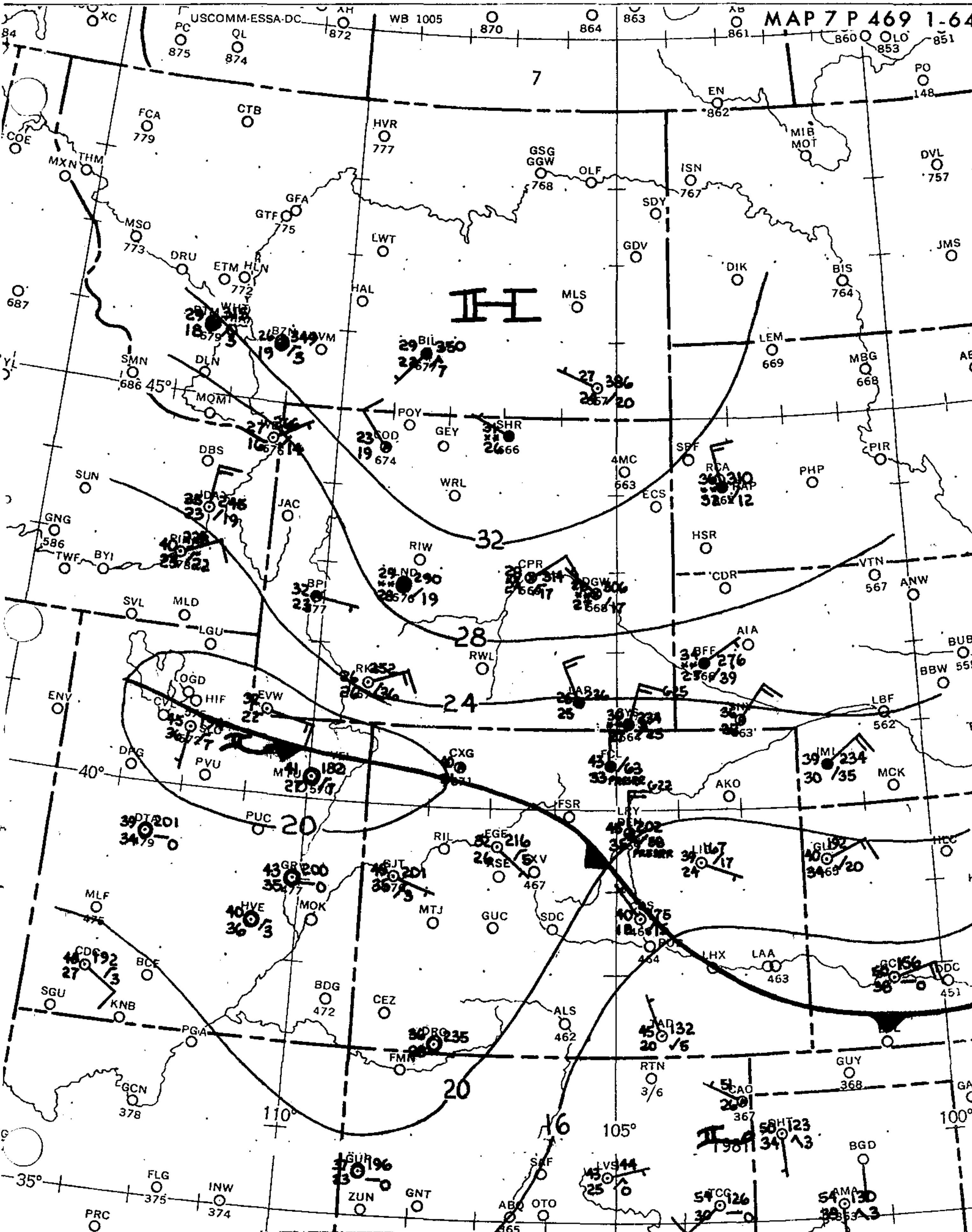
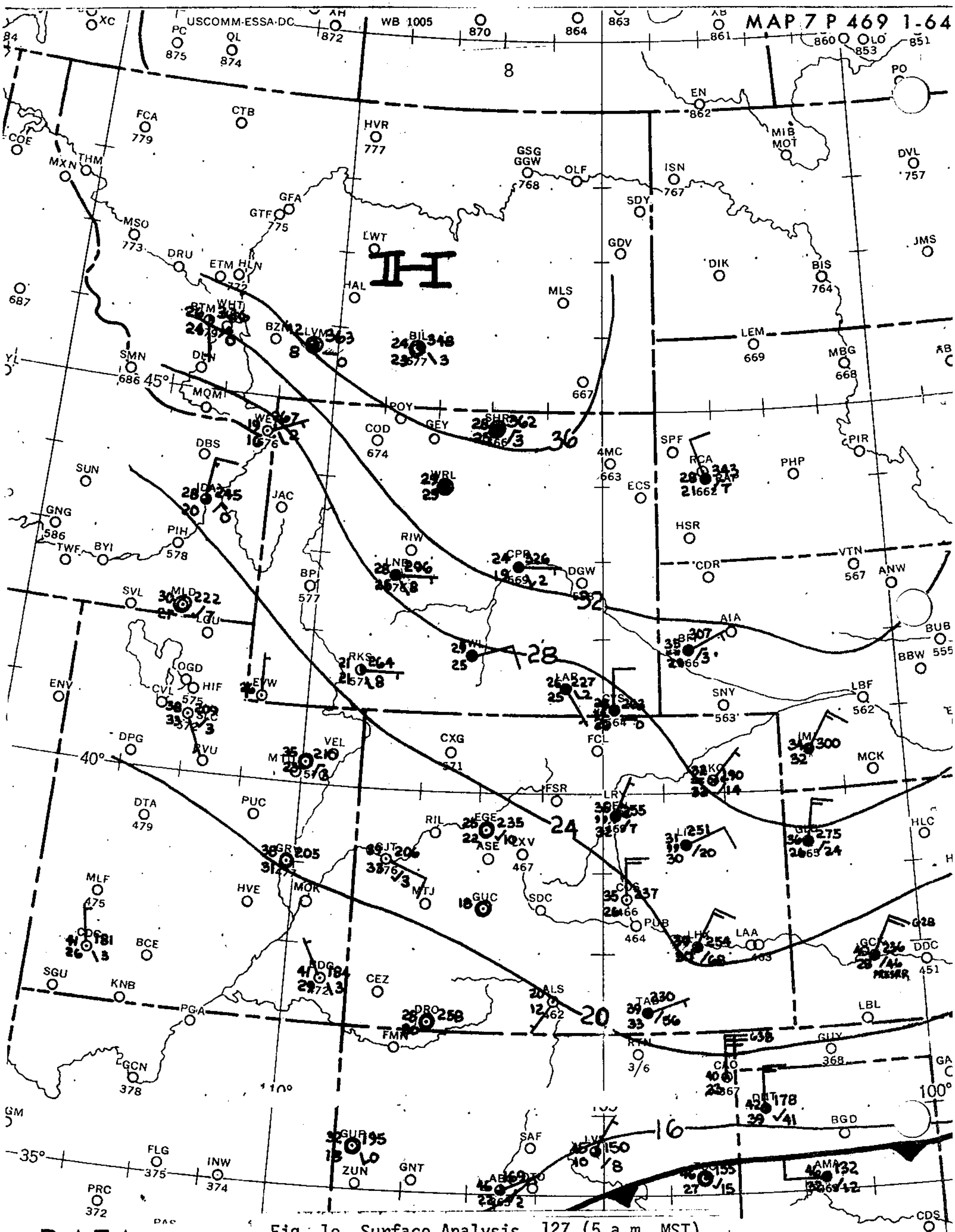


Fig. 1d Surface Analysis 06Z (11 p.m. MST)
21 Oct. 1981

DATA______



DATA

Fig. 1e Surface Analysis 12Z (5 a.m. MST)
21 Oct. 1981

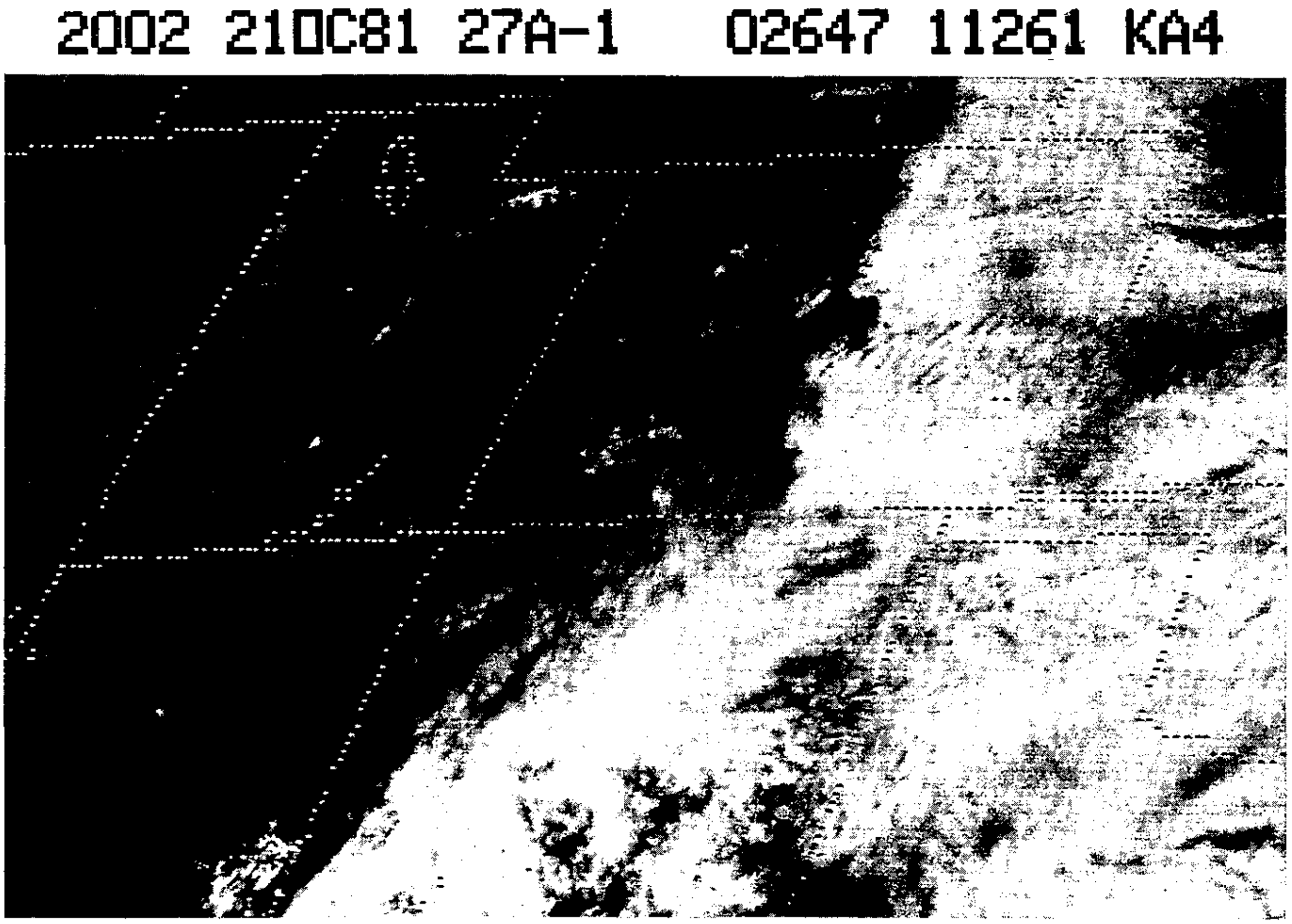


Fig. 2 GOES Visible Satellite Imagery
20Z (1 p.m. MST) 21 Oct. 1981

STATISTICS OF PAST FRONTAL PASSAGES AT DENVER

With what frequency do cold fronts really pass through eastern Colorado at night? To what degree does diurnal heating affect their movement? To address these questions, surface observations at Denver for the years 1960 through 1981 were examined. Time and date of each frontal passage were entered in a log. Notations were made of any clouds or precipitation that may have accompanied the front. Other very weak frontal passages may have occurred but were excluded from the samples. The span of twenty-two years that the data covered was a necessity in order to be statistically representative and to minimize the effects of anomalous years. For frontal passages during all months of the year, it was found that more than two-thirds or 69 percent occurred between the hours of 6 p.m. and 6 a.m. (Fig. 3). There is an unmistakable peak frequency from 5 p.m. to midnight, during the hours of most rapid radiational cooling. There is also a second curious peak between 5 a.m. and 6 a.m. This second high frequency period is difficult to explain, but may bear some relationship to what is usually the coolest time of the day.

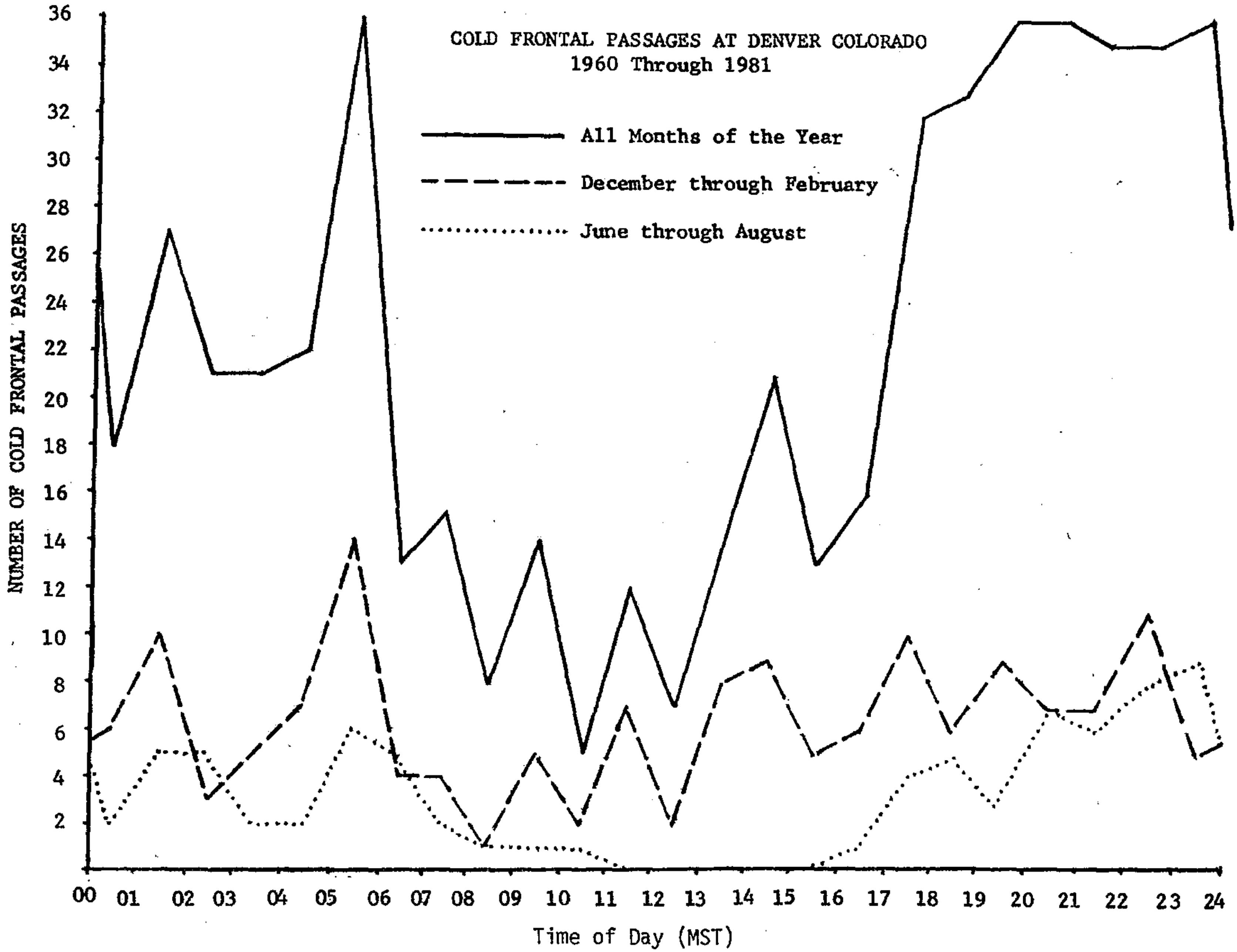
When considering only the warmest months of June, July, and August, fully 80 percent of all frontal passages occur between 6 p.m. and 6 a.m. In fact, none at all were recorded between the hours of noon and 3 p.m., ordinarily the hottest time of the day. It was thought, however, that convective activity might actually contribute to this high figure. Since convective storms are an almost daily occurrence during the summer months, and since most occur during the afternoon and evening hours, convection along a cold front might "mask" its passage during those hours. But it was found for October and November that the figure is still maintained at a relatively high 70 percent, during months when surface heating is still fairly strong, but convection is at a minimum with each month averaging one or less thunderstorm. Moreover, a study by Sullivan and Severson (1) showed that peak thunderstorm activity in Denver occurs between 5 p.m. and 6 p.m. during June, July, and August. This is precisely the hour in which there is a marked increase in the frequency of cold frontal passages, which would tend to disprove the idea of "masking" making the fronts more difficult to identify. The figure for nighttime frontal passages drops considerably during the subsequent cold months.

During the coldest months of December, January, and February, the frequency of frontal passages at Denver is much more evenly distributed throughout the day and night (Fig. 3). A slight majority still occur during the nighttime hours, but the figure is much smaller then that of the summer months at 57 percent. Cold fronts during the winter months, of course, tend to be much stronger and more frequent, often with strong upper support. Diurnal influences have little effect on their movement.

Up to this point it has been suggested that surface heating affects the movement of cold fronts southward through the High Plains. Little has been said however, as to how and by what mechanism it affects that movement.

THE ROLE OF THE SURFACE GEOSTROPHIC WIND

In a study by Sangster (2), it was shown that there is an important diurnal variation in the surface geostrophic wind over sloping terrain which is not evident in ordinary sea-level pressure analyses. Specifically it stated, "diurnal temperature variation in the boundary layer over the Great Plains leads to an



COLD FRONTAL PASSAGES AT DENVER COLORADO
1960 Through 1981
All Months of the Year
December through February
June through August
NUMBER OF COLD FRONTAL PASSAGES
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of Day (MST)

Fig. 3

Fig. 3

appreciable diurnal variation in the surface geostrophic wind." Furthermore it stated, "an appreciable diurnal shift in (surface) wind direction might take place due to the diurnal variation of the geostrophic wind." Sangster showed that the mechanism by which this occurs is the day to night shift in the thermal winds. To illustrate this consider Fig. 4.

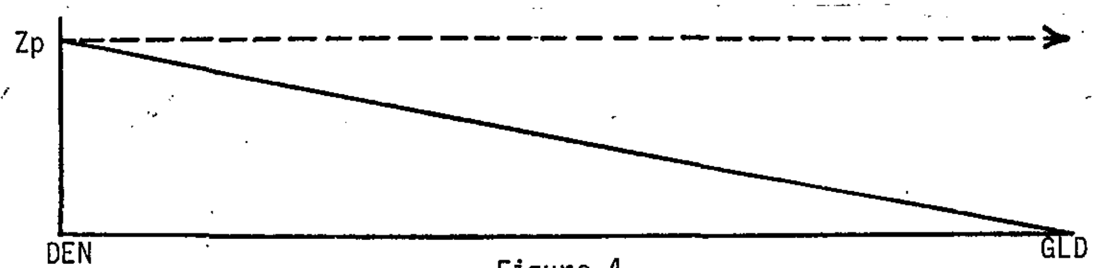
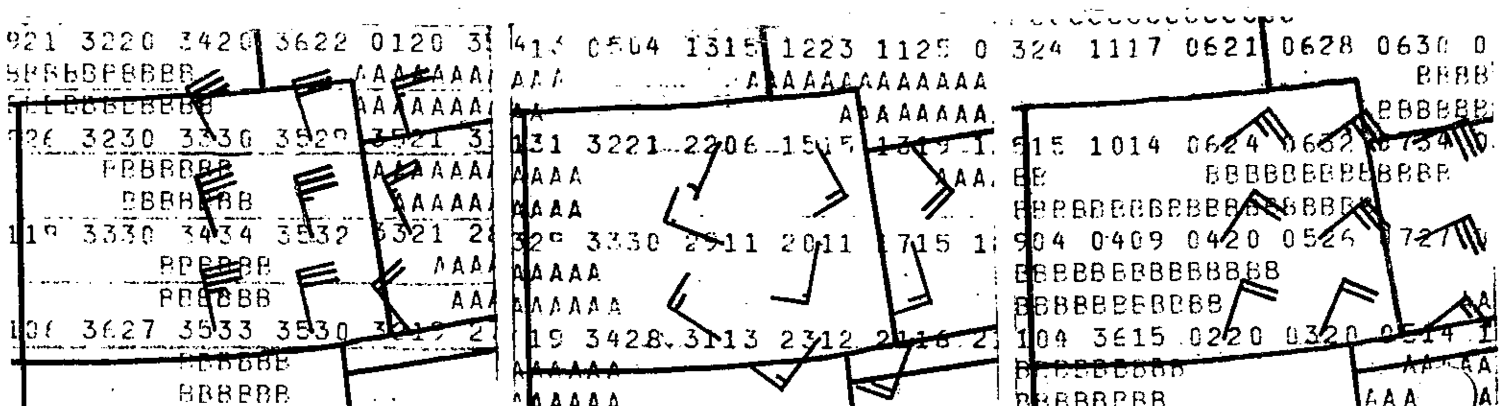


Figure 4

During the day cooler air is encountered moving east along a constant pressure altitude (Zp) from Denver to a city farther east such as Goodland, Kansas. At night the opposite is true with warmer air encountered moving east along the same pressure height. This is, of course, due to the sloping terrain. We know that in the Northern Hemisphere the thermal wind blows along thickness lines with cooler air on the left. Hence, in our example the component of the thermal wind will be northerly during the day, and southerly at night. The thermal wind can be defined as the vertical shear of the geostrophic wind, and Sangster showed using the geostrophic wind equation that the northerly thermal wind in the boundary layer will produce a southerly component of the surface geostrophic wind, and vice versa. In other words, over sloping terrain and in an atmosphere with little upper horizontal pressure gradient, the component of the surface geostrophic wind will be southerly during the day and northerly at night. This is precisely what was observed during the case study presented in this paper.

Thus, the relationship stated quite simply is that surface heating over sloping terrain leads to a diurnal shift in the thermal wind in the boundary layer, which correspondingly leads to a shift in the surface geostrophic wind. A southerly component of the surface geostrophic wind might tend to inhibit the southward movement of cold fronts during the day, while a northerly component would aid in their acceleration at night.

A number of surface (not sea-level) geostrophic wind charts (see Sangster (3)) were collected for the period covered by the case study. Three of them are shown in Fig. 5.



a. 12Z 20 Oct. 1981 b. 21Z 20 Oct. 1981 c. 06Z 21 Oct. 1981

Fig. 5. Surface Geostrophic Wind Charts

Fig. 5a shows the surface geostrophic winds at 12Z (5 a.m. MST) on October 20 when the front was across central and northern Wyoming. By 21Z (2 p.m. MST), at the warmest time of the day, the northerly component has been lost completely with a dramatic shift in speed and direction, as shown in Fig. 5b. By 06Z (11 p.m.), a shift to northeast by the surface geostrophic winds is noted in Fig. 5c, and it was within this period that the front had accelerated southward across Colorado. These charts clearly show a diurnal shift in the surface geostrophic wind over eastern Colorado which may have inhibited frontal movement during the day, while aiding in its acceleration southward at night.

SUMMARY

Diurnal heating profoundly influences the movement of cold fronts through eastern Colorado, especially during the warmest months. The mechanism by which this occurs may be the diurnal shift of the surface geostrophic wind. Fully 80 percent of all cold frontal passages during the summer months in Denver since 1960 occurred between 6 p.m. and 6 a.m. And in this twenty-two year period, not a single identifiable cold frontal passage was recorded in Denver between noon and 3 p.m. during June, July, and August. This is important for public and aviation forecasters to remember since guidance products will, at times, drive cold fronts through the area at all hours indiscriminately. It follows from this that the onset of stratiform clouds and precipitation that often develop or advect into the area behind the front, will also occur at night.

During the summer months the main belt of westerlies is usually displaced well to the north across southern Canada, Idaho, and Montana. Progressive weather systems frequently still affect those areas in summer. However, over the central and southern Rockies where flow may be considerably weaker with little horizontal pressure gradient, strong diurnal influences come into play. As one might expect, the frequency of frontal passages in winter is much more evenly distributed day and night when strong dynamic driving forces are evident, and diurnal influences at a minimum.

Topographic, orographic, and diurnal influences play an important role in shaping the local climatic regime of the Rockies, but also make it that much more complex, subtle, and easily overlooked. Surface heating over sloping terrain, and its subsequent effect on the movement of cold fronts is one such phenomenon.

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ACKNOWLEDGEMENTS

The author would like to thank, from WSFO Denver, Messrs. Maurice Pautz, James Kaplan, and John Schwab for their comments and suggestions, and Ms. Vicki Bailey for her editing. Special thanks go to Dr. Wayne E. Sangster of Scientific Services Division, for his technical assistance in the final preparation of this paper.

CENTRAL REGION TECH MEMOS

(continued from front inside cover)

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