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THE SYNOPTIC AND MESO-ALPHA SCALE METEOROLOGY OF WYOMING FLASH FLOODS

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Abstract. The combination of high terrain features, warm temperatures and moisture intrusions makes Wyoming susceptible to dangerous thunderstorms which produce very heavy rains with flash floods. Since such storms are difficult to forecast, a study was performed investigating synoptic and meso-alpha scale meteorological factors associated with their occurrence. Data and meteorological patterns were examined for an eight-year period for all days in which Wyoming experienced at least one flash flood. Climatologically, it was found that the vast majority of Wyoming's flash floods coincided with the southwest U.S. monsoon season, taking place in July and August during the afternoon and evening hours. The circulation pattern over the western and central U.S. were similar several hours prior to heavy rainfalls. At the surface, thermal troughing west of the Continental Divide combined with high pressure over the Northern or Central Plains to generate a low level easterly wind component with inflow of abundant moisture into the state. In the middle troposphere, weak to moderate winds with a westerly or southerly component were established with advection of Pacific or Gulf of California moisture aloft. In such an environment a moist unstable air mass could form over Wyoming with a marked vertical directional wind shear favorable for deep convection. A primary trigger for Wyoming heavy thunderstorms was terrain-forced upward motion due to the easterly component of the surface winds. In addition, in most, though not all cases, dynamic lifting was present due to the approach of a short wave trough embedded in the middle tropospheric flow.

1. Introduction

Flash flooding associated with heavy convective rainfall remains a concern for the population of the United States, because of the death, injury and substantial property damage which can occur with this weather-related event. As a result, weather forecasters and operational research meteorologists have attempted to improve flash flood forecasting by identifying common synoptic and meso-alpha scale weather patterns and air mass characteristics conducive to flash flooding (Maddox et al., 1979; Maddox et al., 1980). In this way weather forecasters, particularly at the National Weather Service (NWS), may recognize a

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potential flash flood event and issue watches and warnings with adequate lead time for the public. This recognition is especially important for flash flood watches because, unlike watches for severe thunderstorms and tornadoes, watches for flash floods are the responsibility of individual NWS forecast offices.

Maddox (1979) found that to properly delineate atmospheric conditions favorable for flash flood-producing convection, the forecaster must often do an enhanced analyses of the surface and upper air maps provided by the National Meteorological Center (NMC). Unfortunately, routine operational duties at NWS forecast offices usually interfere with any attempt to analyze weather data in the necessary detail required to issue timely watches. Therefore, the need to identify flash flood-producing weather patterns in a relatively short time is especially important at the local forecast office level.

Wyoming is among those states which experience strong convection, heavy rainfall, and deadly flash flooding. During the summer months the abundance of warm surface temperatures, low level moisture intrusions and high terrain all combine to create periods of great instability with intense thunderstorms. A recent example was the flash flood which occurred in Cheyenne on August 1, 1985. On this particular day, severe thunderstorms produced over six inches of rain in the city killing 12 people and doing 65 million dollars worth of damage (Glancy and Dasseler, 1987). Unfortunately, radar coverage over Wyoming is incomplete and the density of weather observing stations is comparatively small. Thus, for successful flash flood forecasting, identification of synoptic and meso-alpha scale circulations favorable for such events is perhaps more important than many other locations.

This paper examines the meteorological conditions associated with flash flood-producing convective storms over Wyoming. Data were examined for all days from the years 1980 to 1987 in which Wyoming experienced at least one flash flood event. A climatological summary of such events is presented in section 3, briefly describing the occurrence of flash flooding with respect to place, season, and time of day over Wyoming. In the following three sections the meteorological environment best conducive for Wyoming flash flood events are discussed based on derived composites of vertical soundings, and both surface and upper air maps. Emphasis is placed on convective instability, lower and middle tropospheric wind flows, and the location of fronts and pressure centers with respect to the location of major rainfalls. Finally, a case study is presented with a more in-depth analyses of a specific heavy rain event over the state. In this way it is demonstrated how various atmospheric features can come together over Wyoming and produce such dangerous storms.

2. Data Analyses Technique

Storm Data and records of the Geological Survey and U.S. Bureau of Reclamation were examined from 1980 to 1987 to determine all days over the period in which Wyoming experienced at least one flash flood event. As stated by Maddox et al. (1979), there are no specific criteria required when flash floods are reported and the quality of information is dependent on its source. Thus, the decision to consider an "event" a flash flood was somewhat subjective. For this study, the criteria used to define an event included rainfall amounts (when available) of over one inch falling at a rate greater than an inch an hour, substantial property damage caused directly from the heavy rain, and the washout of roads or bridges. Flash floods related to dam breakages and snow melt were not included unless they concurred with heavy rainfall meeting the above criteria.

Storm Data and Bureau of Reclamation reports do not comprise an all inclusive list of flash floods over Wyoming during this period since many events likely go unreported in population-sparse areas. In fact, in section 3 it is demonstrated how a disproportionate amount of floods are reported near more densely populated regions of the state. Nevertheless, it is felt a representative sample was obtained given the period covered and the number of events studied.

For each flash flood day over Wyoming, NMC three-hourly surface maps and 12-hourly 850, 700, 500, 300 and 200 mb maps were examined for location of fronts, pressure centers, troughs, ridges and available moisture. From this, surface and upper air maps were derived depicting synoptic conditions around Wyoming on typical days with flash flooding. In addition, surface and upper air data were interpolated in time and space to get an average vertical profile of the air mass in which torrential rains developed.

More detailed analyses were performed for the case study which was considered a typical example of a Wyoming heavy rain episode. For this case standard upper air wind, temperature and dew point data were interpolated over the western U.S. using the Barnes objective analyses scheme (Barnes, 1973). Using 350 km grid spacing and finite differencing, fields of positive vorticity advection (PVA), temperature advection and moisture convergence were evaluated so to enhance the analyses and provide more detailed numerical information.

3. Climatological Overview of Wyoming Flash Floods

In the period covering 1980 to 1987, there were 38 days in which flash floods were reported in Wyoming. Figure 1 gives a breakdown of the time of year these events occurred. Eight days took place in late spring from mid-May to mid-June. The remaining 30 days were in early and mid-summer with a pronounced peak between July 15 and August 15, the warmest period of the year. These overall trends agree with Maddox et al. (1980), who found Rocky Mountain region heavy rain events are most frequent during the summer months. This is due to the summer monsoon circulation pattern (Hales, 1974), the effects of which will be discussed in section 4.

With only two exceptions, information was available for the period of the day with heaviest rainfalls. Twenty of these 36 days, or 56 percent, developed during the evening between 1800 and 2400 LST while 15 flash flood days were recorded as taking place in the afternoon from 1200 to 1800 LST. Only one event was reported in the morning.

The preference for deep convection forming in the afternoon as opposed to the morning is related to the diurnal heating cycle. The warmest surface temperatures typically occur from 1400-1600 LST. Hence, the air mass can reach maximum instability during this time, especially if the convective temperature is attained.

The fact that many Wyoming flash floods occur during the evening hours after sunset is more difficult to explain. Heavy diurnal rainfall over the plains of the United States have been related to the low level jet (Bonner, 1968), which usually increases after dark with a resulting enhancement of warm air and moisture advection from the Gulf of Mexico. Unfortunately, little research has been published establishing the existence of such a jet as far west as Wyoming.

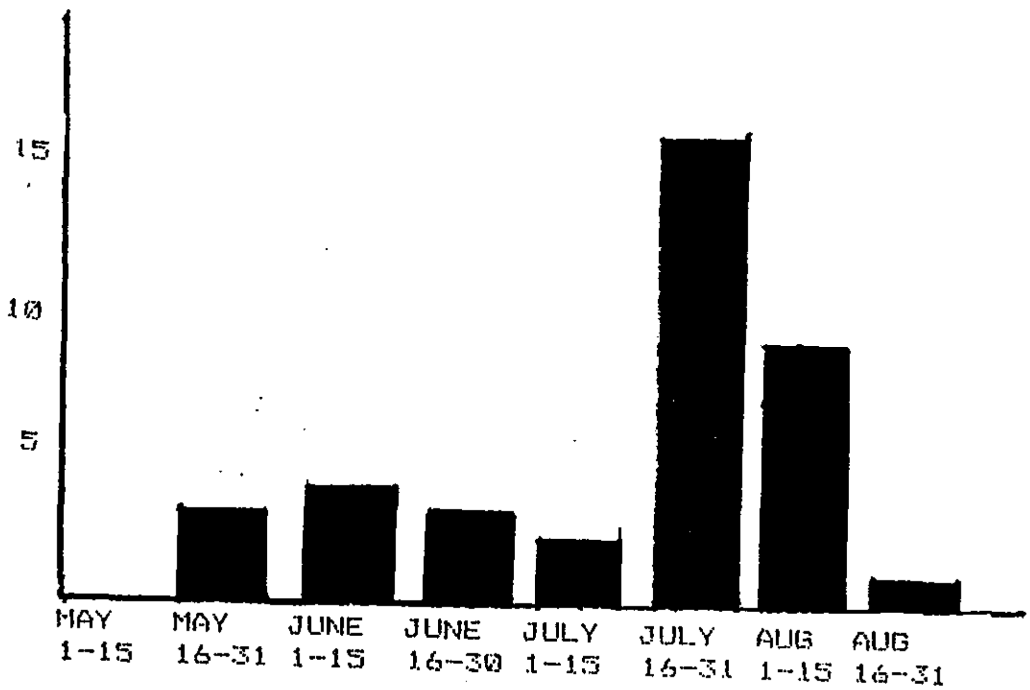

Fig. 1. Distribution of flash flood reports over Wyoming with respect to month and days for period 1980-87. No events were reported for the months September to April.

A second theory relates deep nocturnal convection to differential radiational cooling between large thunderstorm complexes and adjacent clear areas. Briefly, according to this explanation, there is less nocturnal cooling beneath a cloud covered convective area as compared to the surrounding region with clear skies. As a result, there is a low pressure perturbation beneath the clouded zone with low level convergence, upward motion and increased rainfalls (Lussky, 1986). Obviously much research is required before the exact mechanism of nocturnal heavy rains over the mountains and High Plains becomes known.

Figure 2 shows the state geographical distribution of flash floods over the eight year period. An obvious population bias exists as most reports are near relatively larger towns and cities or along major roads, especially Highway I-25. As will be discussed in section 4, another reason for the locational preference east of the mountains is due partly to the synoptic weather patterns in which they most often occur.

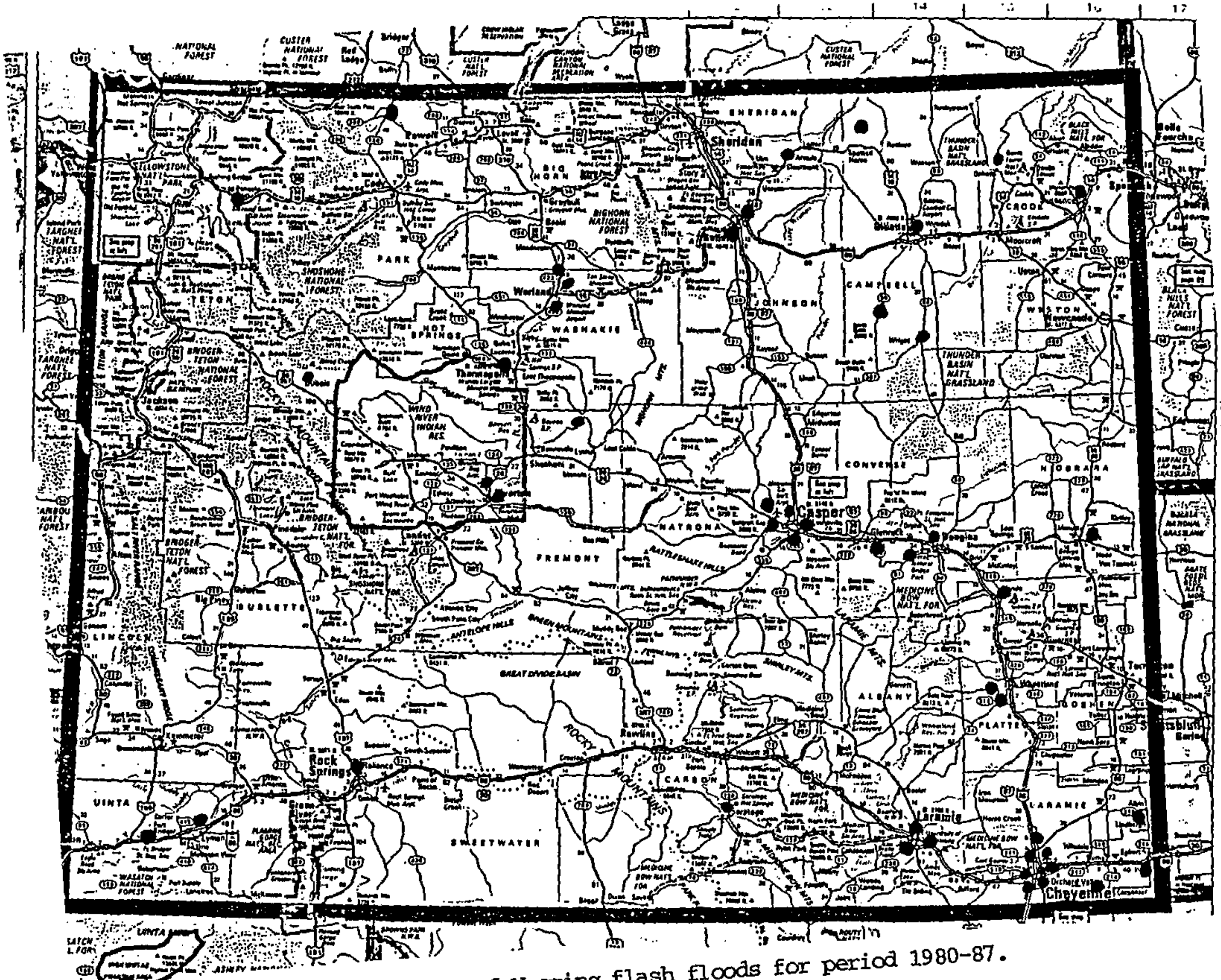

Fig. 2. Geographical locations of Wyoming flash floods for period 1980-87. Black dots denote each flash flood report.

4. Surface Weather Pattern and Wind Flow

Figure 3 shows a composite surface analyses associated with flash flood-producing convective storms over Wyoming. It is very similar to the surface pattern derived by Doswell (1980) for High Plains severe thunderstorms with or without heavy rains. This similarity, therefore, concurs with the study by Maddox et al. (1980), which noted that western U.S. heavy convective rainfall events usually accompany thunderstorms which often produce large hail and damaging winds. In fact, of the 38 days with flash floods over the state, 17 such days also had severe thunderstorms which produced large hail, damaging winds, or even tornadoes.

Figure 3 denotes a most typical scenario at the surface about three hours before flash flood development. An extensive surface high pressure area is centered, on the average, northeast of Wyoming in the northern Great Plains. A high pressure center could also be found due north or east of Wyoming. Examination of individual cases showed that, in reality, the high pressure center was often found either due north or east of Wyoming. However, the northeast location appeared to be the most preferred.

West of the Continental Divide a broad low pressure area covers the western quarter of the Nation. In the desert regions, from Arizona northward into central California and Nevada, warm case low pressure develops from extremely hot temperatures in the lower troposphere and thus lies under relatively high pressure aloft. Low pressure in the northwest area of the U.S. usually correlates to a surface front and/or a middle and upper tropospheric trough lying off the West Coast. However, in some instances, synoptic scale diabatic heating may be so extensive that the desert heat low expands as far north as Idaho.

The surface pressure gradient configuration over the western half of the U.S. favors a northeast to southeast wind over most of Wyoming. In cases of deep convection such a wind often transports moist air into the plains and foothills east of the mountains (Maddox et al., 1981), with dew points usually near or above 50°F around the heaviest rainfalls. Of equal importance is the resultant easterly component to the wind creating the commonly called "upslope flow" in which the elevated terrain forces lower level upward vertical motion.

Figure 4 is a map showing the terrain elevation across Wyoming. Given the mean surface pressure gradients shown in Figure 3, it is clear that there are favored regions for upward motion, especially over the plains and foothills east of the mountains. For example, Cheyenne is located such that air coming anywhere from a northerly to southeasterly direction at the lower levels is forced upward by the irregular terrain. Sheridan is just east of the Big Horn Mountains where an easterly wind component would lift a surface air parcel from 5,000 to 9,000 feet above sea level over a relatively short horizontal distance. Similarly, northerly to easterly winds would cause upslope conditions around Casper and indeed as far west as Lander. Given a convectively unstable air mass over these regions, such terrain forcing could trigger numerous thunderstorms.

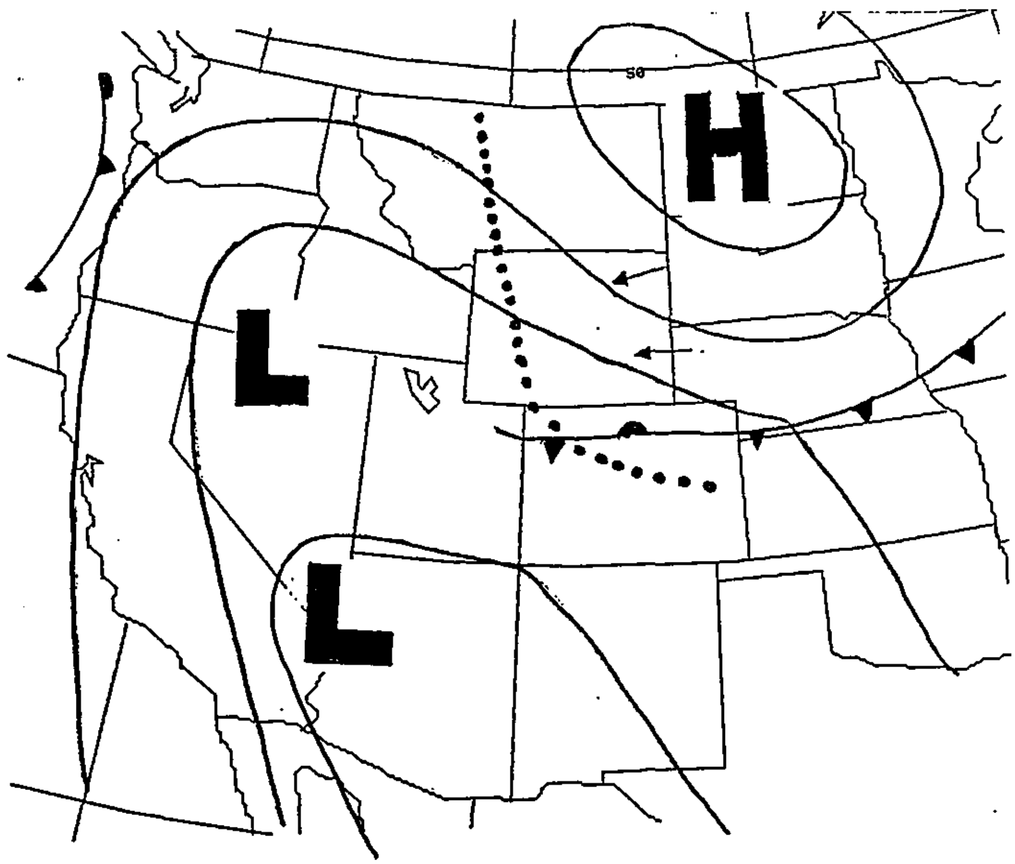

Fig. 3. Composite map depicting synoptic weather pattern at the surface several hours before flash floods occur over Wyoming. Frontal symbols are conventional with "H" and "L" signifying pressure centers. Arrows indicate surface wind and solid lines of the isobaric configuration. Surface dew points equal to exceed 50°F to right of dotted line.

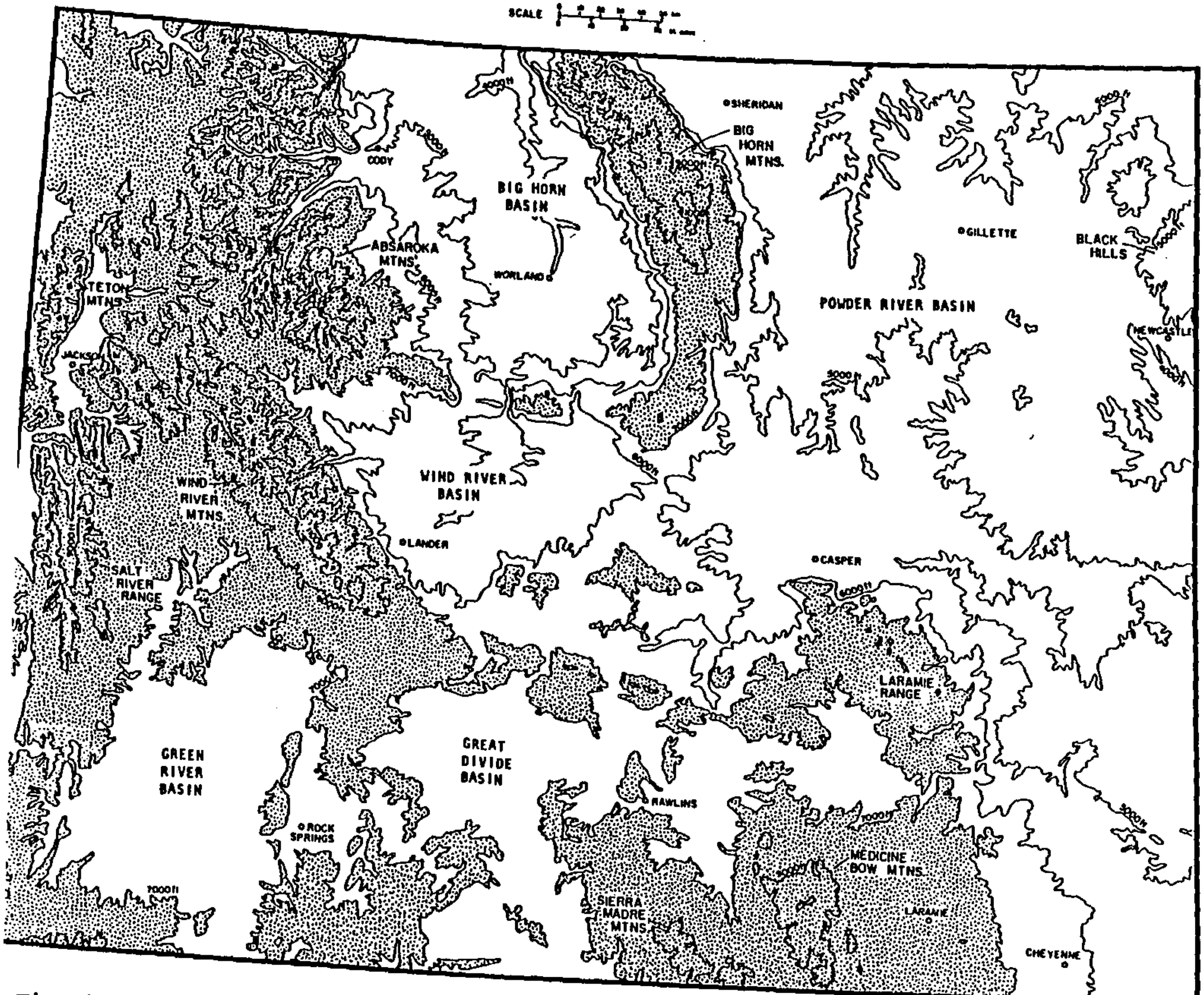

Fig. 4. Topographic map of Wyoming. Regions above 7,000 feet are shaded.

The irregular terrain may also influence the surface winds on the meso-alpha scale over Wyoming independently from the synoptic pattern, especially in the east. The differential heating between an elevated surface and the free atmosphere at the same height often creates a type of inland sea breeze affect with warm air moving toward the higher elevations during the day (Pielke and Segal, 1986). Toth and Johnson (1985), using mesonet data, found a mean easterly wind component developing during the afternoon over the surfaces of the Eastern Plains and foothills of Colorado during the summer months.

Since the general terrain features of Wyoming are similar to those of Colorado (i.e., plains in the east giving way to mountains in the center) it is suggested that state geography would also induce upslope winds via the differential heating just described. The prime result is during days with flash flooding, the synoptic pattern enhances the diurnal trend of upslope flow and with it, forced upward vertical motion.

The position of the surface front and the timing of its passage with respect to areas of deep convection were variable over the eight year study. However, in all but four of the days examined, flash flooding occurred north or on the cool air side of the frontal boundary. The front was as close as within ten miles of heaviest rains but could also be as distant as 500 miles or more. The most common position of the front was from southern Wyoming to northern New Mexico.

In cases where heaviest rains fell on the cool side of a front, flooding developed anywhere from less than one hour to over 24 hours after frontal passage. However, in over 70 percent of these cases (27 days), flash flooding developed over areas in which a cold front had passed after eight hours. This is similar to Doswell's study which found High Plains deep convection usually formed well after a surface front moved through the region.

Although flash floods were a pre-frontal phenomena in only four of the 38 cases, they deserve a brief description. In each of the four cases the surface patterns were similar in that a cold front approached northwest Wyoming while a pre-frontal trough was located in eastern portions of the state. A composite surface map is shown in Figure 5. This composite suggests that moist air flows ageostrophically into the trough from the south. Thus, low level convergence is maximized along the boundary, forcing upward motion which produces the heaviest rainfalls in the vicinity of this axis. These troughs are partly thermal in origin with an orientation near the 1000-500 mb thickness ridge.

5. 500 mb Flow Characteristics Preceding Heavy Rainfalls

Figure 6 shows the 500 mb flow pattern most often found over the western U.S. on Wyoming flood days. A broad area of high pressure aloft is centered over the south central part of the country with a stationary long or medium wave trough along the West Coast. In response to these features, the wind direction in the middle and upper troposphere is southwesterly, flowing from near southern California into the central and northern Rockies. Thus, moisture is transported into the region from the eastern Pacific. This pattern is similar to that

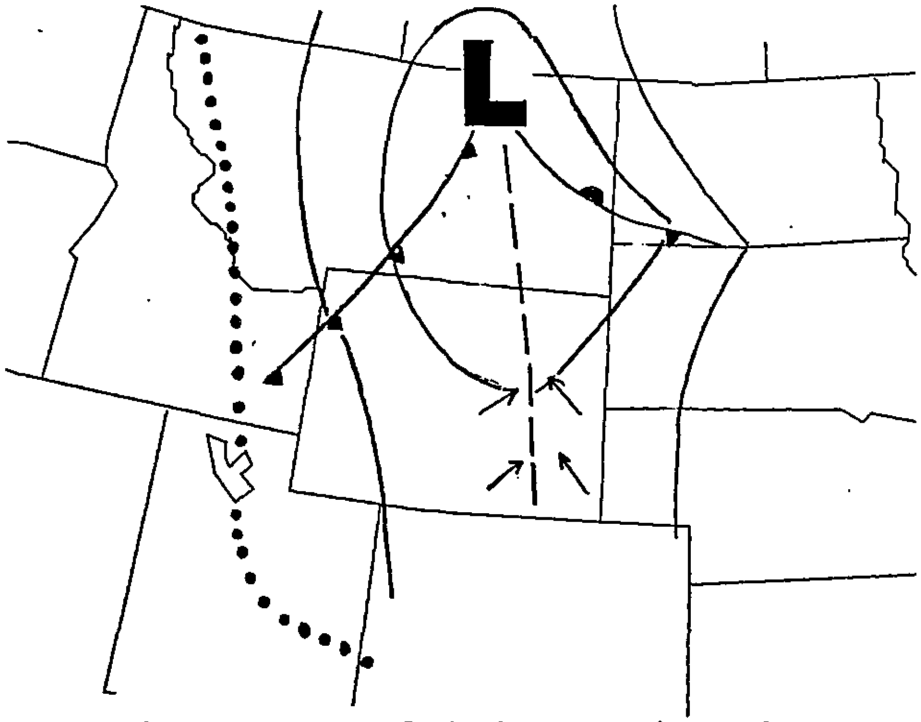

Fig. 5. Composite surface map depicting synoptic weather pattern for pre-frontal flash floods over Wyoming. Details same as Fig. 3.

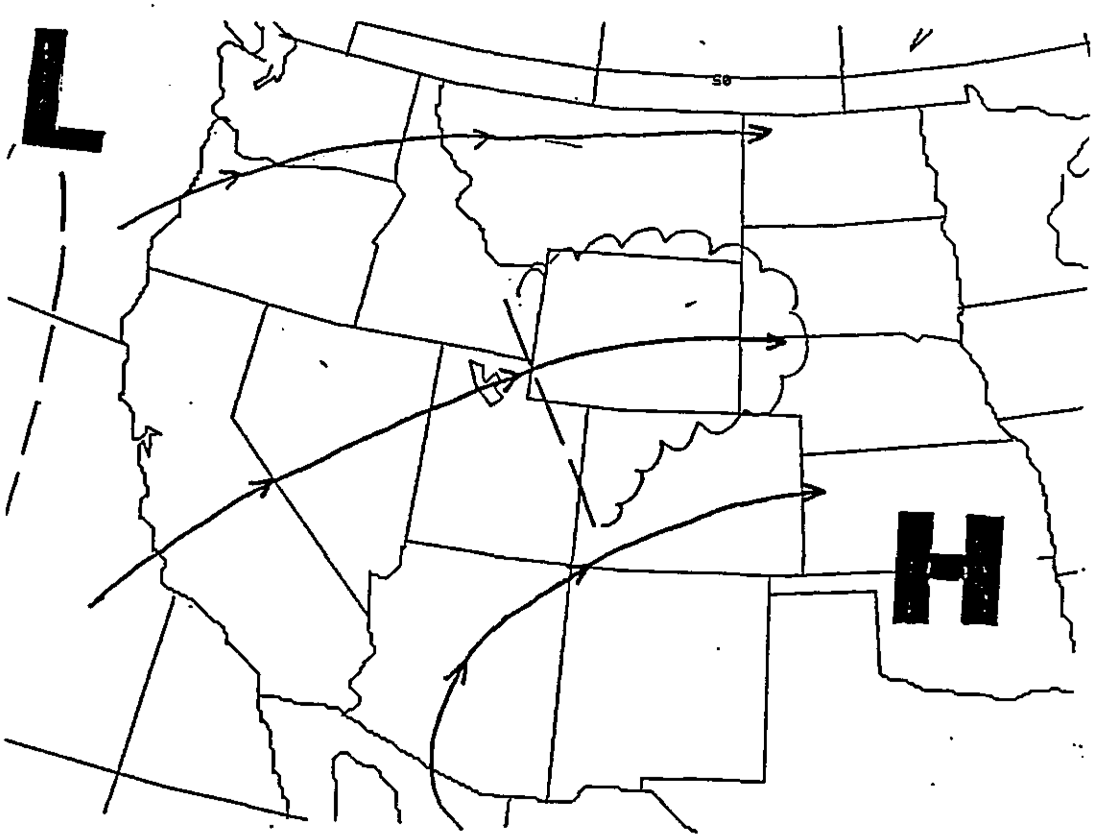

Fig. 6 500 mb Maps showing general synoptic patterns three to six hours preceding Wyoming flash flood occurrences. Streamlines as well as conventional symbols for pressure centers and trough and ridge axis are used. Scalloped area encloses region where dew point depression is equal to or less than 6°C. See text for further details.

depicted by Doswell as being associated with eastern High Plains severe thunderstorms. But there is also a resemblance to the 500 mb pattern often found with heavy rainstorms in the northern and central Rocky Mountain region (Maddox et al., 1980). The Maddox study also found that over half of such storms occurred in conjunction with severe thunderstorms.

Variations of this pattern can occur without reducing the potential for heavy rains over Wyoming. In many instances, the West Coast upper long wave trough deepens and moves into the extreme western U.S. while to the east, an extensive high pressure area builds over the Central Plains (Fig. 7). This leads to a more southerly flow from northern Mexico through the Rocky Mountain states with advection of tropical moisture from the Gulf of California or Mexico. Wyoming precipitable water values may be especially well above normal within this type of pattern.

Conversely, a lesser number of days had the upper high center or ridge axis west of the Continental Divide with a westerly or northwesterly wind at 500 mb over Wyoming (Fig. 8). Moisture transport aloft was not as great given the lack of southerly component to the winds. But in this study, heavy rains did fall with northwest winds aloft when there was sufficient instability and adequate moisture at lower levels.

Figures 6 through 8 all indicate a short wave trough embedded in the prevailing flow just west of Wyoming preceding deep convection. This study confirms those by Doswell and Maddox et al. (1980), that such waves are usually poorly defined, especially during the summer months, and may not be easily detected using conventional upper air wind data. As they suggest, close scrutiny of cloud patterns on satellite images may give the best clue as to the position and movement of these disturbances.

Nevertheless, there are days with deep convection over the Rocky Mountain states when upper short waves may be absent. Instead, thunderstorms are triggered by terrain lifting at lower levels via upslope winds plus diurnal heating of the boundary layer to its temperature of convection. In short, a lack of 500 mb positive vorticity advection (PVA) by no means precludes flash flooding over Wyoming provided other favorable convective triggers exist.

6. Vertical Profile of Air Mass

Using available upper air and surface analyses, a sounding was constructed based on average atmospheric conditions about one to three hours prior to heaviest rains (Fig. 9). There is a large variability for some of the temperature and wind data at several levels. For example, surface temperatures in flash flood situations ranged from the middle 50's to the upper 90's for the period studied. Wind directions at 700 mb were found for all four quadrants of the compass while 200 mb wind speeds were as low as 15 kts and as high as 70 kts. Therefore, this sounding should be considered more of a typical example instead of a composite encompassing most cases.

But despite these variabilities, important consistencies were found for the vast majority of cases. First, an unstable air mass was always present with the lifted index averaging -4 for locations which experienced flash floods.

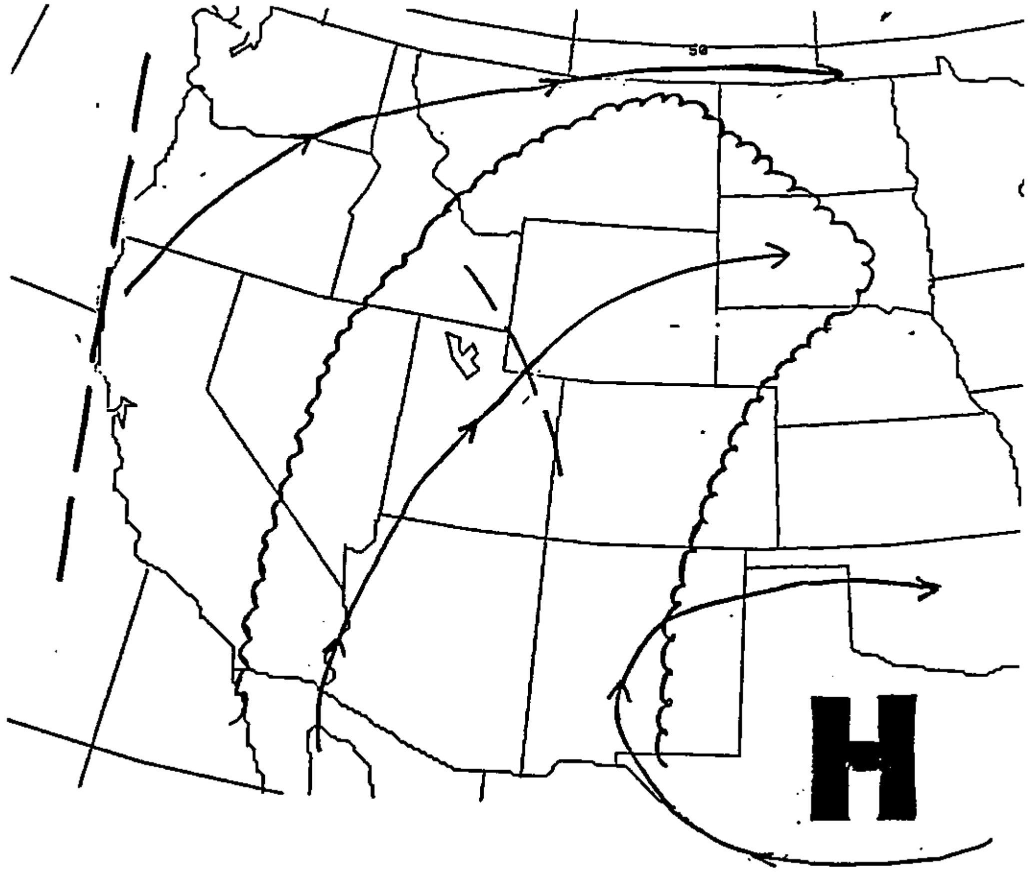

Fig. 7   Same as Fig. 6.

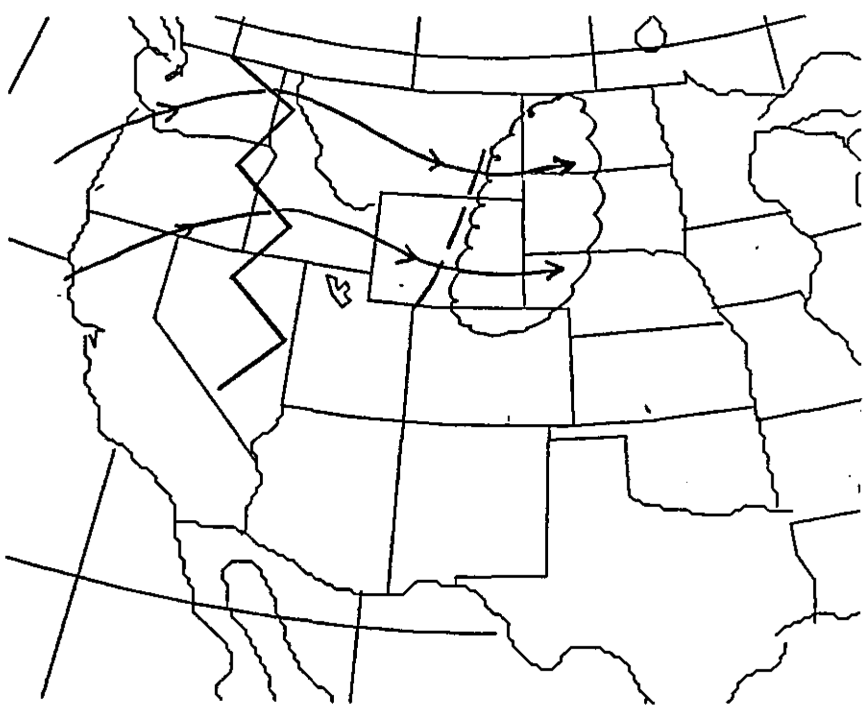

Fig. 8   Same as Fig. 6.

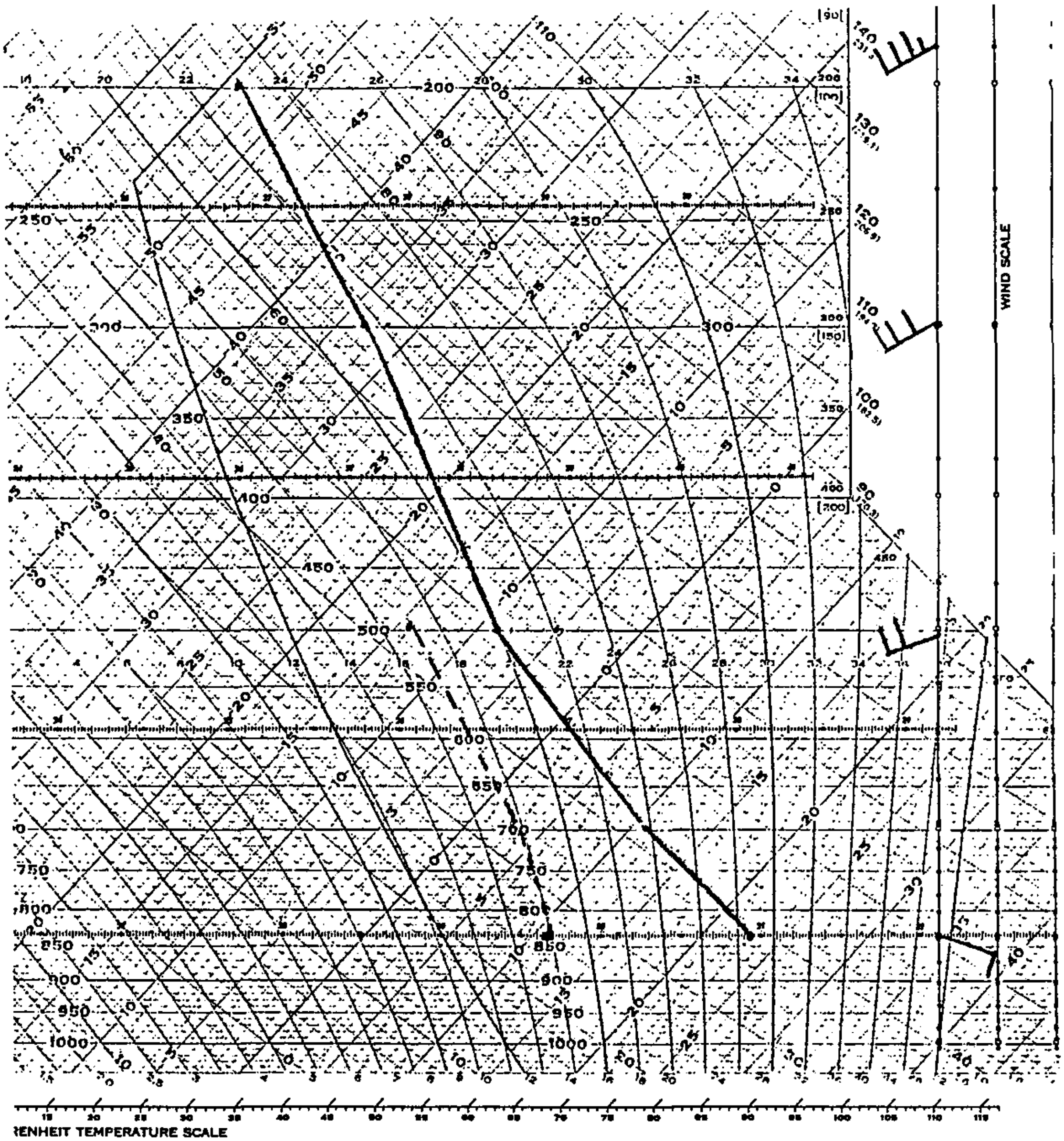

Fig. 9. Average vertical sounding of air mass associated with Wyoming flash floods.

Furthermore, the lifted index was never higher than -2 for such days. Low level moisture often made the difference between a stable and unstable sounding, especially during the summer months when surface temperatures are at their highest.

A second consistency, related to the first, was that the moisture content was high over areas experiencing heaviest rains. Surface dew points were rarely below 45°F while the 500 mb dew point depression on most days deviated little from its average value of five. Average precipitable water from the surface to 500 mb totaled .88 inch (2.20 cm) which is 175 percent above normal. The importance of this is two fold. Low level moisture is what ultimately feeds into the thunderstorm updraft, condenses aloft and falls out as rain. Moisture aloft directly contributes little to the amount of water vapor entering a convective updraft. However, it does reduce the erosion of an existing updraft by entrainment and mixing and thus increases precipitation efficiency.

Finally, with very few exceptions, flash floods were in an environment where surface winds had a marked easterly component while winds at 500 mb and above had components from the west and/or south. Such veering with height has been shown to strengthen thunderstorm updrafts by creating an upward directed dynamic pressure gradient (Weisman and Klemp, 1982). By intensifying the updraft, such a shear ultimately contributes to rainfall production and overall thunderstorm intensity. Thus, it is likely the predominant vertical wind profile is a major reason why many of Wyoming's flash floods are produced by severe thunderstorms.

7. Case Study of a Wyoming Flash Flood

During the evening of July 22, 1984, torrential rains in conjunction with severe thunderstorms struck southeast Wyoming. Flash floods just west of Wheatland (50 miles north of Cheyenne) extensively damaged homes and especially crops with some persons forced to evacuate the area. Thunderstorms also produced golfball-sized hail and strong winds with overall damages in the millions of dollars.

Figure 10 shows the 12Z surface map for the continental U.S. A cold front had passed southeast Wyoming the previous day and was quasi-stationary along the Colorado-Wyoming border. High pressure covered southwest Canada and the northern Rockies while a broad surface low was along the West Coast. The pressure gradient over southeast Wyoming favored a northeasterly wind which advected moist air into the area as dew points were near 60°F around the Wyoming-South Dakota border. However, dryer air with dew points near 40°F was in Montana advecting into eastern Wyoming possibly reducing the low level moisture.

More detailed analyses begin at 00Z several hours before flash floods and severe thunderstorms struck southeast Wyoming. At the surface, subtle but important changes had occurred over the past 12 hours (Fig. 11). The high pressure center was now in northern Wyoming while troughing was intact west of the Continental Divide. As a result, the easterly wind component increased over southeast Wyoming which in turn allowed a continuous inflow of moisture while simultaneously creating upslope lifting at lower levels.

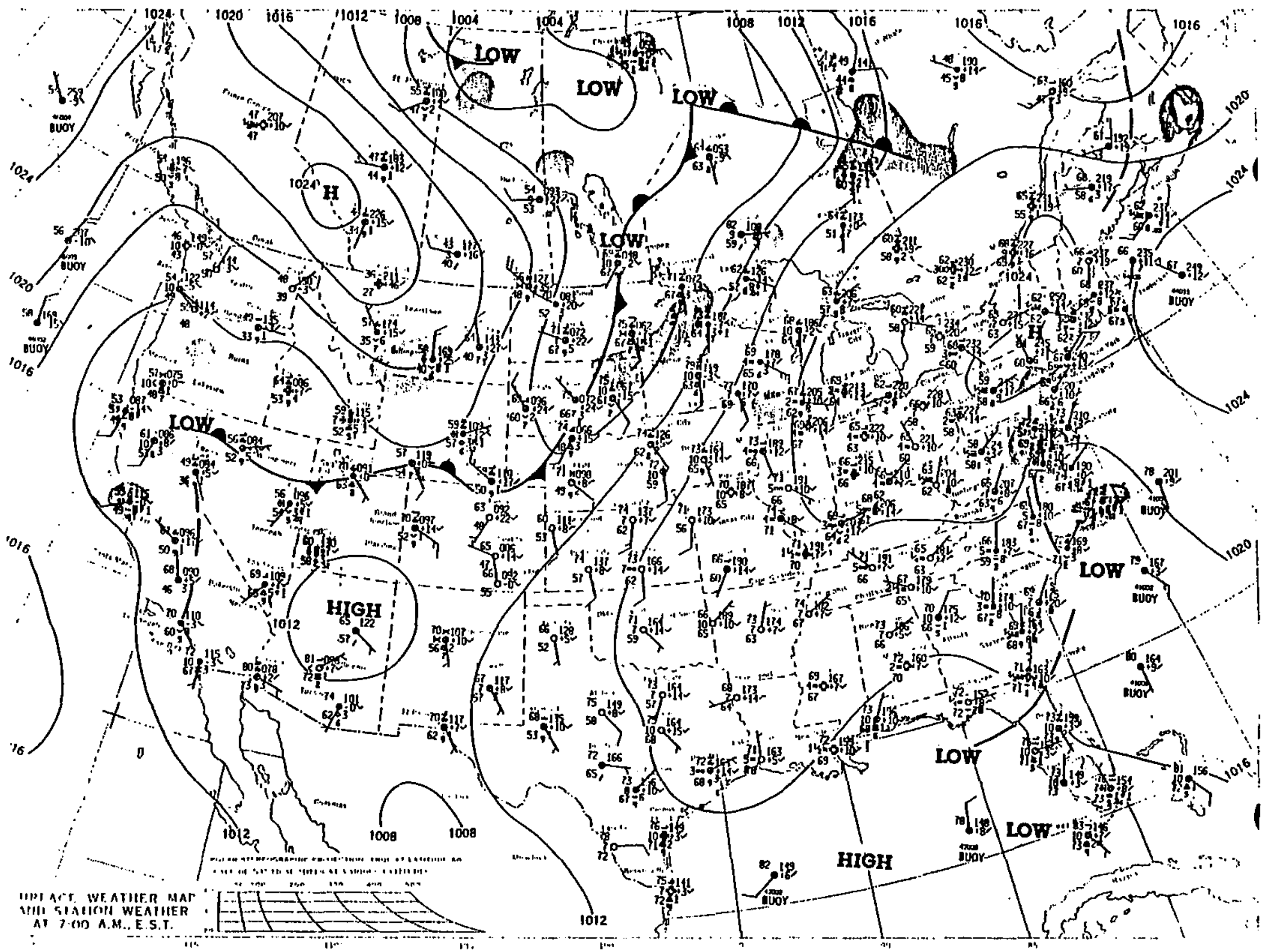

Fig. 10. NMC surface map for 12Z, July 22, 1984.

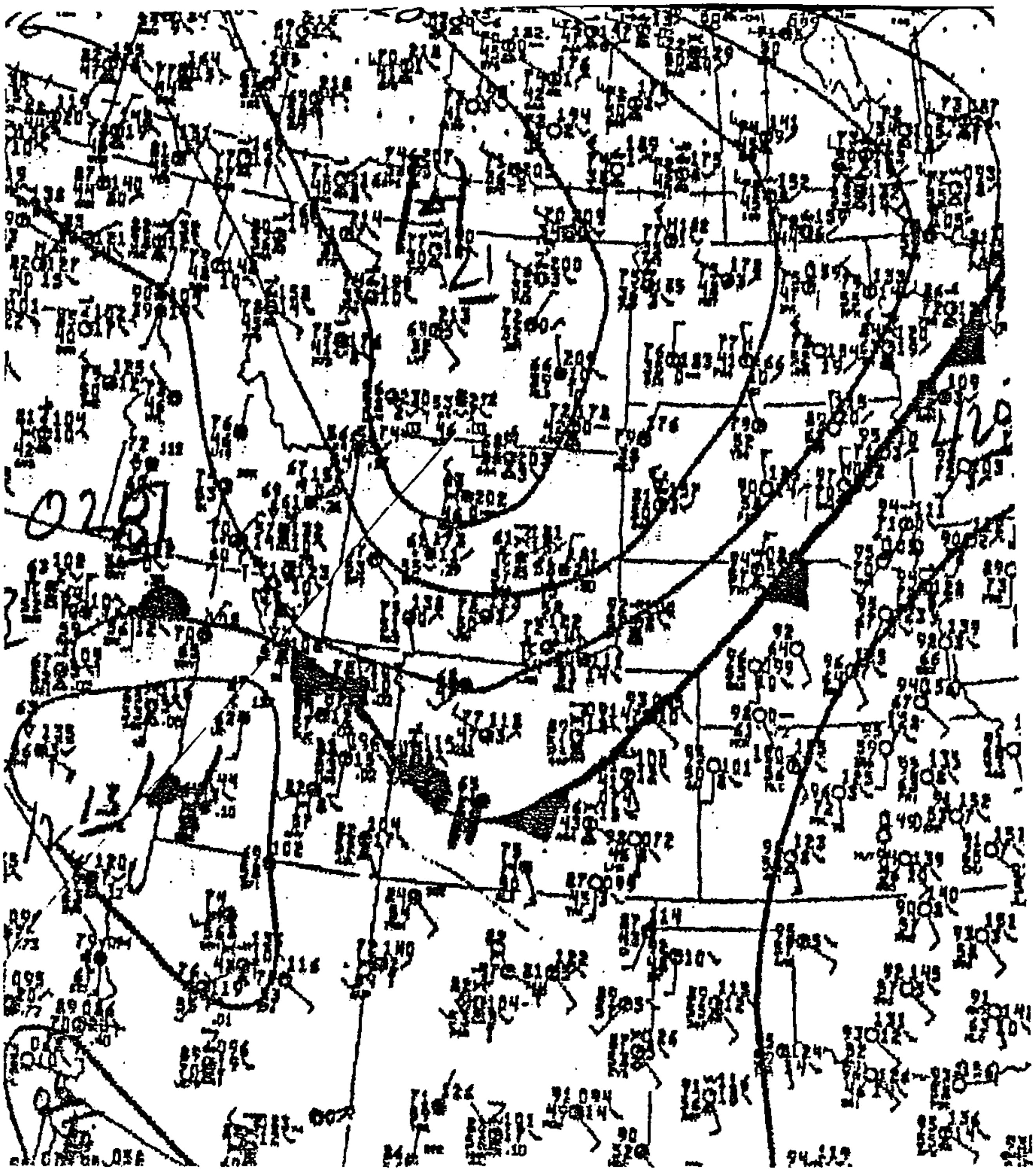

Fig. 11. NMC surface map for 00Z, July 23, 1984.

In the middle troposphere, the 500 and 700 mb levels were much alike on the synoptic scale (Figs. 12 and 13). A closed low off the West Coast combined with high pressure centered in the Midwest to generate a pronounced southerly wind component over the western U.S. with tropical moisture advecting from northern Mexico. While the flow brought moisture aloft into the region, there was evidence that the upper flow was contributing to weak dynamic lifting.

An examination of the winds give hint of a weak short wave embedded in the flow and entering Wyoming from the southwest. Figure 14 shows weak moisture convergence at 700 mb. Finally, maps of vorticity advection (Figs. 15 and 16) show neutral advection at 500 mb with positive values at the 300 mb level. Therefore, the evidence suggests that thunderstorms were triggered in a moist unstable atmosphere by a combination of terrain lifting from upslope winds in conjunction weak dynamic forcing aloft.

The air mass was very likely unstable over southeast Wyoming during the time deep convection developed. The afternoon high temperature at Wheatland climbed to 92 while dew points were around 55. From the available surrounding upper air data, Wheatland had an estimated -4 lifted index despite above normal 500 mb temperatures. Precipitable water from the surface to 300 mb was about one inch or 180 percent above normal. A comparison of the surface and 500 mb charts also gives evidence of significant directional wind shear with height with surface easterlies beneath southwesterlies aloft.

Figure 17 shows a 0030Z radar plot as well as local 00Z observations for southeast Wyoming and western Nebraska. Strongest activity is 12 miles north of Cheyenne where an isolated cell reached a level 6 reflectivity. A larger area of moderate to heavy thunderstorms was over the Laramie Mountains and Valley in Albany County and in the plains north and northeast of Wheatland, particularly over Platte County. Surface temperatures over southeast Wyoming fell into the 70's and lower 80's due to outflow plus cloud coverage associated with the area convection. However, hot moist air remained over Nebraska as indicated by Scottsbluff's temperature of 92 and dew point of 58. East to northeast winds continued to advect this air into southeast Wyoming toward the developing thunderstorm complex and maintained an inflow of unstable air which allowed the storms to persist. Thus, given the instability of the air mass, the above normal moisture content, upslope lifting and the vertical shear, deep convection was almost inevitable over southeast Wyoming during the evening.

8. Summary and Conclusion

This study investigated flash flood events over Wyoming for the period 1980 to 1987 to determine the meteorological conditions most favorable for heaviest rains over the state. It is found that such storms are most common during the mid-summer months when surface heating is greatest. Convective storms which produce flash floods and are most frequent over eastern portions of the state which, in part, is due to the surface weather pattern which frequents this region.

This pattern includes high pressure at the surface over the northern Rockies or northern and eastern Great Plains with a broad area of low pressure usually over the southwest deserts and sometimes extending to the Pacific

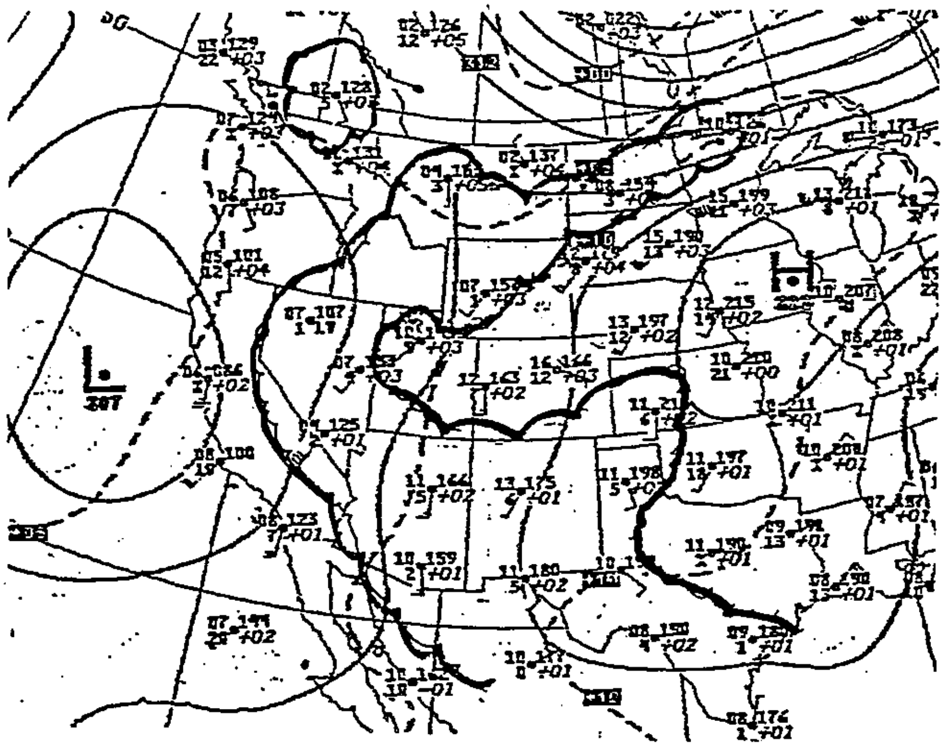

Fig. 12. Map of 700 mb for 00Z, July 23, 1984. Dew point depressions less than or equal to 6°C enclosed by scalloped regions.

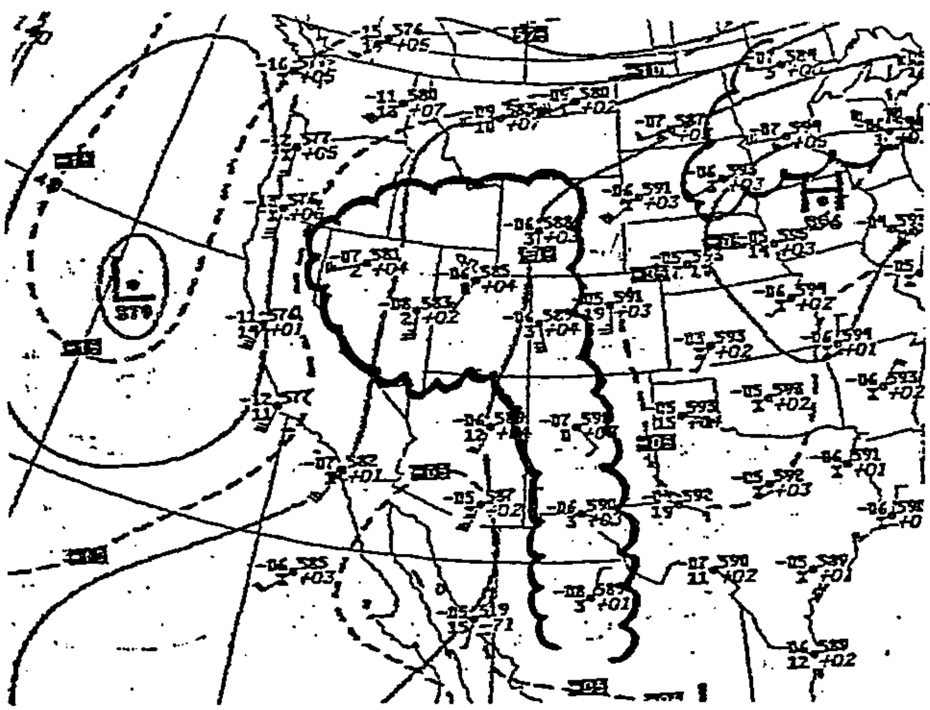

Fig. 13. Same as Fig. 12, except for 500 mb.

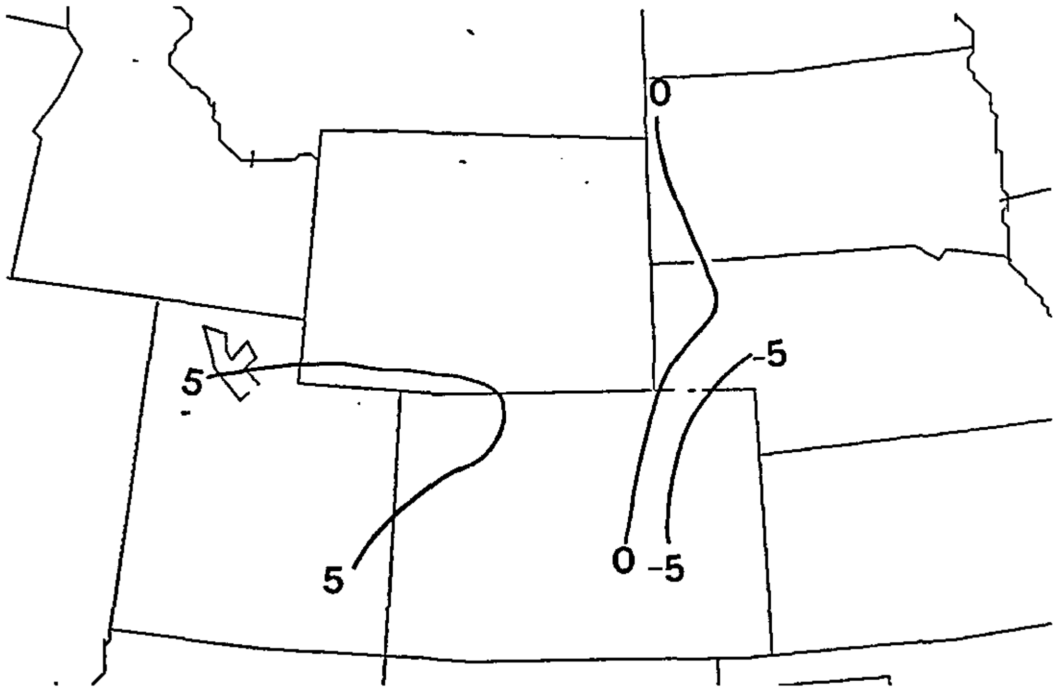

Fig. 14. 700 mb Moisture convergence at 00Z, July 23, 1984. Units are gr/kg $sec^{-1} \times 10^{-5}$.

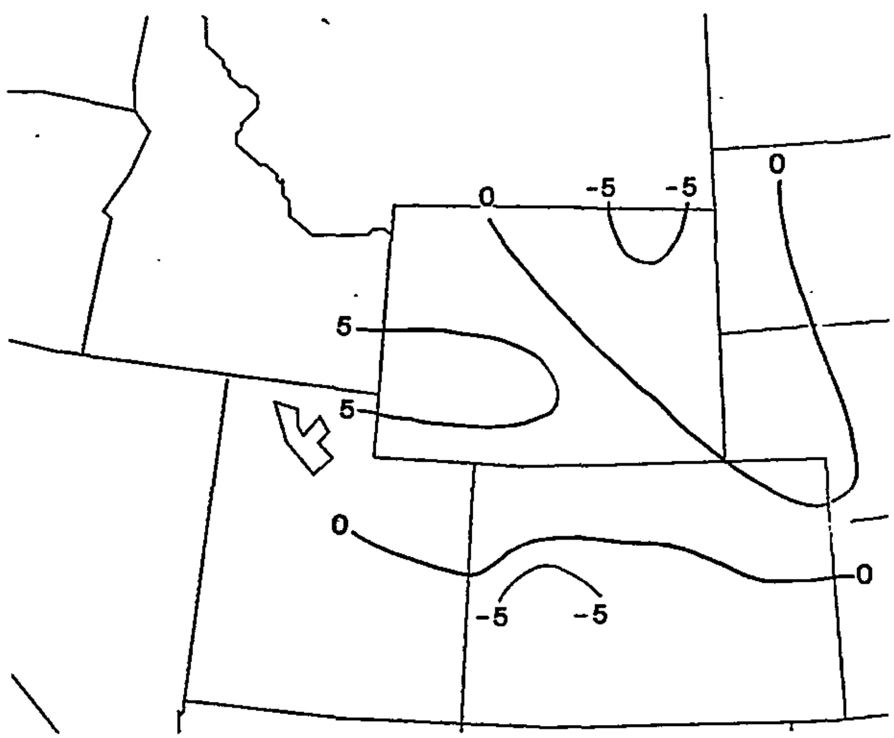

Fig. 15. 500 mb Vorticity advection for 00Z, July 23, 1984. Units are $sec^{-2} \times 10^{-10}$.

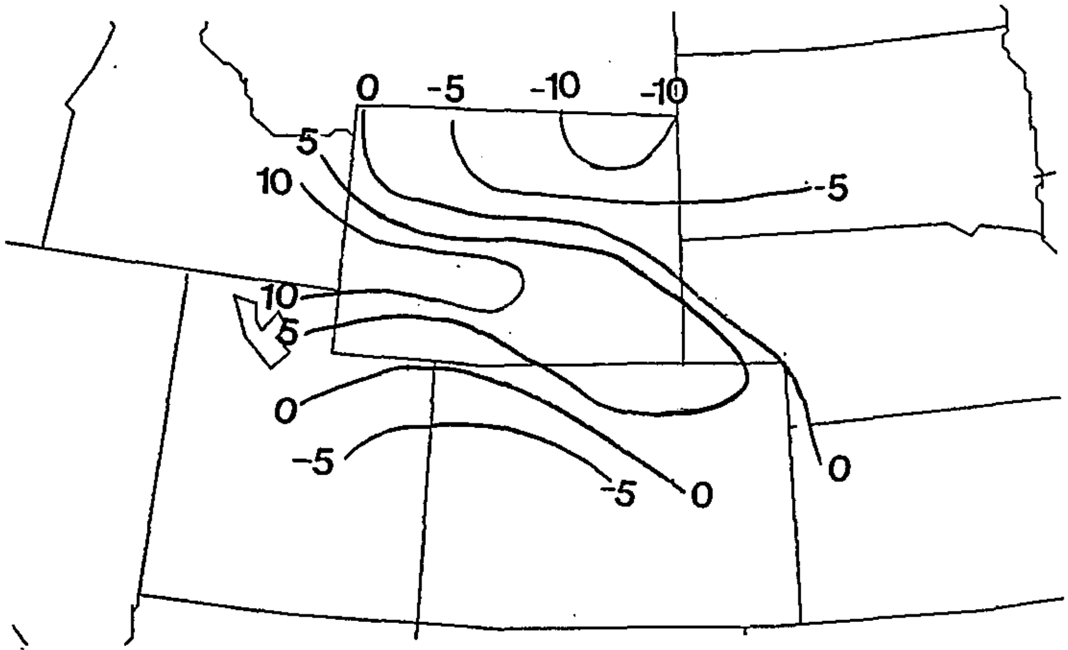

Fig. 16. Same as Fig. 15, except for 300 mb.

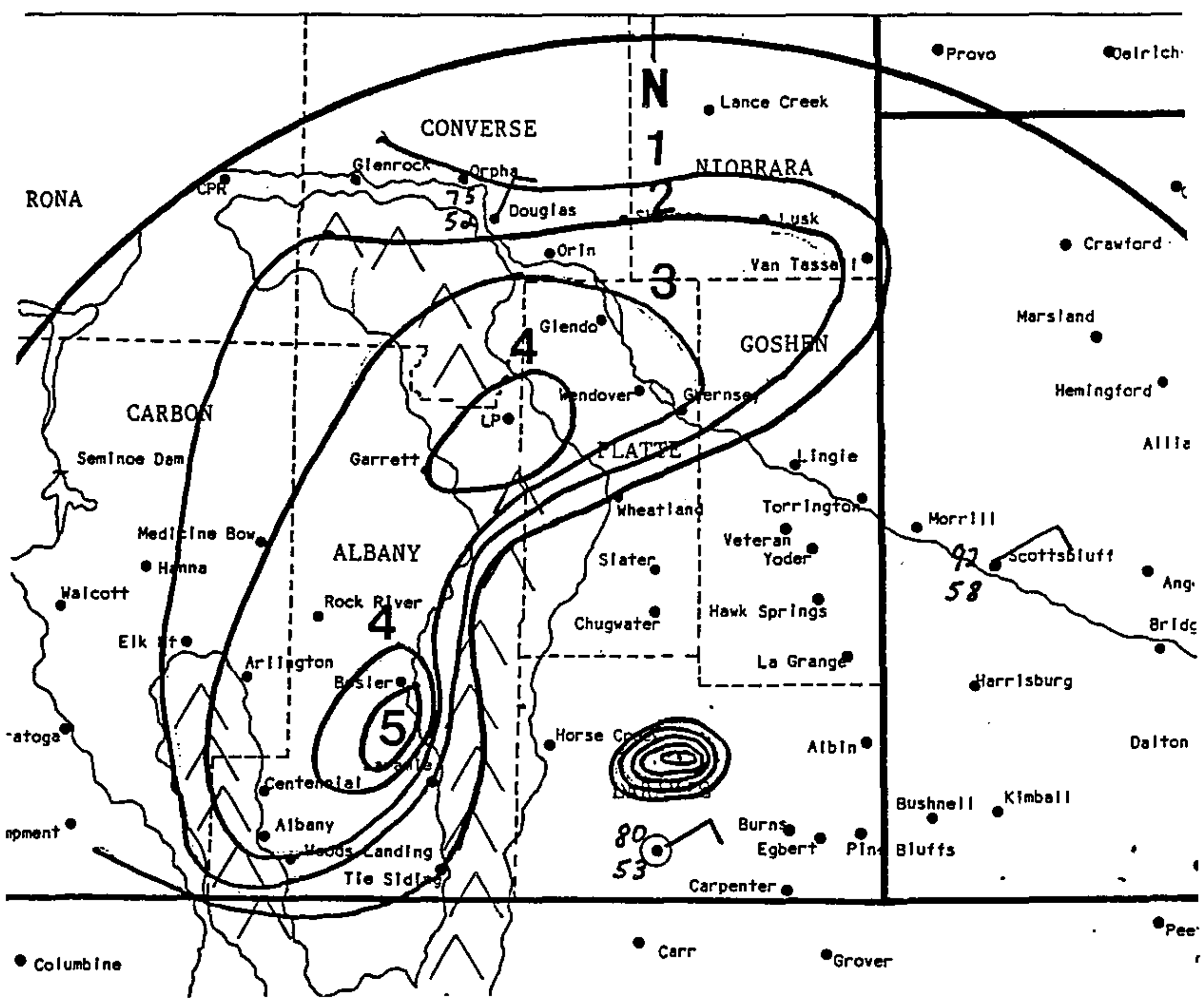

Fig. 17. Plot of radar reflectivities over southeast Wyoming as detected by Cheyenne WSR74C radar at 0030Z. VIP levels are contoured. Local 00Z observations also included.

Northwest. Such a pattern results in an easterly surface wind component over Wyoming with both advection of moisture and terrain-induced lifting in the lower troposphere, especially in eastern sections.

In the middle levels, winds have a westerly and sometimes southerly component through Wyoming with moisture flowing into the state from the Pacific or from the tropics by way of Mexico. In addition, short wave troughs may be embedded in the flow to provide dynamic lifting of the air mass over Wyoming. But it is important to remember that upslope lift alone can trigger convection even if such short waves or PVA aloft are absent, especially if the air mass is moist and unstable.

Wyoming convective storms with flash flooding invariably form in moist unstable air. The average lifted index for such days is -4 with precipitable water almost twice the normal amounts. In addition, the directional vertical wind shear is very pronounced with low level easterlies usually beneath middle and upper tropospheric southwesterlies. As a result, when convection does develop, the updrafts are dynamically forced with thunderstorms producing torrential rains and occasionally large hail, strong winds and even tornadoes.

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