NOAA Technical Memorandum NWS HYDRO 46

A CLIMATIC ANALYSIS OF OROGRAPHIC PRECIPITATION OVER THE BIG HORN MOUNTAINS

Hydrometeorological Design Studies Center
Office of Hydrology
Silver Spring, Md.
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U.S. DEPARTMENT OF COMMERCE
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U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary
National Oceanic and Atmospheric Administration
D. James Baker, Under Secretary for Oceans and Atmosphere
National Weather Service
Elbert W. Friday, Jr., Assistant Administrator for Weather Services

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A CLIMATIC ANALYSIS OF OROGRAPHIC PRECIPITATION OVER THE BIG HORN MOUNTAINS

Agnes Takacs[1], John L. Vogel[2], Peter Corrigan[2]
and Susan Gillette[2]

[1]Division of Weather Forecasting
Meteorological Service of the Hungarian Republic
Budapest, Hungary

[2]NOAA/NWS, Office of Hydrology
Silver Spring, Maryland

ABSTRACT

An analysis of orographic precipitation patterns in the Big Horn Mountains of Wyoming and Montana was made using climatic data from 1980 through 1990. Annual, seasonal and monthly spatial patterns were examined using data from 83 stations in and around the Big Horn Range, at elevations ranging from less than 3,000 feet (914 meters) up to nearly 10,000 feet (3048 meters). The variation of precipitation with elevation during a number of individual storm events was also examined and these orographic factors were compared to the monthly and seasonal averages. Significant differences in factors were found between the averages and those occurring in specific storms. A synoptic climatology of precipitation producing storm types for the Big Horns was developed in order to examine the effect of these various storms on the distribution of precipitation with elevation. A total of 108 storms, ranging in length from 2 to 11 days, were selected for the analysis. The eight storm types and a ninth miscellaneous category which were identified, showed considerable variation in orographic factors and precipitation characteristics. Some storm types were far more effective in generating precipitation at high elevation (high orographic factors) than other types. It is anticipated that such a classification system would form the basis for improved estimates of rainfall and snowfall in other mountain areas.

1. INTRODUCTION

Precipitation provides water for drinking, irrigation, recreation, transportation, industry, and other needs. However, too much precipitation can generate general floods and flash floods. Consequently, water managers, planners, and hydrologists are interested in the volume of precipitation that falls over both small and large catchments. For example, information about the amount, spatial, and temporal distribution of precipitation from storms in real time over a season is used to predict the streamflow or reservoir storage. This is especially important in mountainous regions where precipitation is often enhanced by topography. In the mountains large quantities of precipitation in the form of snow is stored waiting for the spring thaw. In the warm season mountains can act as the perturbation to initiate rainstorms, and often are the only areas over which rain falls.

Information about the spatial distribution of precipitation in near real time and for historical purposes is usually obtained from raingauge reports supplemented by snow surveys, radar, and satellite observations. The spatial distribution of rainfall is a difficult enough parameter to define over flat terrain because of a lack of observations. Over mountains the spatial distribution of precipitation is even more difficult to estimate, and can only be approximated for individual catchments or over large areas because of even fewer observations (Hiatt, 1953; Peck and Schaake, 1990).

Estimates of the spatial distribution of precipitation for the western mountainous regions involves two different scales: the general storm scale which dominates in the cold season, and mesoscale storms which control in the warm season. During the cold season snow accumulates in the mountains forming a reservoir of water held in place by freezing temperatures. Snowfall often increases with altitude because of the forced lifting of the moisture into lowered temperatures and the resulting condensation. The spatial distribution of the water equivalent of snow is difficult to define in any detail because of a lack of raingauges at higher elevations and the inability to monitor or forecast quantitatively the precipitation in storms that falls throughout the winter. Accurate estimates of the precipitation stored in the mountains are needed to provide information about the magnitude of spring flooding (Cudworth, 1989).

During the warm season, convective storms are the main causes of heavy precipitation and again it may be difficult to quantify the amount or location of precipitation in mountainous areas. Intense, isolated storms often form over relatively small areas causing flash floods (Maddox, et al., 1977). Less frequently, general storms with embedded intense mesoscale convective storms can cause general flooding (Reid, 1975).

It has been widely observed and accepted that precipitation usually increases with elevation, at least up to some critical elevation. At the same time, the amount of moisture within the atmosphere available for precipitation decreases with elevation. Recent paleohydrological investigations (Jarrett, 1989) hypothesize that significant rains do not occur above 7500 feet (2286 meters). However, other observational evidence for the same region of the Rocky Mountains does indicate intense thunderstorm rainfall above this level (Henz and Kelly, 1989). Hanson (1982), using a dense raingauge network in Southwest Idaho, found only a slight increase in precipitation with elevation during summer months. In winter the precipitation was found to increase significantly with elevation.

The main objective of this research is to investigate the variation of precipitation with elevation across the Big Horn Mountains of Wyoming and Montana. This variation is looked at in terms of seasonality and with regard to different synoptic weather regimes. A future objective is to determine how orographically induced vertical motion triggers the release of potential instability to create or enhance the amount of precipitation which originates within the larger-scale weather system (Orlanski, 1975).

Research on orographic precipitation points to the scale problem in the atmosphere. Cotton and Anthes (1989), in a review of orographic precipitation, showed that the air motions, thermodynamics, and precipitation processes associated with clouds do not operate in isolation. Instead they are dependent upon and interact with a broad range of scales of motion spanning the scale from the global atmosphere down to turbulent eddies of a few tens of meters. The atmospheric processes which produce precipitation are very complicated, and the numerical models need to make many simplifications in order to study the dynamics of a storm (Colton, 1976).

Operationally, quantitative precipitation forecasts (QPFs) are made using numerical prediction models. The reliability and accuracy of precipitation forecasts vary from model to model because of variations in grid sizes, simplification in model physics, and different representations of the triggering mechanisms that initialize the heaviest precipitation. Since intense precipitation events usually occur in the mesoscale, a mesoscale model that incorporates orographic effects should be used to improve QPFs for forecasts ranging up to 24 to 36 hours. Such a model should incorporate both convection and mesoscale storm dynamics for both the warm and cold seasons. Parameterization should be able to describe the mesoscale precipitation features peculiar to specific areas (hydrologic catchments) in an effort to meet the hydrologist's needs.

A number of numerical mesoscale models are available today with fine resolution that are capable of treating the interaction between different scales. Meyers and Cotton (1992) demonstrated the feasibility of producing QPFs with an explicit cloud model. Another model capable of forecasting intense rainfall amounts is the National Meteorological Center's Eta model (Black, et al., 1990). Another possibility is the Limited Area Model (LAM) developed in the Swedish Meteorological and Hydrological Institute (SMHI). An advantage of this model is that a dynamical orographic precipitation model has also been developed, which utilizes the larger-scale numerical model and information about local orography to represent initial and boundary conditions (Gollvik, 1984).

In spite of the results of these advanced models, QPFs are most reliable over regions that have no orographic effects. This study attempts to increase our knowledge about the spatial distribution of precipitation in mountain areas. It is planned to use the information about the relation between non-orographic and orographic regions in operational forecasting by parameterizing atmospheric numeric models over mountains. This climatic analysis of precipitation shows some general features of orographic precipitation, and some local effects which would be difficult to incorporate in numerical models. It is anticipated that the factors describing orographic modification of precipitation from climactic analysis can be used to improve short-range QPFs (1-3 days), estimates of probable maximum precipitation, precipitation frequency studies, and even the near real-time estimation of storm precipitation in mountains.

2. LITERATURE REVIEW

Elliott and Shaffer (1962) developed quantitative relationships between orographic precipitation and air-mass parameters for use in forecasting. The study areas were the Santa Ynez mountains in southern California, an east-west oriented ridge of 3500 to 4000 feet (1067 to 1219 meters) elevation which parallels the West Coast, and the San Gabriel mountains, another east-west mountain range lying north of the Los Angeles basin, with average elevation of 8000 feet (2440 meters) and one peak over 10000 feet (3050 meters). Heavy orographic precipitation is often associated with prefrontal southerly winds which flow upslope in the vicinity of both mountain ranges (Weaver, 1962). Elliott and Shaffer used seven years of storm data and compared mountain and valley precipitation during storms. Storms were characterized by the air masses in which they occurred: unstable (superadiabatic lapse rate below the 750-mb level), stable, and mixed types. It was found that the largest orographic forcing occurred during the unstable regime. In the San Gabriel mountains about two-thirds of the precipitation events were from the unstable weather type, but these weather types produced approximately three-fourths of the mountain precipitation.

A relationship between instability and precipitation was developed by plotting hourly precipitation totals at higher elevation gauges against coastal gauges for associated peak values (Elliot and Shaffer, 1962). An extraordinarily high mountain to coastal plain precipitation ratio was found with some of the unstable cases. A lower envelope of precipitation was found that can be regarded as a direct measure of the non-orographic component of precipitation on the mountains. The amount by which the mountain precipitation exceeds the lower envelope was considered to be the orographic component of precipitation.

Hill (1983) used average annual rainfall to derive estimates of the orographic enhancement of frontal rain over England and Wales for different wind directions. The orographic enhancement was defined as the mean rainfall rate inland minus the mean rate over the upwind coast. The location of the upwind coast was determined from the 700-mb wind fields. The basic concept is that the average annual rainfall is dominated by the patterns which occur during the passage of frontal systems, and this pattern is strongly tied to the surrounding topography. The relationship between the rainfall patterns and topography was found to be much less during periods of thunderstorm activity. The main premise of Hill's paper was that low-level wind direction and speed can be used as indicators of the pattern and magnitude of orographic precipitation enhancement. Rainfall patterns conforming to the regional topography in the study area (England and Wales) were found to occur only for winds from southeast through west; other wind directions gave inconsistent results. Within this range of wind direction different categories of direction and speed were used to study the effects on rainfall distribution. The orographic fields obtained from the five wind categories confirmed that changes in wind direction have important effects on the distribution of the enhancement. The higher wind speed categories showed an increase in the overall level of enhancement over terrain receiving maritime winds. For forecasting purposes synoptic charts are used to estimate the wind speed and direction associated with the ratio, then the probable enhancement can be calculated for the appropriate field.

Jakus, et al. (1986) also studied the effects of elevation on the mesoscale distribution of precipitation in Hungary. Annual average precipitation amounts were determined for various elevation zones; then the annual average enhancement effects were calculated for each zone by dividing the zone averages by the base precipitation. The base precipitation was defined as the average precipitation for the lowest elevation zone. To improve the forecasting of precipitation amounts the weather types that were favorable for the formation of orographic precipitation were defined. The results from this analysis showed:

- the largest orographic enhancement was associated with southerly wind directions perpendicular to the mountains and hills,
- the maximum enhancement of the rainfall rate occurred within an optimal wind speed interval,
- the orographic rainfall pattern is determined by the wind direction, while any orographic enhancement of rainfall rate is defined by the wind speed and available atmospheric moisture.

3. PURPOSE AND METHODOLOGY

A key objective of this study is to determine the effect that topography has on precipitation. The development of orographic precipitation factors could be a valuable tool in the improvement of quantitative precipitation forecasts (QPFs) in regions of mountainous terrain or areas with sparse raingauge networks. A statistical approach was used due to the limitations of modelling precipitation processes in complex terrain. Precipitation amounts resulting from atmospheric-terrain interactions should over time incorporate the physical variation that actually exists over a particular barrier.

The aim of this study was to determine orographic factors as a function of a "base precipitation." Base precipitation was defined as an areal average precipitation close to the particular mountain range, but in an area with minimum orographic effect. For the purpose of constructing some cross sections the base precipitation was taken at an individual station in lower elevations.

The general region chosen for this study was the Big Horn mountains in Wyoming and Montana in the western United States. This U-shaped range (Fig. 1) is oriented northwest through southeast. Elevations along the crest line average over 8000 feet (2440 meters), with several areas over 10,000 feet (3050 meters). The highest elevations are observed on the eastern part of the range with isolated high peaks extending to 12 or 13,000 feet. Elevations along the southern ridge extend generally to about 7000 feet (2135 meters).

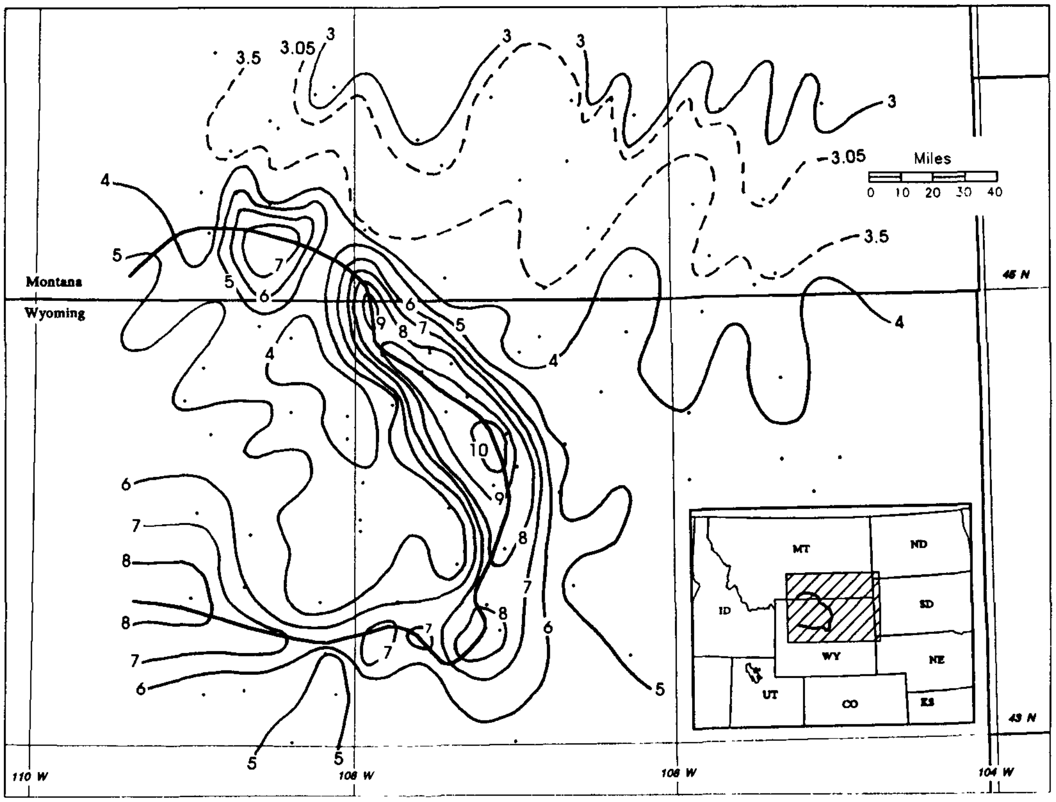

Figure 1. *Elevation (1000's ft.) in the Big Horn mountains study area.*

Precipitation data were obtained from the National Cooperative raingauge network from the National Climatic Data Center, and SNOpack TELemetry raingauges (SNOTEL) from the Soil Conservation Service, now the Natural Resources Conservation Service (NRCS). The latter were especially important in defining the high-elevation precipitation regime. The period from 1980 through 1990 was used for this analysis. This is the first period for which the SNOTEL gauges are available on a daily basis. A total of 83 stations with daily precipitation data were used, although for some stations the length of record varied somewhat.

The initial portion of the study concentrated on determining the spatial and temporal climatology of precipitation. This work was required as background in order to establish orographic factors. Following this, the variation of the orographic factors was examined using various cross sections of the mountain range. Seasonal and monthly variation of the orographic factors were also determined. Finally, the orographic factors were stratified according to specific storm types.

The most important step involves the computation of the orographic factors. This is a comparatively simple procedure. As noted earlier the base precipitation is measured in non-orographic areas or least orographic areas as close to the mountains as possible. Precipitation amounts in the adjacent mountains are then divided by the base precipitation. This provides a rough measure of the effect that orography has upon the precipitation. Any comparisons between base and mountain precipitation must obviously be for the same period. The base precipitation can be a single-station value or preferably an areal average. Selection of an adequate and representative base value is an important aspect of the study. While it is impossible to completely remove any orographic influence for the base precipitation, it is important to minimize it. At the same time the base values must be from stations close enough so that they are representative of the same storms experienced in the mountains.

The selection of the base area is based on the prevailing wind directions and speeds (during precipitation events), important moisture sources, and other climatic and synoptic considerations. In addition, topographic factors such as elevation, slope, orientation, and exposure need to be considered. Ideally it would be desirable to change the base area for different storm types, durations, and low-level wind directions.

For the Big Horn range, the base area was located north and northeast of the range and only stations with an elevation less than 3050 feet (930 meters) were selected. It was not possible to establish a second base area south of the Big Horn range, due to rough terrain. Since the stations in this area were not free of terrain influences, they did not qualify as base stations.

A key assumption of this study was that the observed precipitation in both base and mountain stations come from the same weather systems. While this is almost certainly not true in the case of isolated thunderstorms, large synoptic-scale systems will produce precipitation across the entire study area. Other studies have shown that 10 to 15% of individual rain events at a station cause 50% or more of the precipitation (Huff and

Schickedanz, 1970). The variation in smaller-scale convective precipitation across the region is expected to be smoothed out using longer duration precipitation records.

4. PRECIPITATION CLIMATOLOGY

Annual average precipitation (1980-1990) for the Big Horn mountains is shown in Fig. 2. The highest precipitation amounts are found along the ridge line running southeast from the Montana-Wyoming border, with a maximum annual total of 33.89 inches (861 mm) at an elevation of 9380 feet (2859 meters). Minimum values are found southwest of this ridge line in the interior valley formed by the Big Horn mountains. The lowest observed annual precipitation is only 5.12 inches (130 mm) at an elevation of 4110 feet (1253 meters) in the protected valley west of the main ridge line. The precipitation decrease with elevation can easily be seen both north and

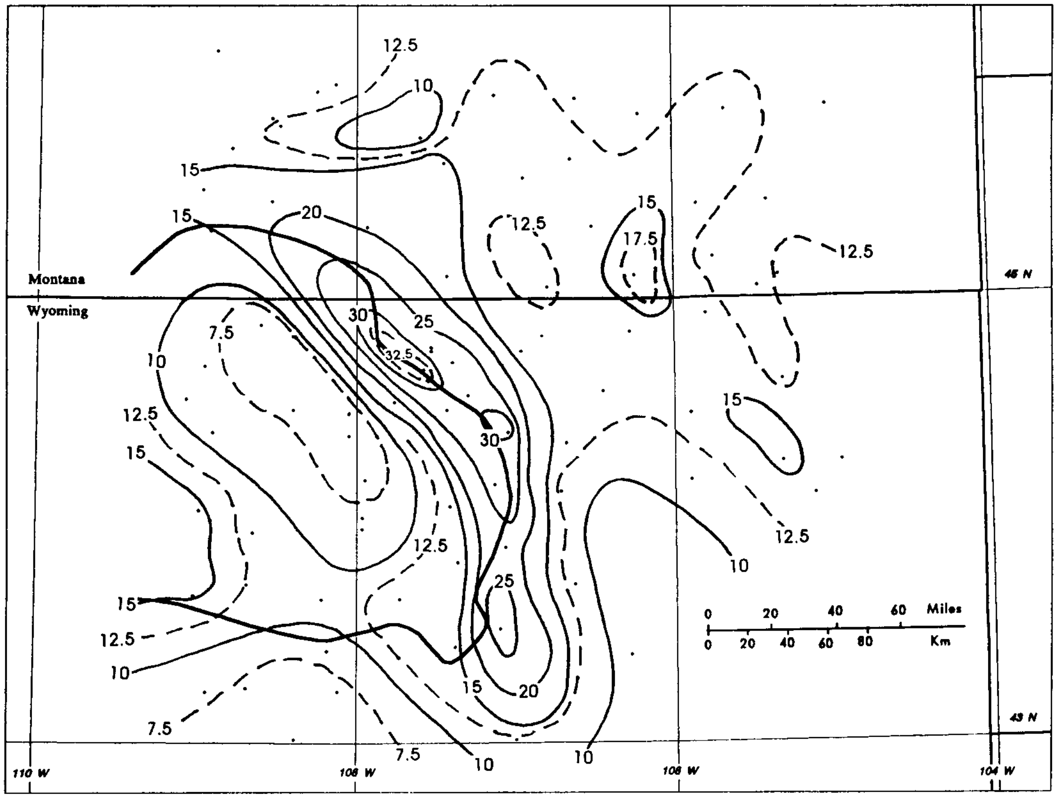

Figure 2. *Average annual precipitation (inches) for the Big Horn mountains (1980 - 1990).*

south of the main ridgeline. In the valleys below about 5000 feet (1524 meters) south of the Montana border, annual rainfall is generally below 10 inches (254 mm). North and northeast of the range, the annual values are somewhat higher, generally 10 to 15 inches (254 to 380 mm), with some isolated amounts near 17.5 inches (445 mm). Annual precipitation south of the Big Horn mountains drops to less than 10 inches (254 mm) in the region between the Big Horns and the Continental Divide of the Rocky Mountains.

Precipitation seasons were divided as follows:

- Winter: November through February
- Spring: March through June
- Summer: July and August
- Fall: September and October

These seasons were determined from a combination of the average monthly rainfall using the 83 available raingauges in the approximately 40,000 square mile area, the spatial patterns from monthly analyses of the data, and the synoptic storm types which dominate in the various months. Figure 3 gives the composite monthly average precipitation (1980-1990) for all stations in the Big Horn network. For every month from November through February the composite rainfall is less than one inch (25.4 mm), reaching a minimum in January of 0.56 inches (14 mm). The primary limiting factor for precipitation during the winter months is the availability of atmospheric moisture (Ho and Riedel, 1979; Bryson, 1966; Hirschboeck, 1991). During this season the bulk of the precipitation falls as snow, especially at higher elevations. Although the winter season is often dominated by strong synoptic forcing, the lack of available moisture precludes widespread heavy precipitation.

A rapid rise in the composite rainfall begins in March and quickly attains the annual maximum in May, with an average of 2.47 inches (63 mm) for the whole area. The major precipitation-producing storms during the spring season are upslope storms (Whiteman, 1973), and many are associated with snowfall, especially at the higher elevations. For the climatic purposes of this study the entire period of March through June was classified as the spring season.

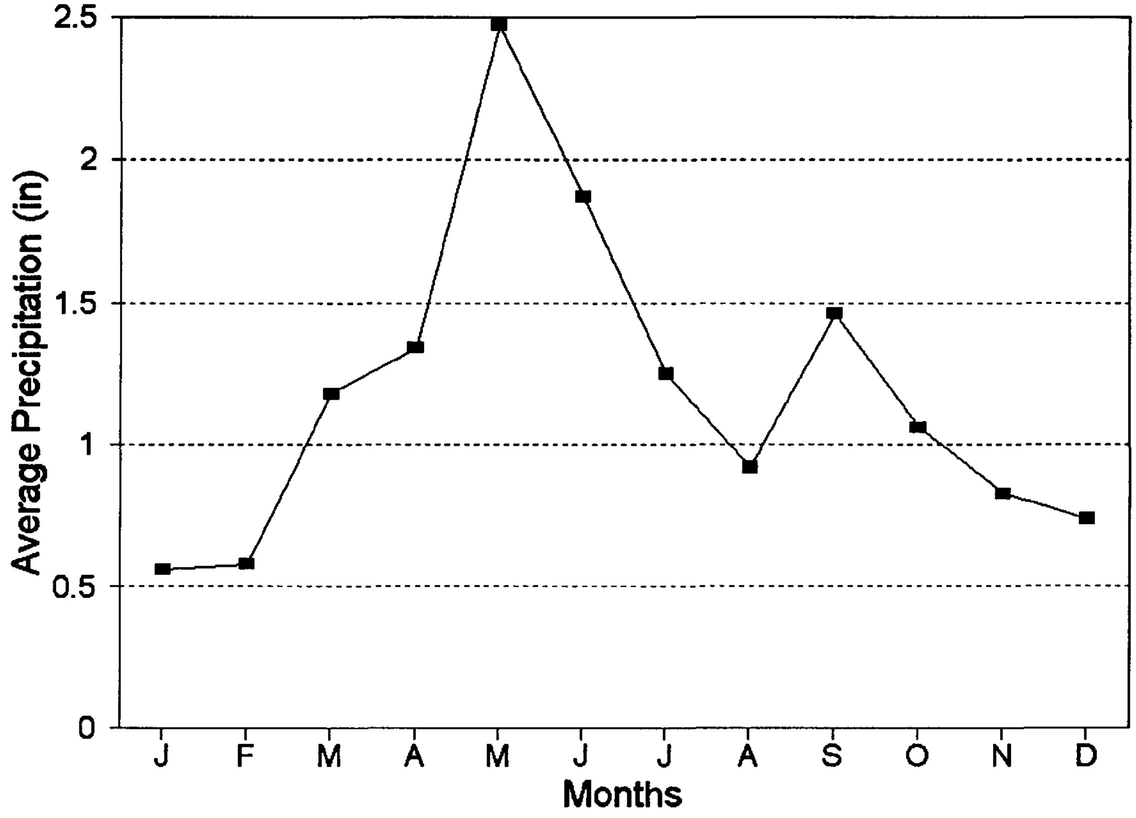

Figure 3. *Monthly average precipitation (inches) for the Big Horn mountains (1980 - 1990).*

The summer season precipitation regime in the Big Horns consists only of the months of July and August. The July precipitation of 1.25 inches (32 mm) is only about half of the May value, and August experiences an even greater dropoff, to less than an inch (0.92 inches, 23 mm). Much of the rainfall in summer falls from brief, but intense convective storms. The composite precipitation shows a substantial increase in September, to about 1.46 inches (37 mm). This is followed by a decrease during October back to near summer values. The normal seasonal reduction in available moisture as the fall season progresses is offset somewhat by an increase in storm frequency.

The spatial seasonal distribution of precipitation is shown in Fig. 4a-d. The general pattern of precipitation in all seasons and months is similar. The highest amounts are found near the crests along the northeast and east

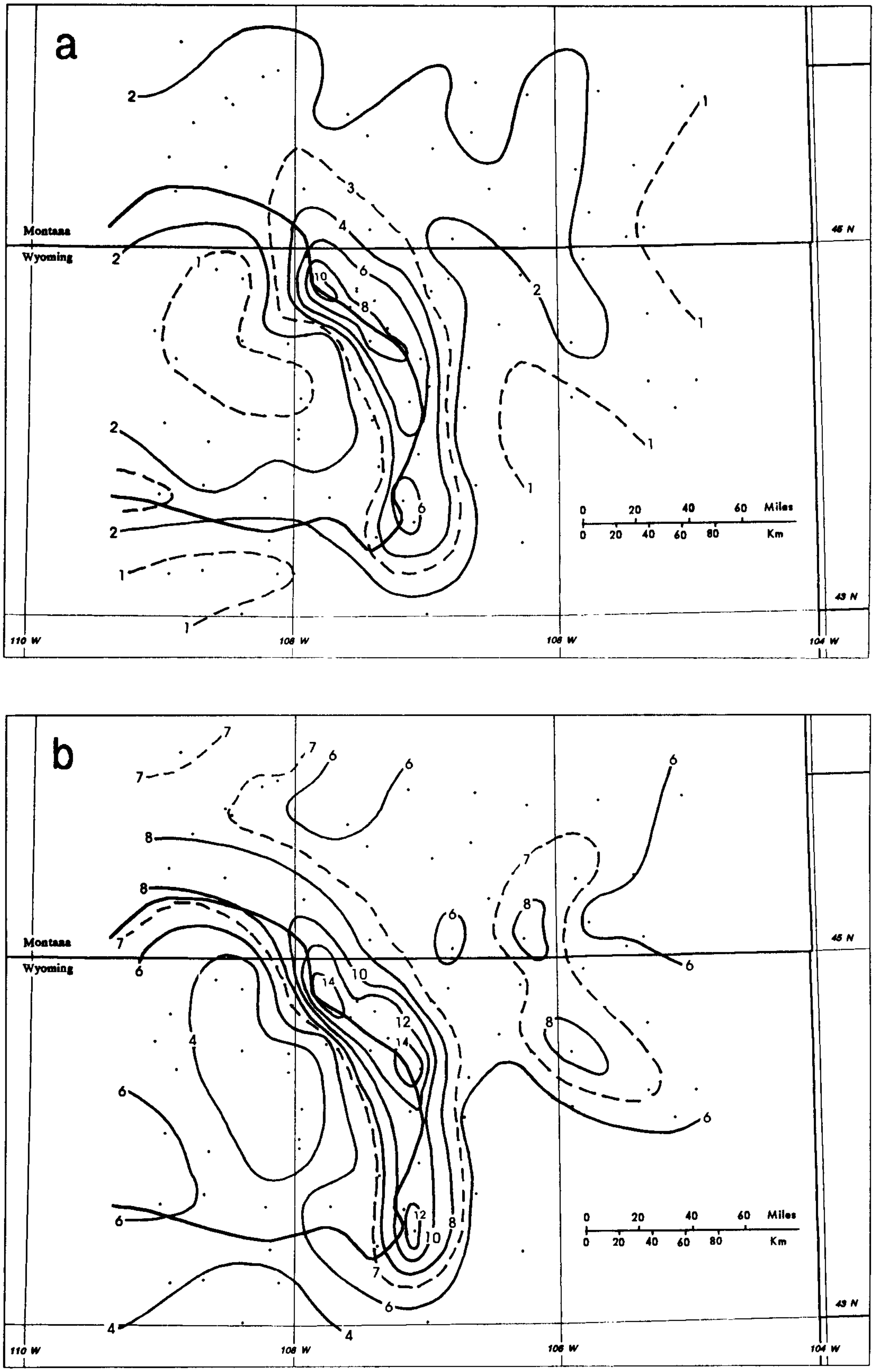

Figure 4. *Average seasonal precipitation (inches) over the Big Horn mountains: a) winter; b) spring.*

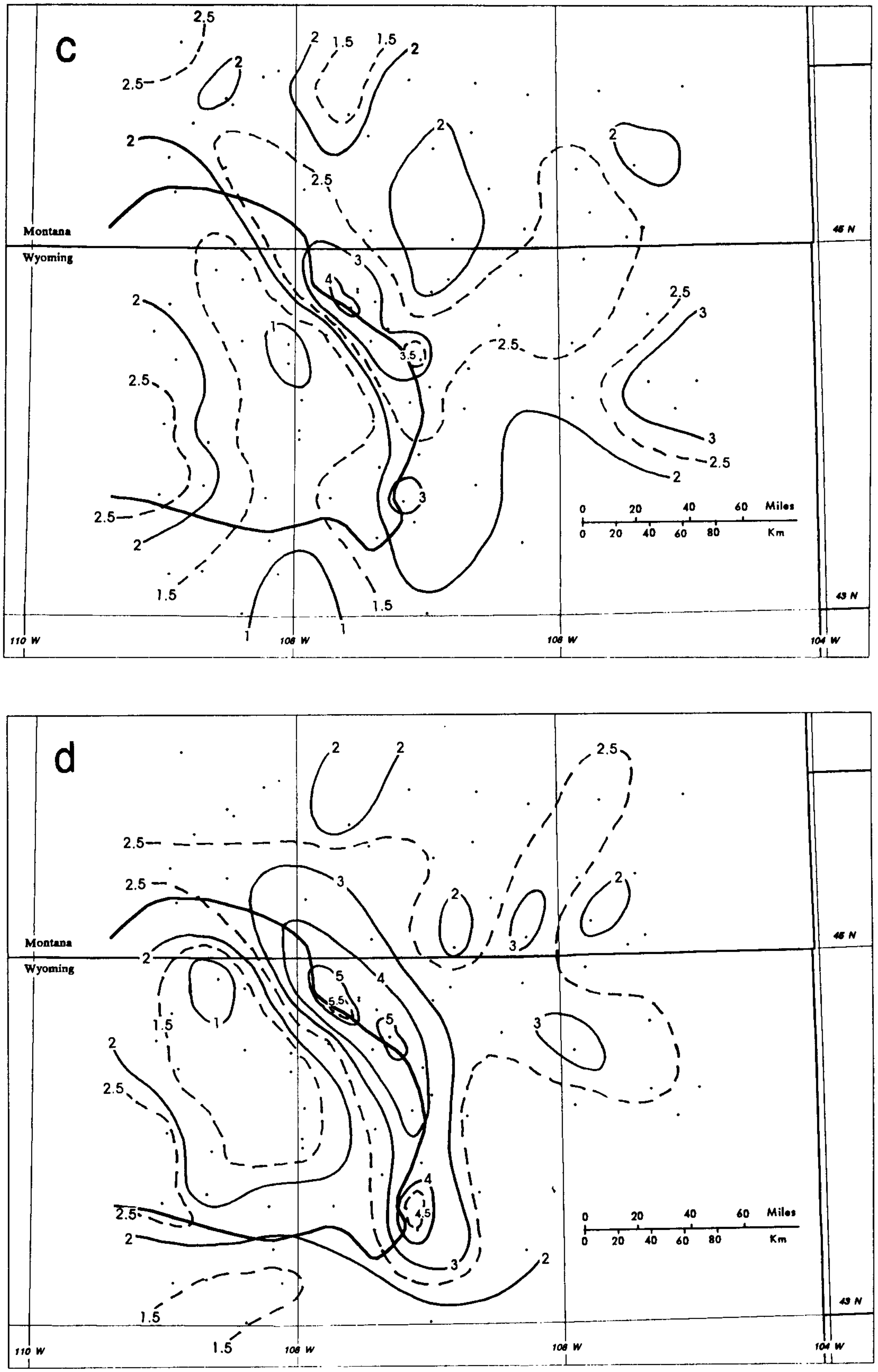

Figure 4. *Average seasonal precipitation (inches) over the Big Horn mountains: c) summer, and d) fall.*

parts of the Big Horn range. A secondary maximum is situated near the southeast ridge of the Big Horn range. Amounts drop off sharply away from the highest elevations of the Big Horns. The most pronounced "rain-shadow" effect is found in the center of the Big Horn basin. As was shown in Fig. 3, the highest seasonal precipitation amounts occur in spring and the lowest are found in winter. The areal precipitation pattern for the individual months varied little from the seasonal patterns. All four seasons show a maximum of precipitation along the ridge line (even in summer), a minimum in the interior basin of the Big Horns, and a more homogeneous pattern to the northeast and south of the range.

Figure 5 shows the variation of precipitation with elevation, both annually and seasonally. The stations are grouped by 1000-foot (305-meter) increments beginning at 3500 feet (1067 meters). A slight decrease in precipitation is noted from 3500 to 5500 feet (1067 to 1676 meters), with a slow increase thereafter. Only above 6500 feet (1981 meters) do the mean annual values exceed the lower elevation averages. It is possible that this decrease from 3500 to 5500 feet (1067 to 1676 meters) is due to a lack of stations between 4500 and 7500 feet (1372 and 2286 meters). If there were more stations at these levels, especially around the crest of the Big Horns, the average annual precipitation might be at least equal to the lower elevations or exhibit a slight increase.

The monthly precipitation for stations in various elevation zones is shown in Fig. 6. The elevations zones are in 2000-foot (610-meter) intervals up to 6500 feet (1981 meters), and in 1000-foot (305-meter) intervals above that point. It should be noted that only one station was available between 6501-7500 feet (1982-2286 meters) and only two over 9500 feet (2896 meters). The greatest seasonal variation is shown between the low and high elevations in the late winter months and least in the summer. This is in agreement with the observations found by Hanson (1982) in mountainous terrain in Idaho using a dense raingauge network. The high elevation bands, greater than 7500 feet (2286 meters), indicate enhanced precipitation for the cold-season months from October through February, relative to the low elevation bands.

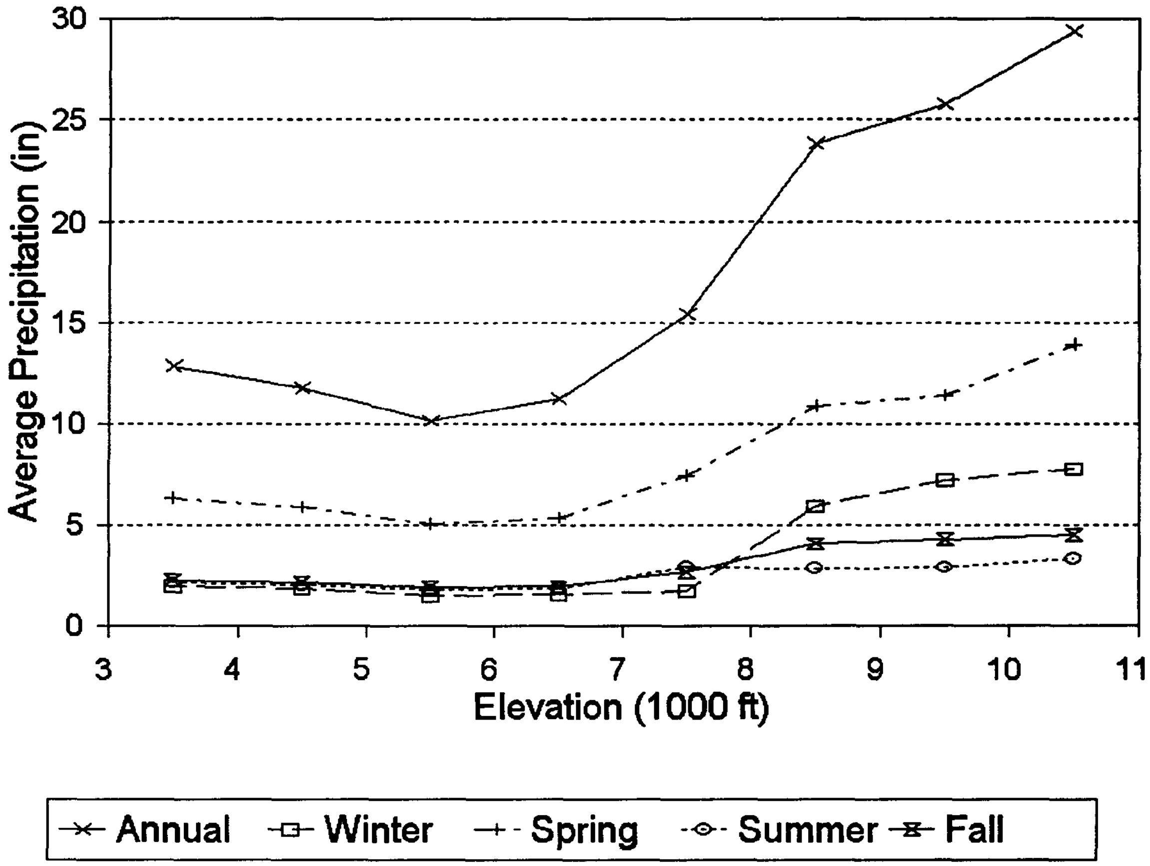

Figure 5. *Precipitation variability with elevation, annually and seasonally (inches).*

5. OROGRAPHIC FACTORS

5.1 Cross Sections

Previous studies have shown that isohyets parallel the elevation contours perpendicular to the prevailing wind direction (Jakus, et al., 1986). This is most obvious when the wind direction is perpendicular to the mountain, then there is little difference between the orientation of the isohyetals and the contours.

A series of cross sections were constructed to define the magnitude of the orographic factors as a function of elevation. These cross sections were

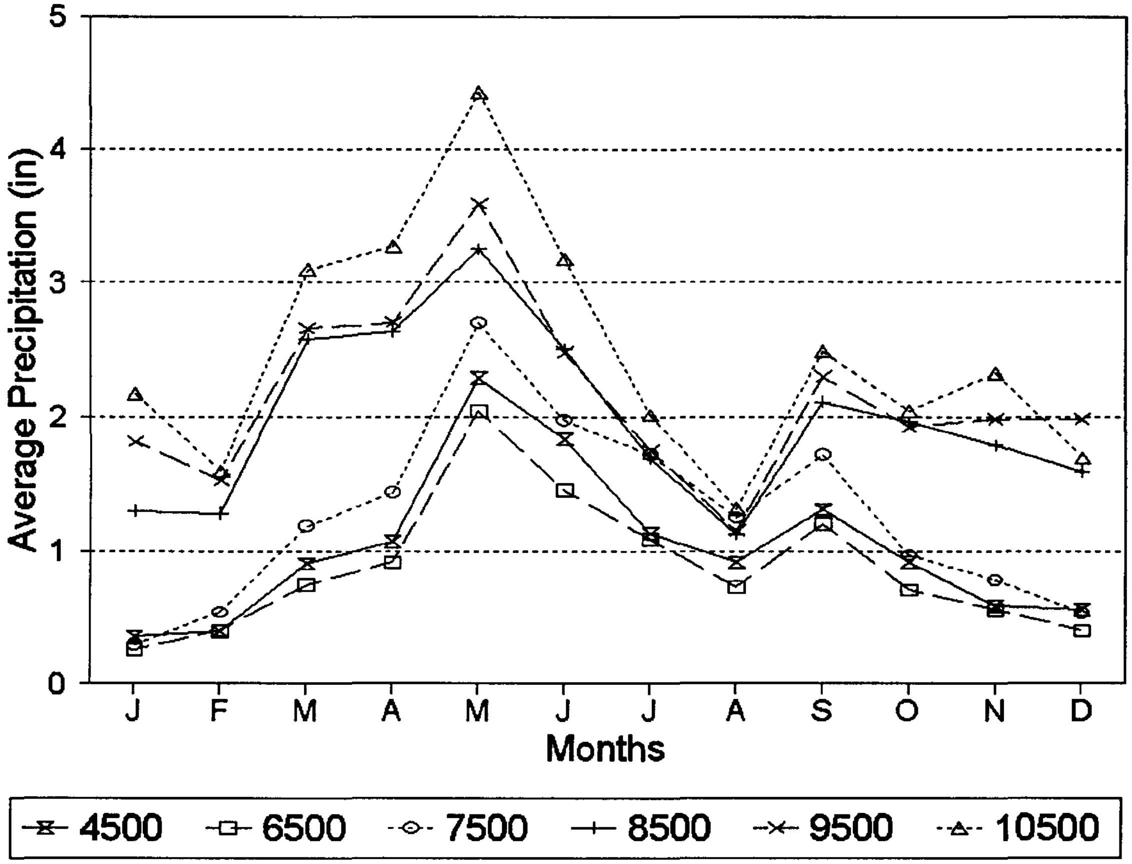

Figure 6. *Monthly average precipitation (inches) by elevation bands (feet).*

done for a number of different orientations to examine possible orographic effects as a function of wind direction. Two such cross sections are shown in Figures 7 and 8. The distance from the origin to the terminus of the cross section is shown along the x-axis of this and other cross section figures.

The inset of Figure 7 shows that the cross section begins from a direction northeast of the Big Horns, crosses the crest into the interior basin, and then goes up the southwest crest of the Big Horns. The orographic factors, calculated by dividing the precipitation at each station by the base precipitation located at the northeast starting point of this cross section, shows a tendency of the orographic factors to follow the elevation contours very strongly during the winter and to a lesser degree annually and in summer. The largest annual orographic factor showed an enhancement of the annual base precipitation station by a factor of three along the northeast side of the

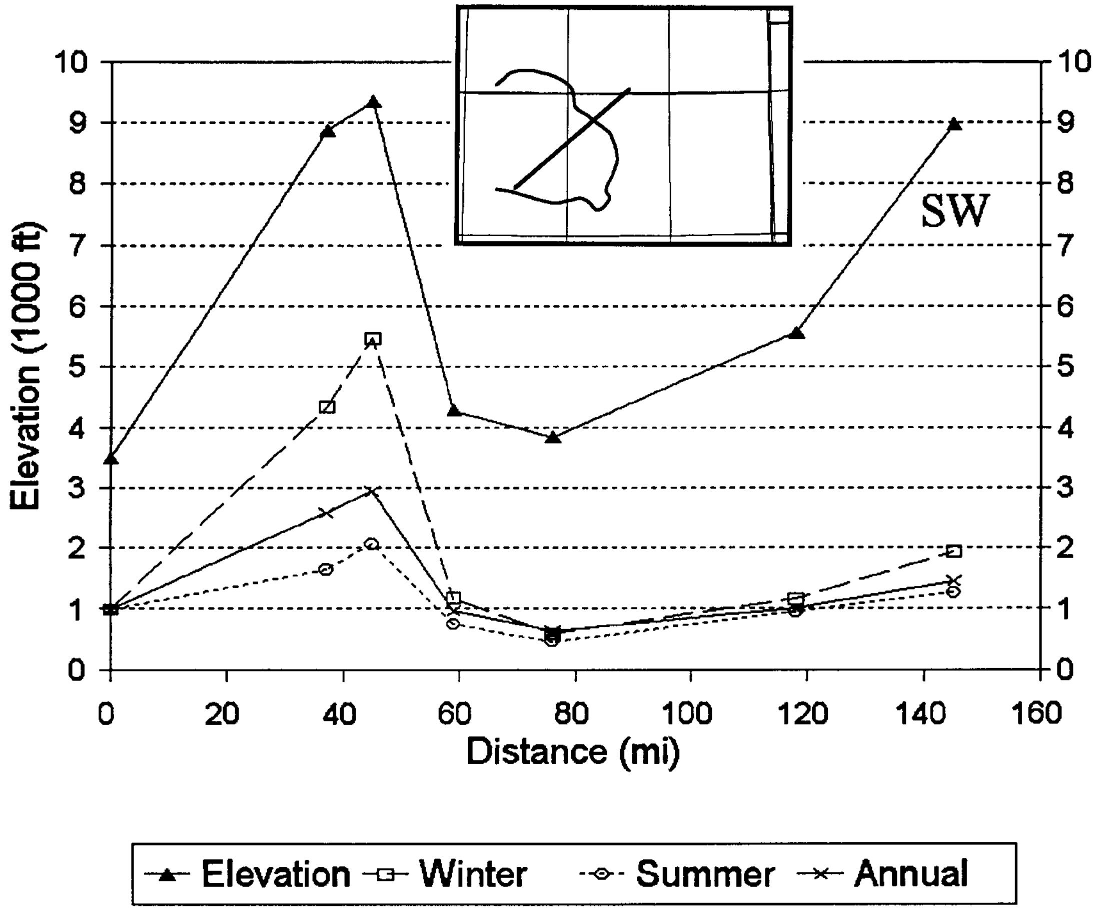

Figure 7. *Northeast-southwest cross section (see inset) of elevation and orographic factors for winter, summer, and annual precipitation.*

Big Horns, while the orographic factor was close to 1.5 on the south crest of the range. During the winter, orographic factors of more than five were noted on the front range (northeast side), while values just over two were observed in the summer in the same area. On the interior crest of the Big Horns (between miles 125 and 140) there was little difference in the magnitude of the orographic factors in winter or summer. In the interior basin the orographic factor never exceeded more than about one, and was less than one in all seasons between about 60 and 100 miles along the trajectory. During spring and fall (not shown in Fig. 7) the orographic factors are similar to the annual orographic factors, falling between the extremes of summer and winter factors. Other cross sections taken perpendicular to the Big Horns showed similar results.

Figure 8 shows a cross section taken in a northwest-southeast direction (see inset of Fig. 8), which partially parallels the eastern crest of the Big Horn mountains. The annual, winter, and summer curves all tend to peak along the highest elevations. Winter orographic factors maximize at slightly more than three, and summer has the smallest orographic factors with the highest value less than two. Again the spring and fall orographic factors are approximated by the annual curves, and are not shown here. At the highest elevations of the cross section, where there is less than a 1000-foot (305-meter) change in the elevation, little or no variation of the orographic factors is noted. This illustrates that the precipitation contours do tend to closely parallel the elevation contours.

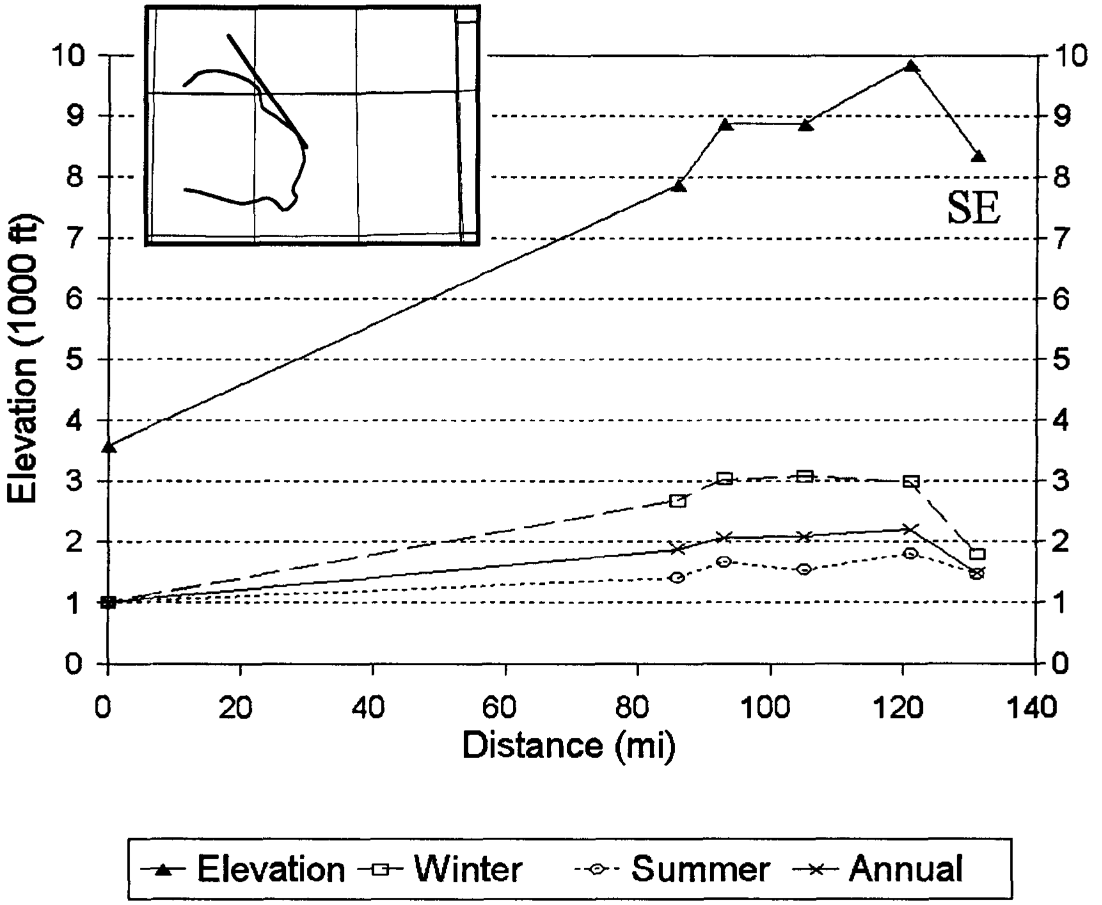

Figure 8. *Northwest-southeast cross section (see inset) of elevation and orographic factors for winter, summer, and annual precipitation.*

The major conclusion found in looking at these and other cross sections shows that there is at least some orographic effects associated with all seasonal and annual precipitation over the Big Horn range. The winter season is associated with the largest orographic factor. Summer has the smallest orographic factor, while the fall and spring seasons are intermediate, and approximate the trend in annual orographic factors.

The orographic factors in these cross sections are sensitive to the base station used, and again points toward the need for a stable, reliable base value for the computation and comparison of orographic factors. Such a base can be found by using an areal average as pointed out previously.

5.2 Storm of May 6-8, 1988

The previous cross sections were all based upon an accumulation of seasonal and annual average precipitation. These cross sections and the climatic maps which describe the annual and seasonal spatial variation tend to dampen the variation found in individual storms, which have maxima and minima specifically dictated by phenomena operating at several different scales, and are strongly dependent upon the wind direction. During individual storms, differences between the average orographic factors should be anticipated. In order to emphasize such differences it was decided to show the orographic factors associated with an individual storm and compare them with the climatic patterns already described. A number of events were analyzed and one of those storms selected was a major event that occurred from May 6 through 8, 1988.

This was an intense, upslope spring storm that developed over the southwestern U.S., deepened and tracked northeast through the Great basin and eventually over Wyoming, as a cut-off, upper-level low. Figure 9 shows surface maps and 700-mb maps at 00Z from May 6-8. An unusually strong upper level trough for late spring, plus the availability of abundant Pacific and Gulf of Mexico moisture combined to produce heavy precipitation across the Big Horn basin. The spatial pattern of the precipitation for the entire storm is shown in Figure 10. The impact of orography on the precipitation distribution is dramatic, with a distinct maximum near or just east of the main crestline of the Big Horns. Rainfall on the northern side of the basin reached over five inches, with a broad 2-3 inch swath near the crests. By contrast, precipitation fell to below one inch in the southwest interior of the basin and well to the east.

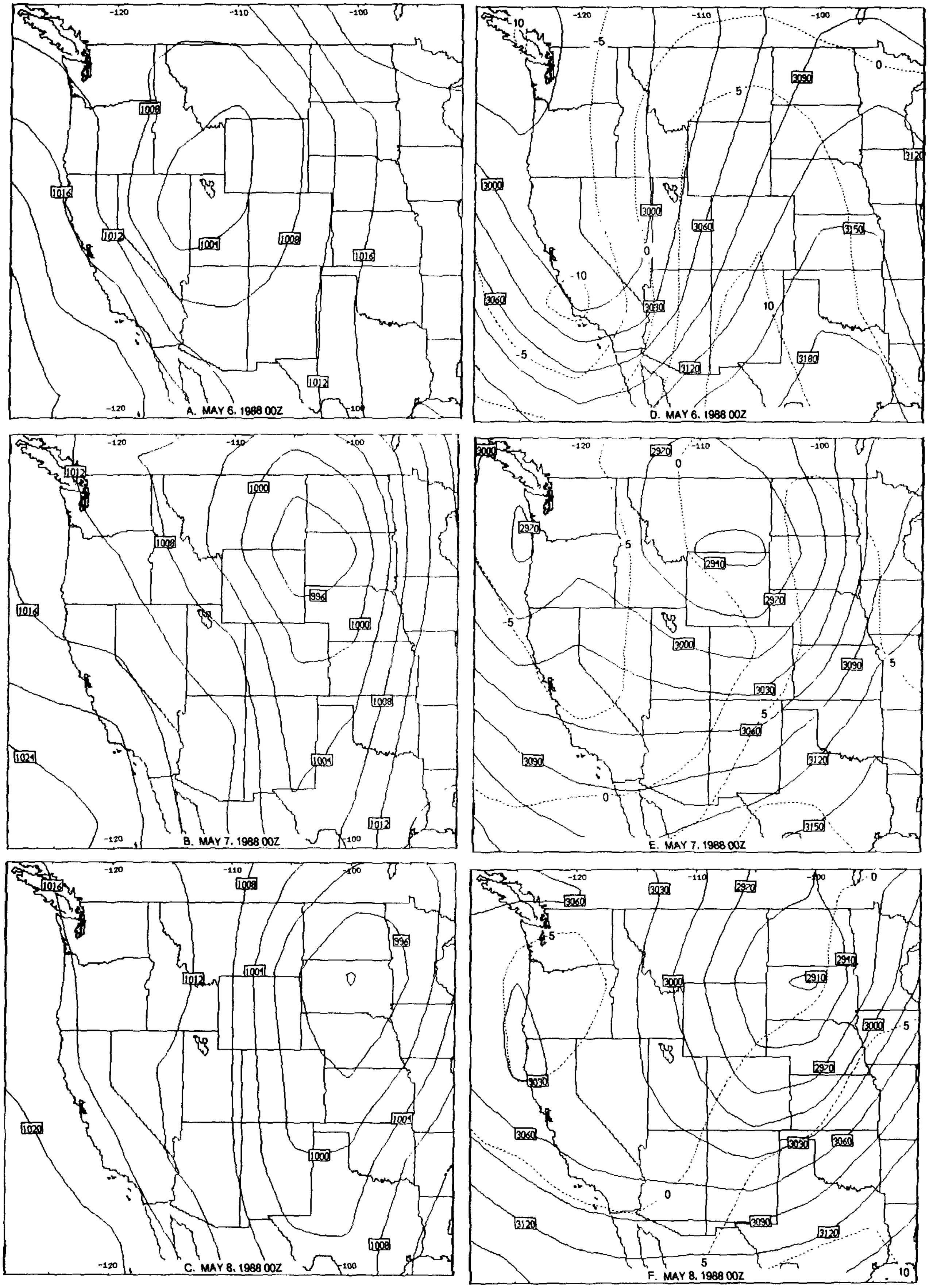

Figure 9. *Surface (a-c) and 700-mb (d-f) maps for 00Z from May 6 through 8, 1988.*

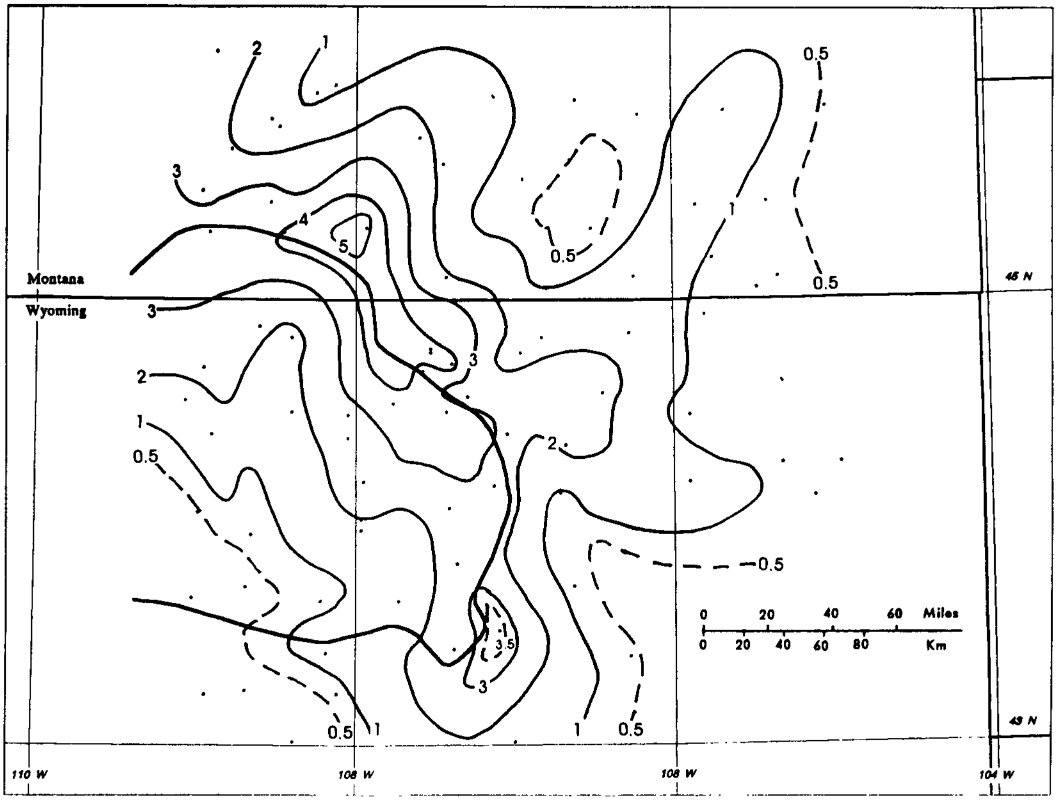

Figure 10. *Precipitation (inches) for storm of May 6-8, 1988.*

As noted earlier, forces operating on a variety of scales within a particular storm will combine to produce variations from long-term values in precipitation minima and maxima, both in terms of magnitude and spatial distribution. Figure 11a shows a cross section of the May 6-8, 1988 storm, demonstrating an example of these differences. This cross section follows along the same line as that shown in Figure 7, but shows the storm orographic factors versus the average factors for all May storms. The storm orographic factors are nearly double the May average (4 versus 2) near the crest of the front range of the Big Horn range. Both sets of factors diminish sharply within the interior basin, reaching a value of 1 where the terrain is beginning to rise again on the south side of the range. There is little increase in storm or May orographic factors on or along the crests of the south side of the mountains.

Figure 11b shows a cross section from the northwest that parallels the eastern ridge of the Big Horn mountains, the same trajectory as in Figure 8.

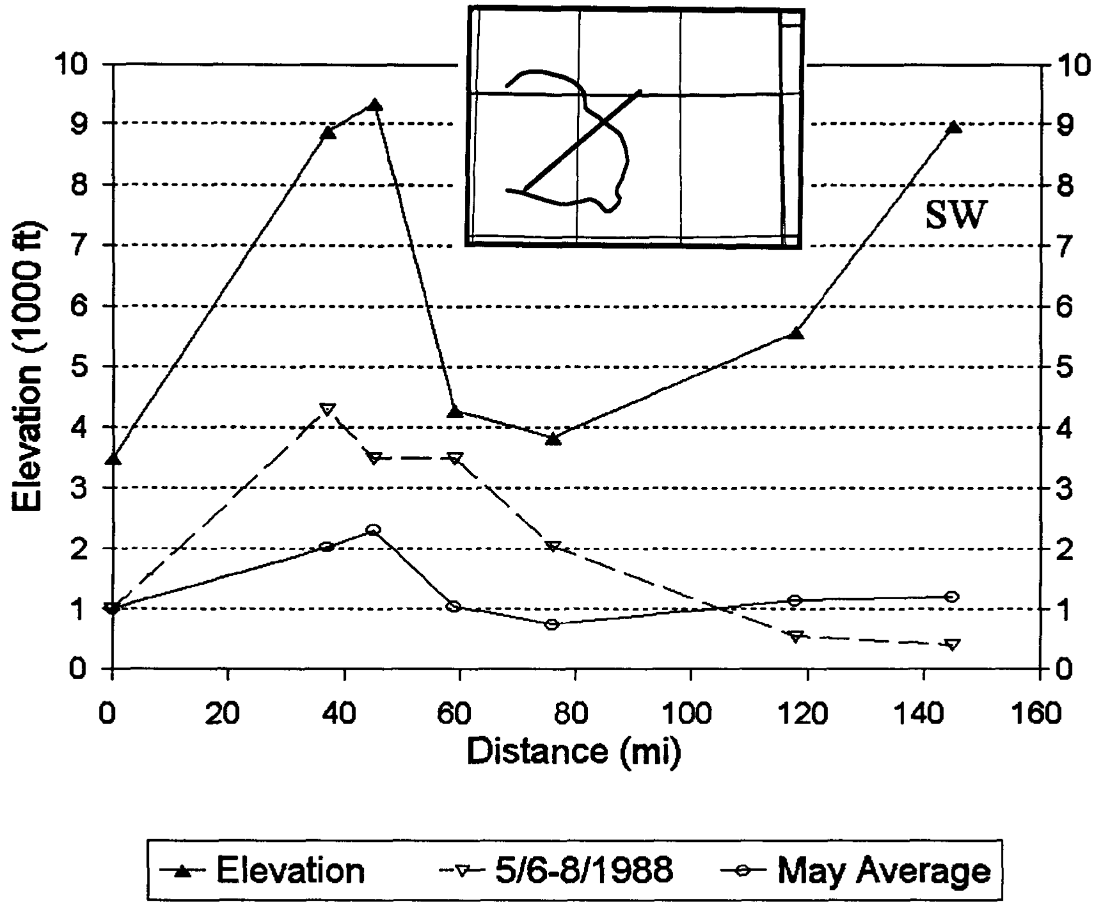

Figure 11a. *Northeast-southwest cross section of elevation and orographic factors for May 6-8, 1988 storm.*

The May average orographic factors for all storms are flat and peak at less than two near the highest point in this cross section. However, this early May storm, which is an unusually strong upslope-type storm (Whiteman, 1973; Reinking and Boatman, 1986) for this time of the year, shows a much stronger orographic effect and the orographic factor curve differs markedly from the average May value. A peak of close to 4 is found near mile 90 with a secondary peak at mile 120. The primary maximum at mile 90 is due to the almost perpendicular trajectory of winds that impinge on the mountains at 700 mb, about 10,000 feet (3 km). This effect will again be shown in the next set of figures. Thus, it can be seen that the orographic factors of individual storms can be very different from those of the average values.

A set of cross sections were also made to examine the orographic factors that would roughly parallel the 700-mb flow on May 7, near the most

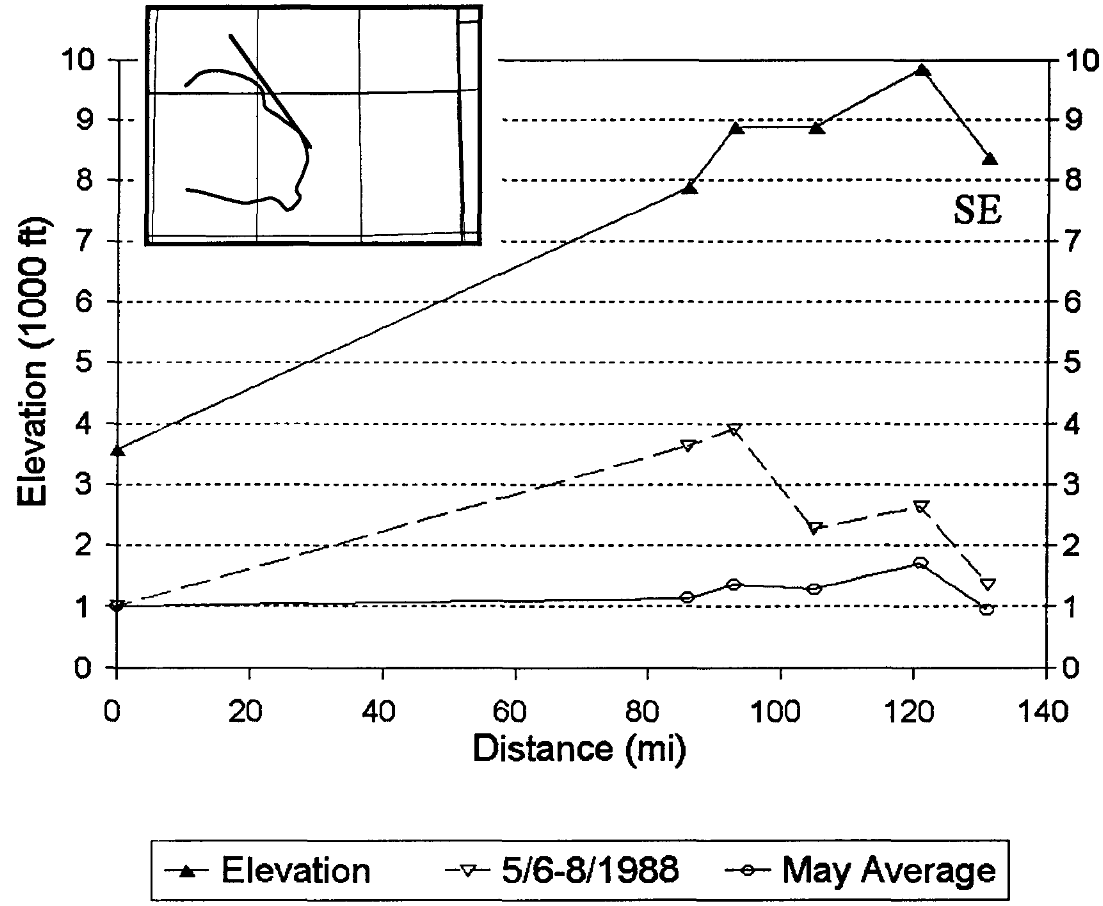

Figure 11b. *Northwest-southeast cross section of elevation and orographic factors for May 6-8, 1988 storm.*

intense portion of the May 6-8, 1988 event. Two of these trajectories are shown in Figure 12. For these trajectories the base precipitation was the average precipitation of stations with an elevation of less than 3050 feet (1000 meters), and the precipitation at each station along the cross section was divided by this number.

The first trajectory (see inset of Fig. 12a) was taken for a wind that began to the north of the Big Horns and then curved cyclonically across the interior valley and across the southern crest (Fig. 12a). This trajectory differs markedly from the average May orographic factors along the same cross section. It maximizes near the top of the first ridge with an enhancement factor of about 3.5, and then falls off to less than two, as the air begins to move downslope and into the interior basin. At the far end of the trajectory there is

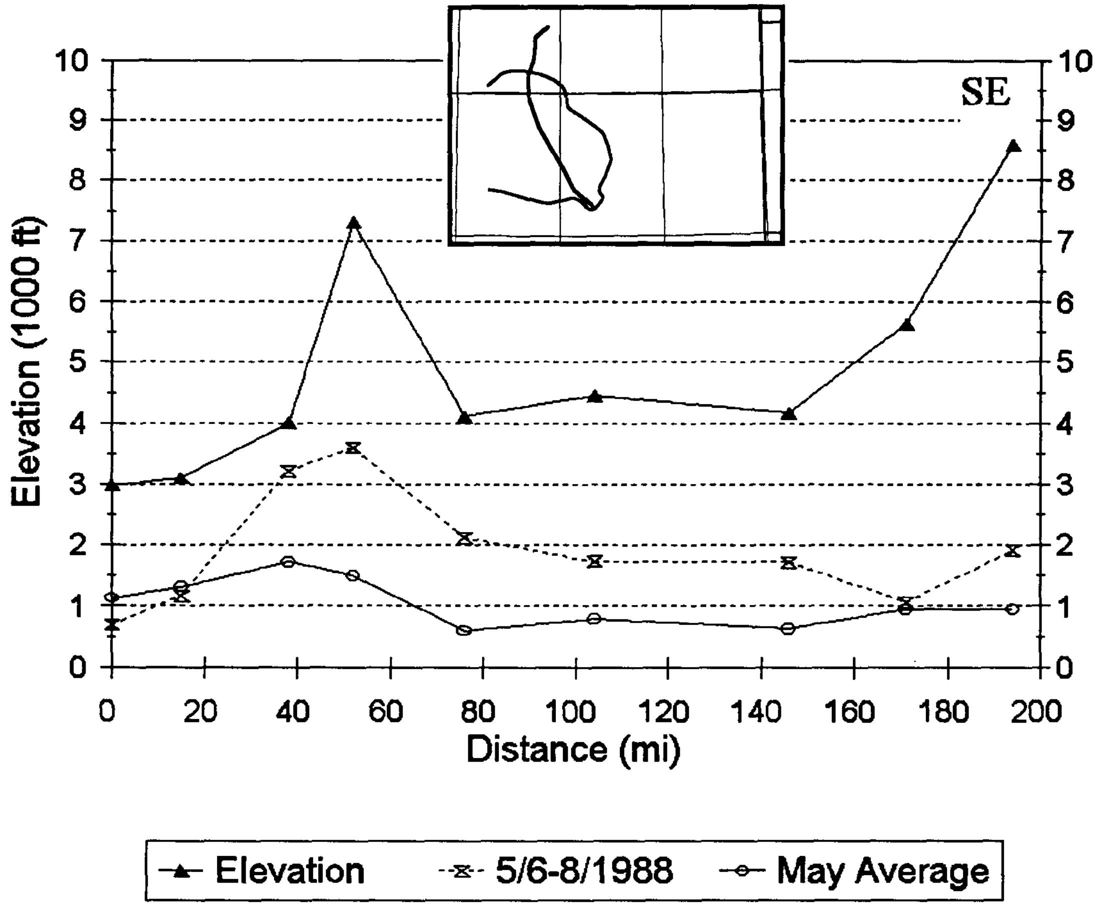

Figure 12a. *Cross sections of elevation and orographic factors for May 6-8, 1988 storm 700-mb trajectories over Big Horn basin.*

only a minor response to the upslope portion of the Big Horn mountains contained in the interior basin.

The orographic component of the second trajectory, taken about 60 miles east of the first trajectory, (see inset of Fig. 12b) maximizes on the upslope side of the mountains and then begins to decrease with the winds roughly parallel to the crest line of the Big Horns. Other trajectories had similar results with peaks being associated with winds perpendicular to the first crest, and decreasing in the basin, and on the downslope side of the crest. These results are not unexpected for they reflect the expected atmospheric dynamics with less potential rainfall on the downslope side of the mountains. In addition, atmospheric moisture depletion by condensation and precipitation fallout occurs as the air is lifted over the first crest, thus reducing

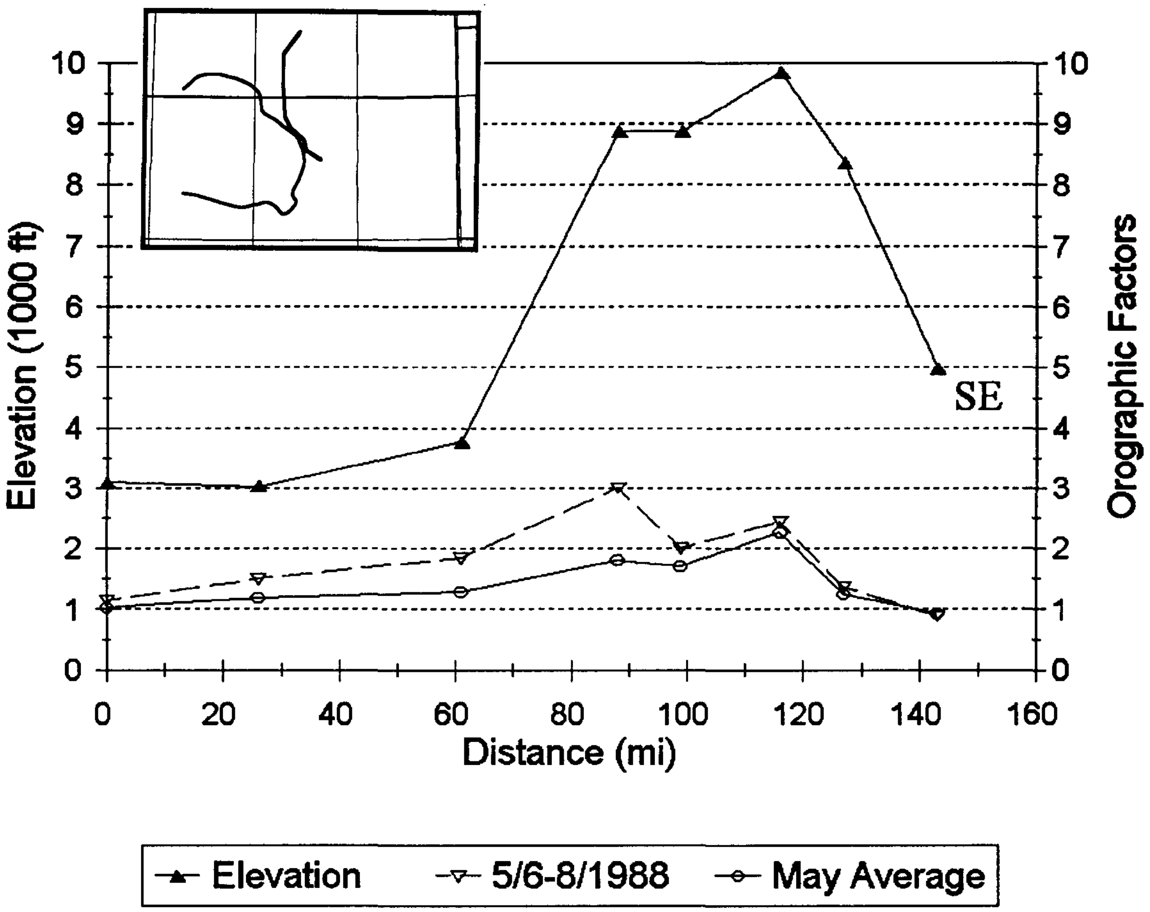

Figure 12b. *Cross sections of elevation and orographic factors for May 6-8, 1988 storm 700-mb trajectories parallel to eastern crest line of the Big Horn mountains.*

available moisture for correspondingly high orographic factors on the upslope side of the second set of mountains

The results from the May 6-8, 1988 storm clearly shows that each storm will leave its own imprint of precipitation due to the wind regime and the consequent orographic influences. The use of seasonal or even monthly averaged orographic factors to predict the amount of precipitation in the mountains could provide unreliable results because the individual storms that provide precipitation during a period may be dominantly of one type. An intense storm such as the May 6-8, 1988 event, may dominate the precipitation pattern for a month, and any calculations using monthly average orographic factors could provide erroneous results about the amount of snow or water equivalent that may fall over individual basins or over general areas. To provide a technique that is operationally useful in real time or for a season, it is necessary to define the direct effects that the wind speed and direction have upon the magnitude and pattern over a particular time period. The wind speed and direction define the magnitude and the pattern of potential orographic effect. These winds are primarily a function of the storms which move across a region. For example, if a storm passes south of an area, the dominant low-level winds and moisture can be expected to flow from the east; however, if the storm moves north of the area, the dominant winds and moisture will come from the west. For an orographic region, this can provide very different results for the magnitude and distribution of precipitation. It was decided to define the various storms types that affect the Big Horn mountains.

6. CLIMATOLOGY OF OROGRAPHIC FACTORS

It was not feasible to examine all the storms that moved across the Big Horns during the 11-year study period (1980-1990). In order to test whether such a limited storm sample would accurately reflect the overall precipitation regime found in the Big Horn basin, it was decided to examine the storms associated with three dissimilar precipitation years: dry, near-normal, and wet. The three representative years selected were 1988 (dry), 1987 (near normal), and 1982 (wet). The variation from the mean for the dry and wet years was over 25%. This was also done to ensure, as much as possible, a wide selection of storms that would include all potential weather systems for this region.

Storms were selected using raingauge data from the stations available from the Coop network, and on the basis of generalized weather patterns that were available from the Daily Weather Maps (USWB, 1940-). For the selection of these storms there was an overt effort to select storms that were associated with large-scale general storms or mesoscale storms that affected a large area. This procedure is not well suited to providing information about localized convective storm events. The use of only the Coop raingauge network means that the storm selection was biased toward precipitation in the lower levels, because most of the Coop raingauges are below about the 7000-foot (2134-meter) elevation level.

Using the Daily Weather Maps and the Coop raingauges, 108 storms were defined. These storms ranged from a minimum of 1-day up to 11-day events, although the median duration for a storm was 3 days. The precipitation within the three years was examined to determine what percent of the total precipitation was accounted for using only this technique. In the lower elevations 80 to 90% of the total precipitation is accounted for, while along the crest of the mountains only 60-70% of all the precipitation in these three years is part of the sample (Fig. 13). An examination of the individual years shows that the highest percentage of missing precipitation occurred during the dry year (1988), and the lowest percentage of missing precipitation during the average year (1987). As one might expect, the dry year is typified by fewer general storms and more isolated convective activity than the average or wet year.

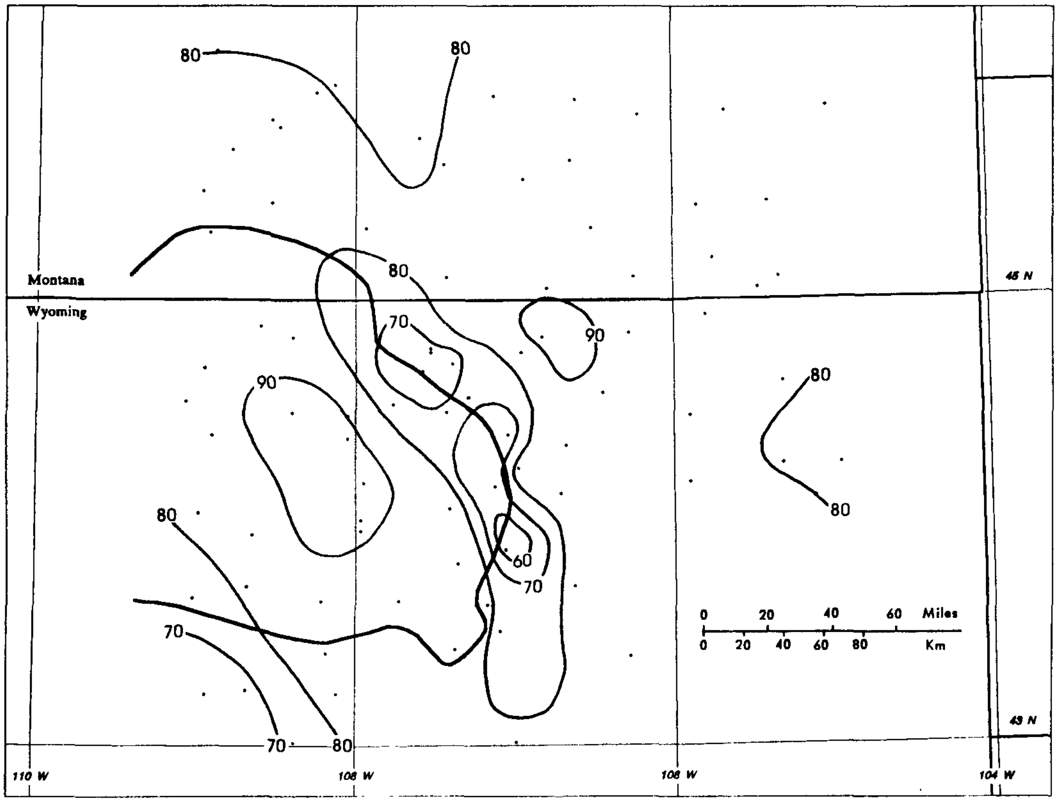

Figure 13. *Percent of total storm rainfall associated with 108 storms from 1982, 1987, and 1988.*

The spatial distribution of the annual orographic factors (Fig. 14), which is the annual precipitation at each station normalized by the average base precipitation, shows that the region northeast through east of the Big Horn mountains is relatively flat ranging from less than 1.0 to about 1.25. Near the vicinity of the 5000-foot (1524-meter) contour on the east side of the ridge, the orographic factors begin to rise rapidly and maximizes near the crest between 2 and 2.7. On the west side of the ridge in the interior valley the gradient falls off sharply, dropping to a value of 1.0 or less at about the 5000-foot (1524-meter) contour. Within the interior basin the value of the orographic factors drop to less than 0.5 to the north. On the north ridge the orographic factors are about 1.0, while along and south of the sough ridge the orographic factors are generally less than 1.0.

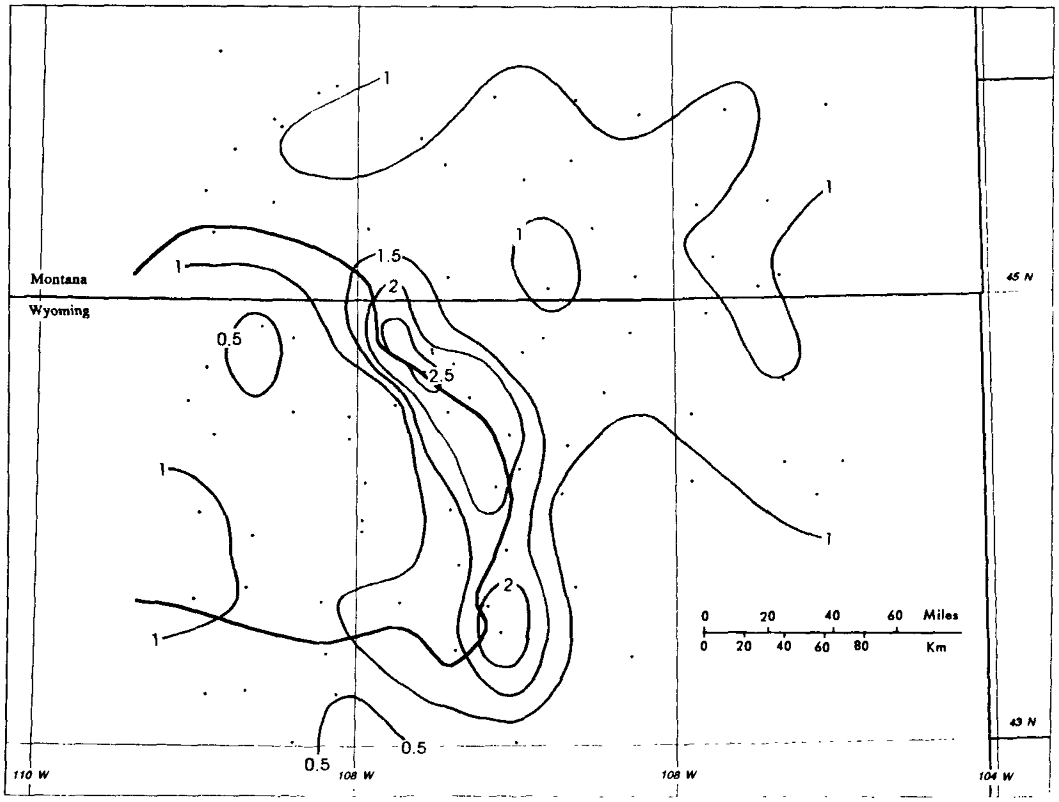

Figure 14. *Annual orographic factors.*

A month-by-month analysis of the spatial patterns and the magnitudes of the orographic factors revealed that the original seasonal designations defined by the rainfall climatology of the region were not well suited as seasons for the orographic factors. Because of this, three new seasons were defined for the orographic factors: cold, warm, and transition seasons. The cold season for the orographic factors consist of December through February (Fig. 15a); the warm season is made up of April through October (Fig. 15b); and the transition season consists of the months of March and November (Fig. 15c). The largest orographic factors were measured in winter with values up to 6.0 on the northeast ridge, and a secondary maximum of 3.5 on the southeast ridge. The warm season pattern is quite flat, with two isolated peaks only slightly higher than 2.0. The transition months (March and November) have a pattern similar to the annual pattern, but with slightly larger values.

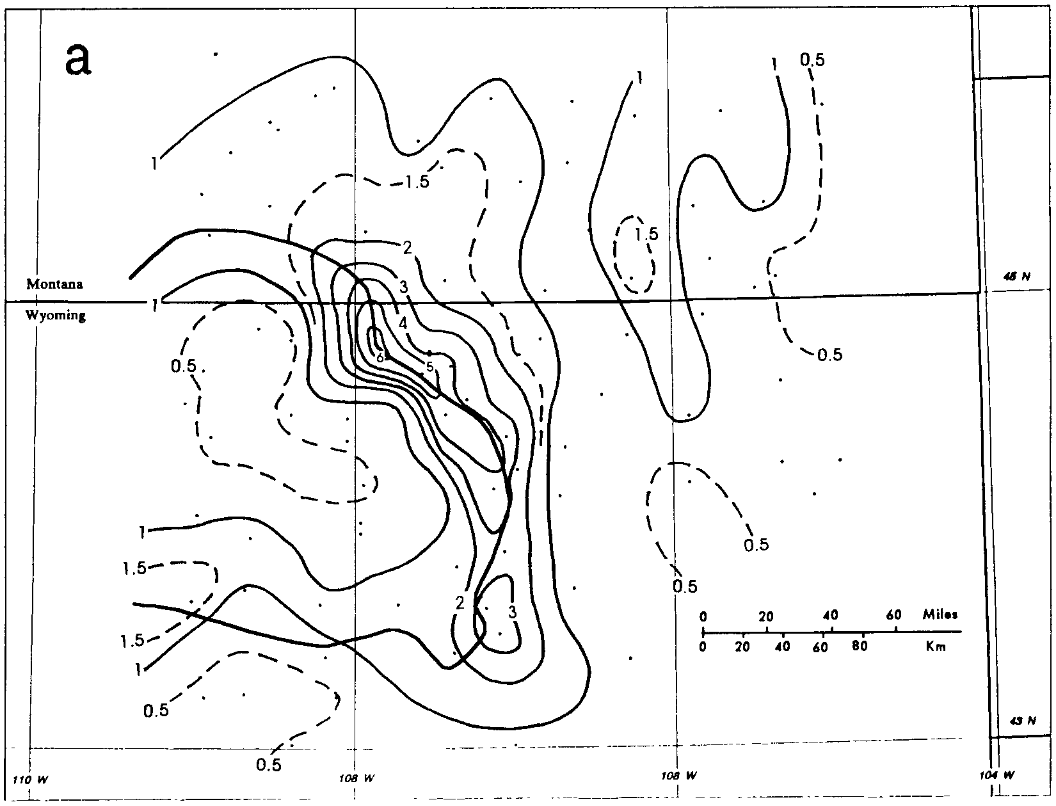

Figure 15. *Seasonal orographic factors: a) winter.*

The pattern shows that the cold season can be expected to have, on the average, the larger orographic enhancement, and the summer the least. The transition months of March and November have significant enhancement at the higher elevations. For climatic analyses or for long-range outlooks (monthly or seasonal) these seasonal values should be used. For the moni-

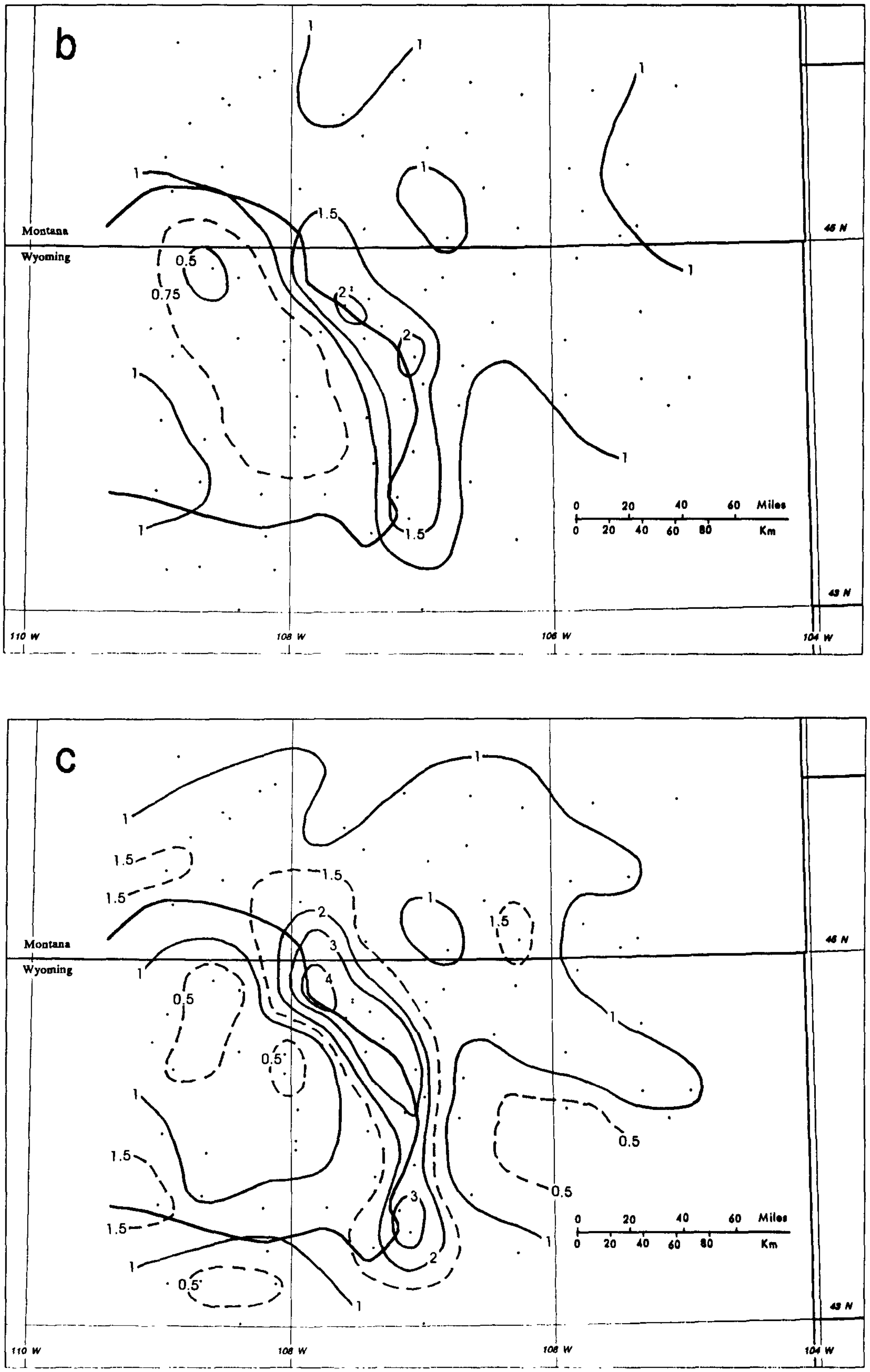

Figure 15. *Seasonal orographic factors: b) summer, and c) transition.*

toring of an individual storm, the storms types developed in the next section should be used.

7. SYNOPTIC CLIMATOLOGY OF STORM TYPES

From the 108 storms described earlier, the synoptic weather patterns were grouped into nine different types. Eleven storms did not fit any of the first eight types and make up the ninth miscellaneous category. A description of each type and some of their characteristics follows. Tables 1 and 2 provide a general summary of their precipitation characteristics, orographic factors and a frequency of occurrence by month. It is expected that each storm type will provide a distinctive precipitation and orographic "footprint". By applying the specific storm type orographic pattern to a storm that either is about to occur or is still occurring, the analyst should be able to provide increased accuracy in expected precipitation amounts in the ungauged regions of this mountain range.

7.1 Storm Type 1

This is the most frequent storm type with 45 events, comprising 42% of all storm occurrences (Table 1). Figures 16 a and b show typical surface and 500-mb maps for this weather type. February 2, 1982 was selected as the typical analog for Type 1. At 500 mb the axis of a long wave trough is located over or just to the east of the Big Horn mountains. The upper-level flow is typically either from the west or northwest with little advection of moisture through the depth of the atmosphere. The surface weather map for this situation shows a strong (1040+ mb) arctic high over central Canada building southeastwards into the northern Great Plains. The clockwise circulation around this high provides an upslope component to the westward moving air. Moisture is necessarily limited with this type of system and residual moisture from past weather activity or what little moisture is advected with the surface system provides the atmospheric moisture for precipitation. Storm Type 1 occurred in all months but August, but is most frequent from November through April when 38 of the 45 storms were observed (Table 2). This type of upslope precipitation represents one end of the spectrum of upslope circulations discussed by Boatman and Reinking (1984). The circulation associated with this weather type exemplifies the so-called shallow toring of an individual storm, the storms types developed in the next section should be used.

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Table 1. Precipitation Characteristics by Storm Type

Storm Types	1	2	3	4	5	6	7	8	X[1]	Total
Number of Storms	45	23	6	6	7	4	4	2	11	108
Percent of Occurrences	42	21	5	5	7	4	4	2	10	100
Percent of Precipitation										
All stations	18	21	9	14	10	15	4	4	5	100
<7500 ft	16	22	10	15	10	14	4	4	5	100
>7500 ft	30	19	6	11	6	16	4	4	4	100
Average Precipitation										
<7500 ft	0.12	0.31	0.53	0.96	0.50	1.19	0.36	0.57		
>7500 ft	0.39	0.48	0.51	1.14	0.44	2.34	0.68	1.17		
Avg Base Precipitation	0.11	0.42	0.42	1.14	0.42	1.10	0.26	0.07		
Avg Orographic Factors										
<7500 ft	1.04	0.73	1.24	0.83	1.15	0.94	1.34	7.85		
>7500 ft	3.58	1.14	1.22	1.00	1.06	2.13	2.63	16.73		
>7500 ft/<7500 ft	3.44	1.56	0.98	1.20	0.93	2.27	1.96	2.13		

X[1] Miscellaneous Weather Types

anticyclone (shallow upslope) precipitation event which is so often found over the western High Plains. As discussed in that paper and others (Whiteman, 1973) such systems tend to produce light precipitation for several reasons. The upslope circulation often develops in the left rear quadrant of the polar front jet, where subsidence predominates and surface pressures are rising. The clouds associated with the lifted air tend to be quite shallow, stratus types and the air mass is usually thermodynamically stable, both factors limiting the amount of precipitation that falls from such systems. In the Big Horn Range, even though this storm type accounts for 45% of all the events, it only accounts for 18% of all the precipitation. Below 7500 feet (2286 meters) the average areal precipitation is only 0.12 inches (3 mm) and above 7500 feet (2286 meters) the average areal precipitation is 0.39 inches (10 mm).

Table 2. Frequency of Storm Type by Month

Storm Type	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**X^1**	**Total**
January	5	1					1			7
February	7		1						1	9
March	8	4	1				1		1	15
April	6					1		1	1	9
May	1	2		2	1	2				8
June	1	3	2	1	3		1	1	1	13
July	1	2	1	1	1				2	8
August		3			1				3	7
September	1	3	1	2			1			8
October	3	3							1	7
November	7	1			1	1			1	11
December	5	1								6
Total	45	23	6	6	7	4	4	2	11	108

X^1 Miscellaneous Weather Types

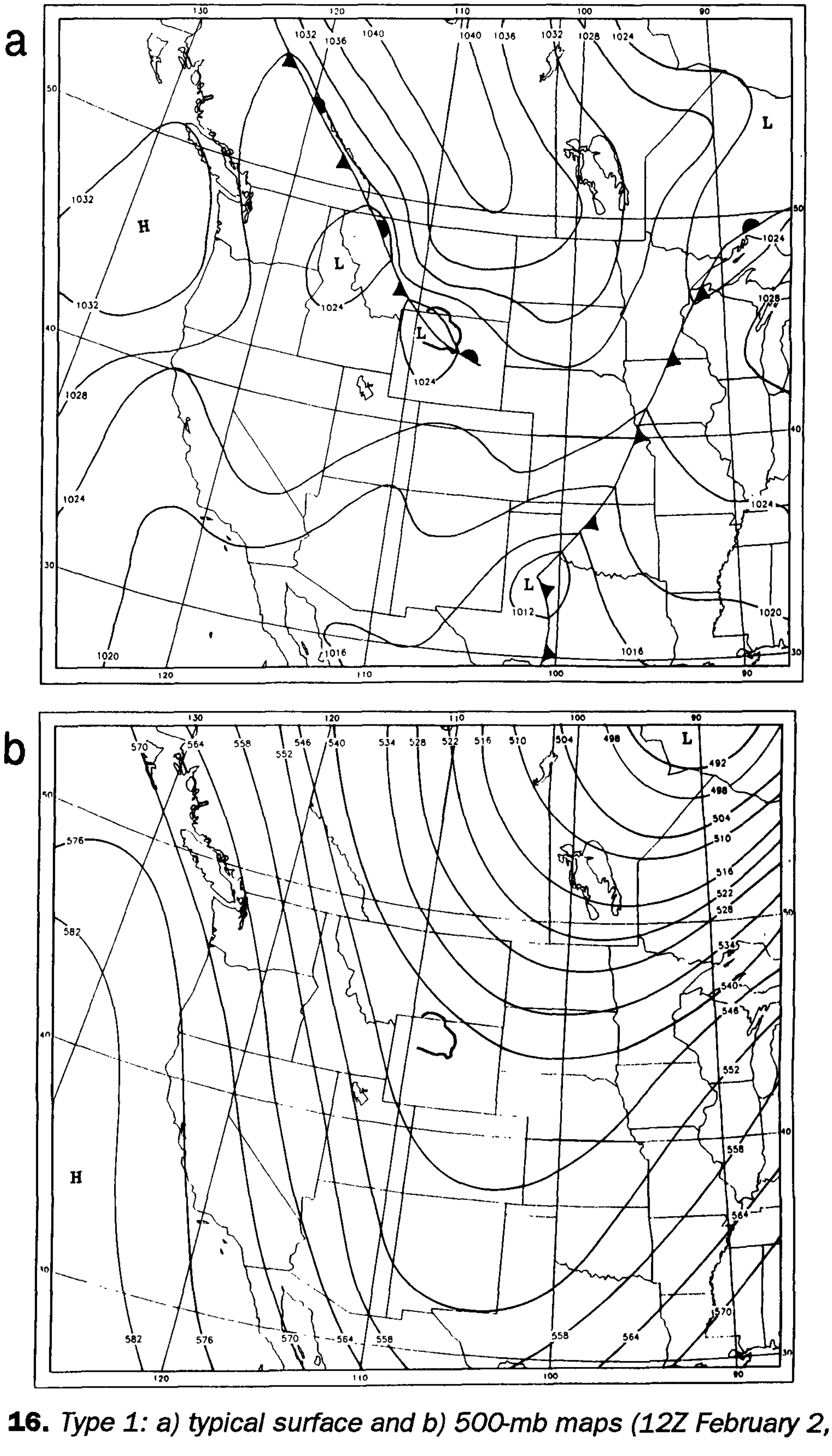

Figure 16. *Type 1: a) typical surface and b) 500-mb maps (12Z February 2, 1982).*

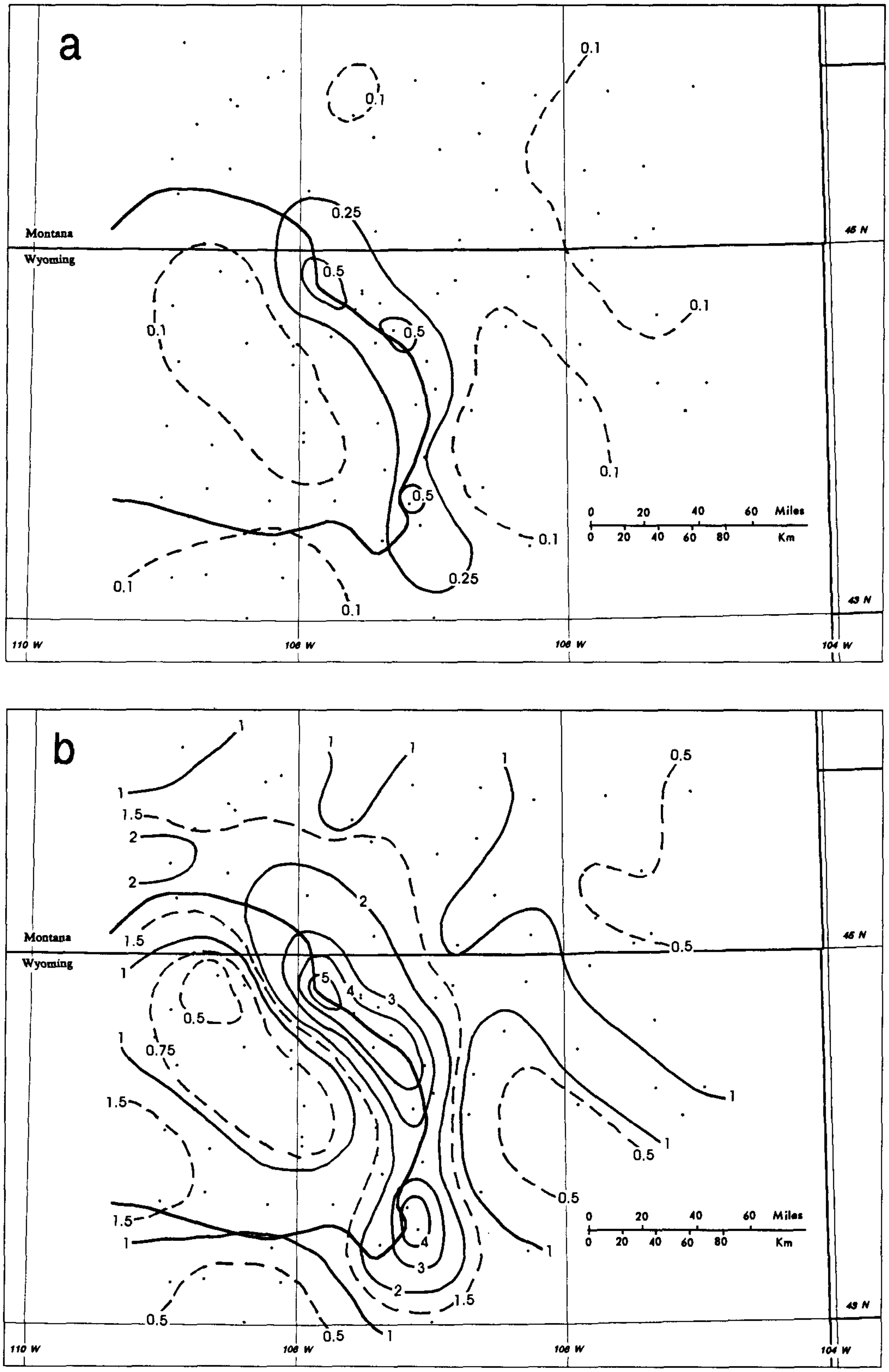

Figure 17. *Type 1: a) average precipitation and b) average orographic factors.*

The average precipitation from Type 1 (Fig. 17a) shows a relatively flat pattern with the highest precipitation amounts of just over 0.5 inches (12.7 mm) on the crest. The average spatial distribution of this storm type closely resembles the winter precipitation pattern of Fig. 4a. The base precipitation amount for this weather type is only 0.11 inches (2.8 mm). Low-level flow for Type 1 is from the east, which affects the whole eastern ridge of the Big Horns. As shown in Fig. 17b, the average orographic factors for these storms reached 5 over the northeast ridge with a secondary maximum of 4 on the southeast ridge. Although the average precipitation from any one storm in this type is not large, the high frequency of its occurrence means that it provides an important seasonal and annual component of precipitation.

7.2 Storm Type 2

The 23 occurrences of Type 2 make it the second most frequent storm type. The upper-air flow (Fig. 18b) is more zonal than Type 1, and usually is associated with a short-wave trough approaching from the west or northwest. Ridging in advance of this approaching short wave provides a generally south or southwest flow at mid- and upper-levels. The surface map from a storm of this type (October 7, 1982) depicts a low north of the Big Horn mountains (Fig. 18a) allowing the Big Horns to be embedded in southerly flow in advance of the cold front. This weather type only occurred four times from November though February and was most frequent from May through October (70% of all of the occurrences of Type 2). During March this weather type was noted four times.

Type 2 storms account for 21% of all storm occurrences and 21% of all precipitation. In the lower elevations, in the region of the average area base precipitation, between 20 to 35% of the precipitation is associated with this storm type, but only 15 to 20% of the precipitation is associated with the remaining region below 7500 feet (2286 meters). The average precipitation pattern (Fig. 19a) is similar to the pattern associated with Type 1, except there is a secondary precipitation maximum east of the Big Horn mountains. The average orographic factors (Fig. 19b) for this type indicates only minor enhancement along the crest area of the Big Horns. The primary maximum of 2 is located on the southeast crest, with a secondary maximum of 1.25 to the north. The low-level winds for this weather type will primarily be from the south or southeast, and the southeast ridge is the windward ridge. The

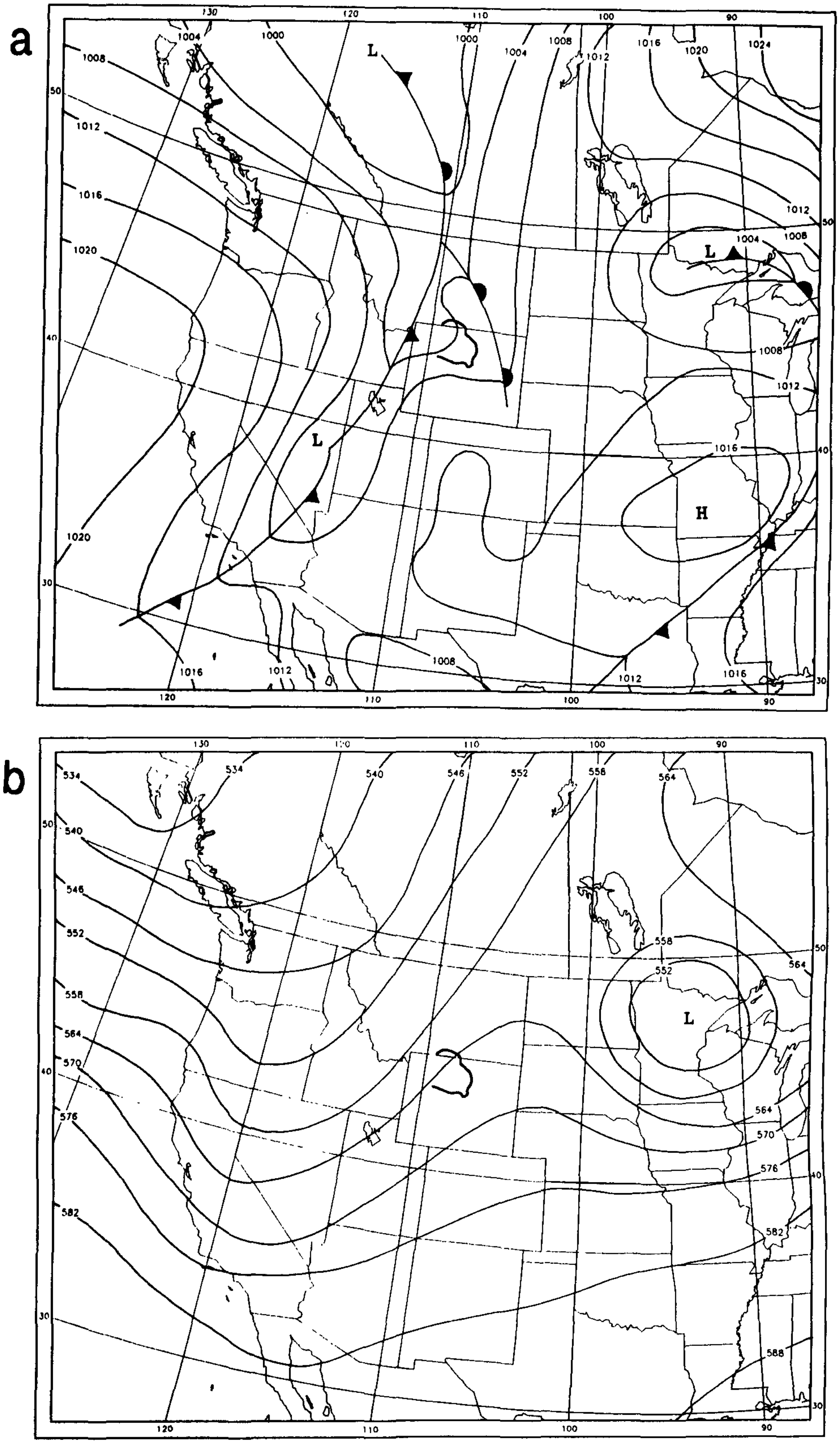

Figure 18. *Type 2: a) typical surface and b) 500-mb map (12Z October 7, 1982).*

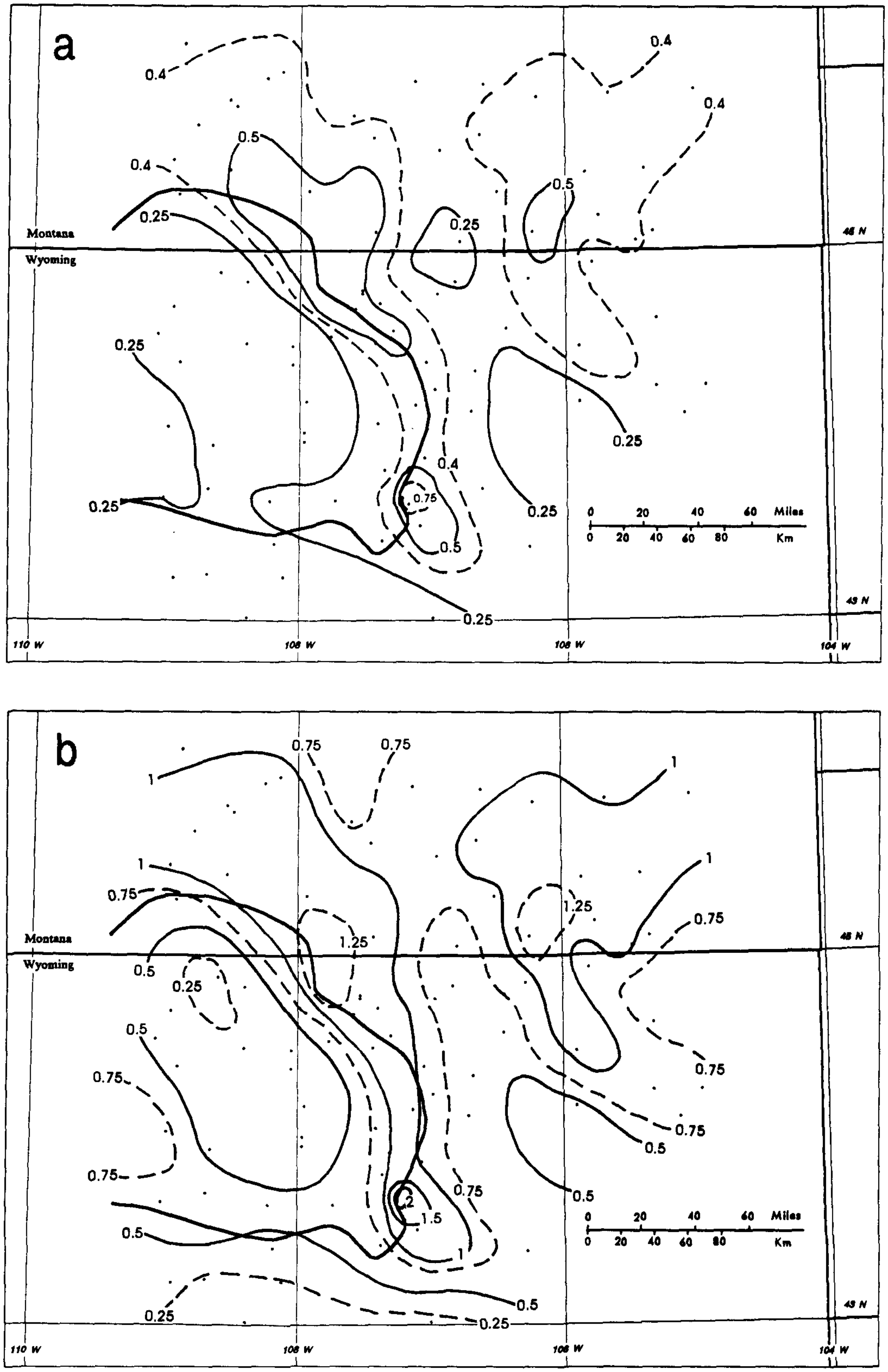

Figure 19. *Type 2: a) average precipitation and b) average orographic factors.*

ridges to the north are to the lee of the low-level flow. Since this is dominantly a warm season event, the lowered orographic factors on the crests of the Big Horn can be expected.

7.3 Storm Type 3

Storms identified as Type 3 are associated with a surface low pressure in the Panhandle regions of Texas and Oklahoma and a 500-mb low near the Four Corners region (Fig. 20a and 20b). February 27, 1987 is the analog for this storm type. Low-level moisture is advected upslope from the east and the Gulf of Mexico, and the flow at 500 mb even has an easterly component. During the three years analyzed there were six such events, or about 6% of all events.

These six events accounted for 9% of all precipitation in the 108 storms, making this a slightly wetter than average type of system. The average precipitation pattern associated with these storms (Fig. 21a) shows a maximum east of the main ridge line and a secondary maximum on the western side of the interior basin where the elevation increases again. The average orographic factor associated with Type 3 (Fig. 21b) shows two maxima of about 3. The first is located about 20 miles (32 kilometers) east of the eastern ridge line; the second is situated on the western edge of the interior basin, where there is an increase in elevation. These maxima reflect the low-level easterly or southeasterly flow and subsequent lifting, condensation and precipitation. Interestingly, the factors along the eastern ridge line are near one for this weather type, but are greater than one in the southwestern part of the research area. This is probably a reflection of more low-level southeasterly flow.

7.4 Storm Type 4

June 5, 1982 is the analog storm for Type 4 and is characterized by an upper trough at 500 mb which swings across the Big Horns. Short-wave energy moves through the base of the long-wave trough serving to deepen it and aid in surface cyclone development (Fig. 22a and 22b). A broad southwesterly flow aloft predominates ahead of the upper trough axis, advecting Pacific moisture into and across the region. At the surface, cyclogenesis is initiated southwest of the Big Horn Range, and moves east over the Rockies staying south of the Big Horn Mountains, and then moves northeast in

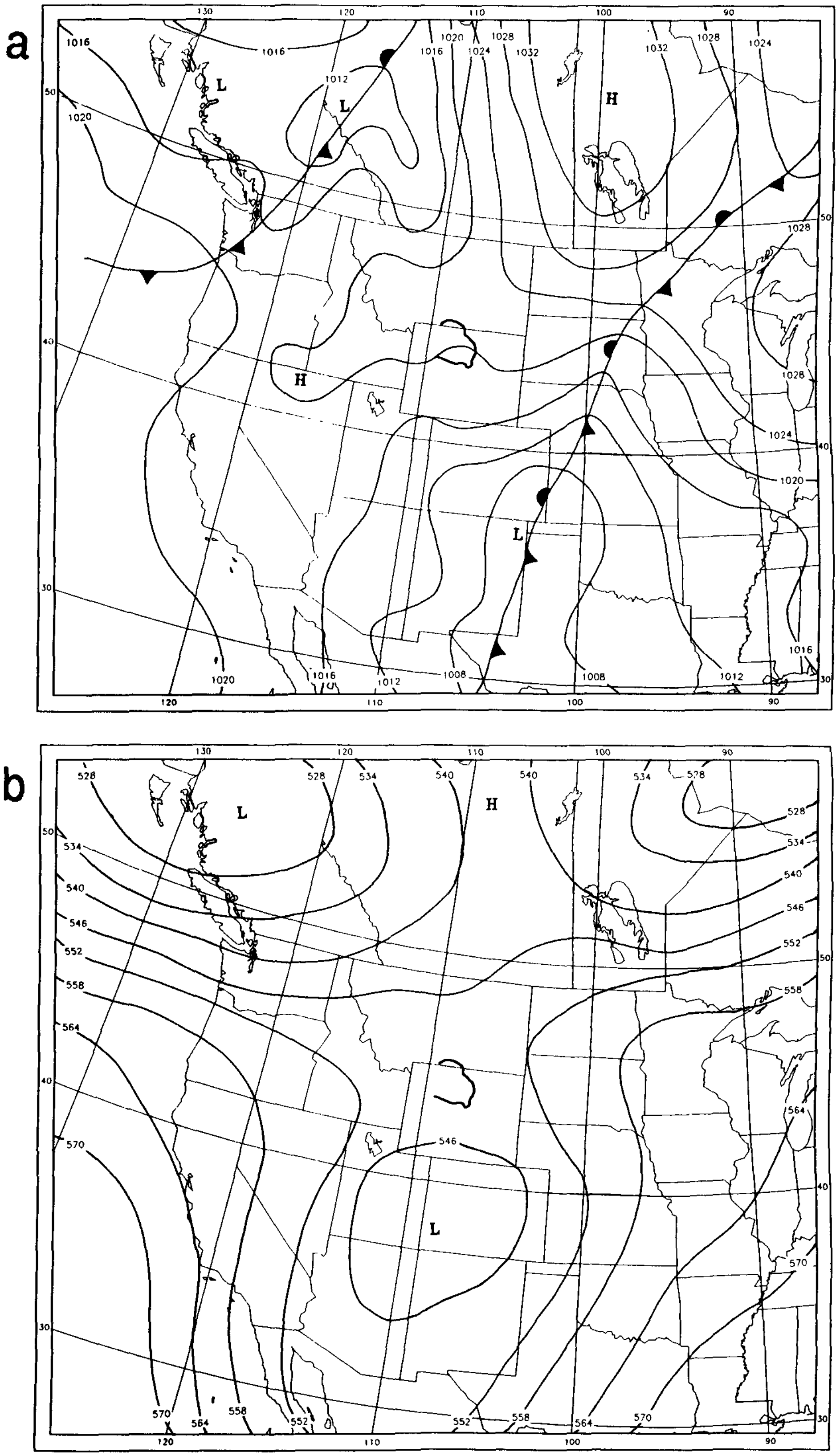

Figure 20. *Type 3: a) typical surface and b) 500-mb maps (12Z February 27, 1987).*

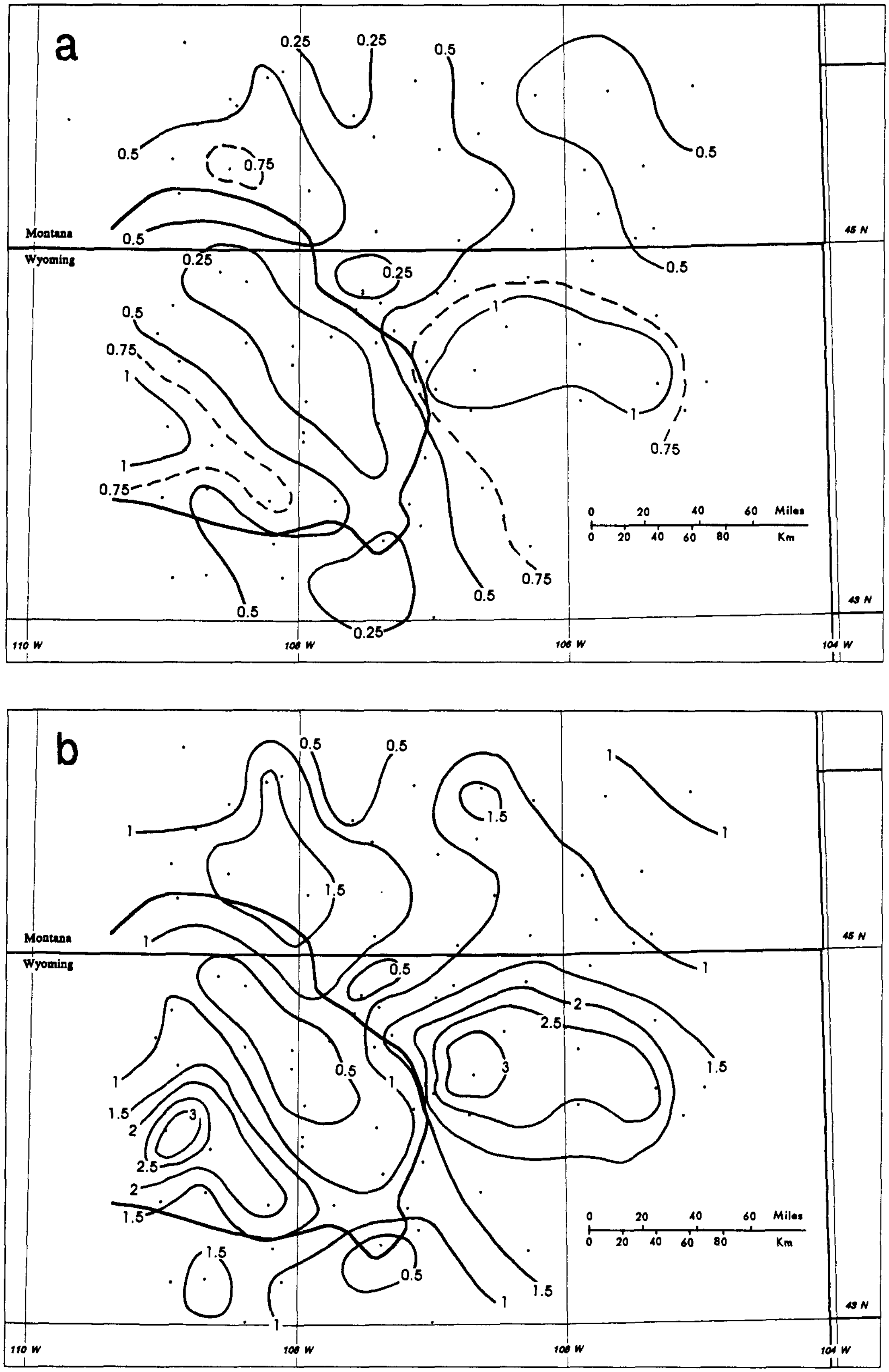

Figure 21. *Type 3: a) average precipitation and b) average orographic factors.*

response to the progression of the upper-level trough to the east of the Big Horns. Flow around the surface high usually located over the central U.S. transports low-level moisture from the Gulf of Mexico westward, which is lifted by the terrain, thus providing another example of upslope precipitation development. A study by Oard (1980) in looking at severe spring storms in Montana said they are typically characterized by a strong upper trough in the Great Basin and a ridge to the east. The strength of the upper ridge, negative tilt and high amplitude all aided in the development of strong storms. The similarities between the Type 4 storm and Oard's strong storm pattern is quite apparent.

Only six of these storms were observed during the three years, but these 5% of all storm occurrences accounted for 14% of all the precipitation from the 108 storms. For elevations less than 7500 feet (2286 meters), Type 4 accounted for 15% of all the precipitation and only 11% for elevations above 7500 feet (2286 meters). This storm type was observed only from May through September, with no occurrences during August. Because this is primarily a warm-season event, no major differences in the rainfall between the lower and upper elevations were observed. Similarities between this type of storm and the results of a study of widespread general rains during summer by Heim (1986) are also evident. This study looked only at July and August general precipitation events in Montana over a 40-year period. The common salient synoptic feature of such storms was an upper low or trough moving across Montana and a strong blocking high over the Midwest. The magnitude and pattern of precipitation was dependent on the exact track and strength of the systems.

The average spatial pattern of precipitation for Type 4 shows maximums east of the ridge line and over the ridge of about the same magnitude (Fig. 23a). Table 1 indicates that the average precipitation for elevations above 7500 feet (2286 meters) is only 0.18 inches (4.6 mm) greater than the precipitation below 7500 feet (2286 meters), 1.14 versus 0.96 inches (29.0 mm versus 24.4 mm). Again this is primarily a warm-season storm type, and the increase of precipitation with elevation is not large, a finding consistent with previously cited research. With this storm type there is a suggestion that some of the easterly winds have a northerly component. From 15 to 20% of the precipitation for all 108 storms was accounted for over the

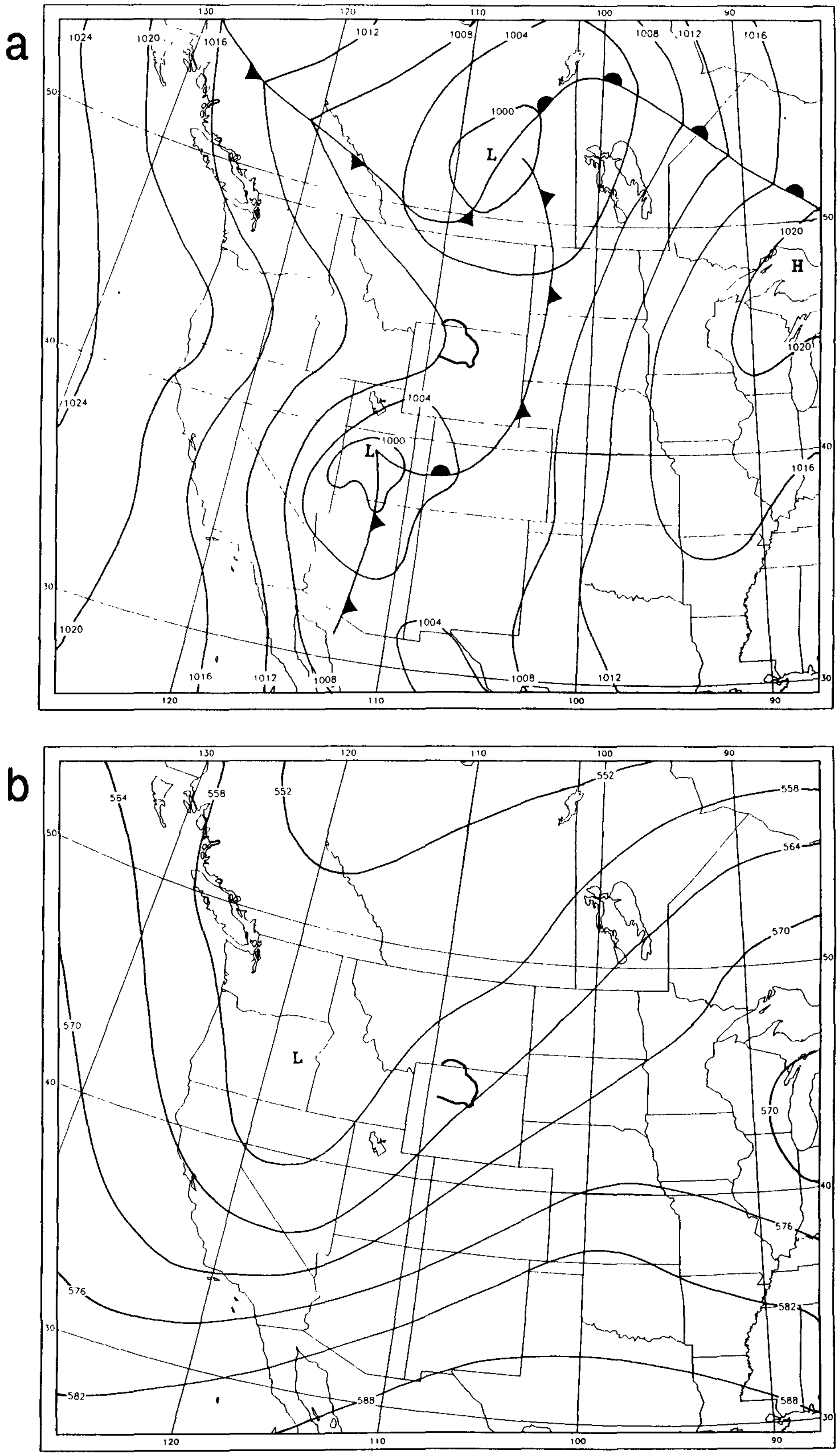

Figure 22. *Type 4: a) typical surface and b) 500-mb maps (12Z June 5, 1982).*

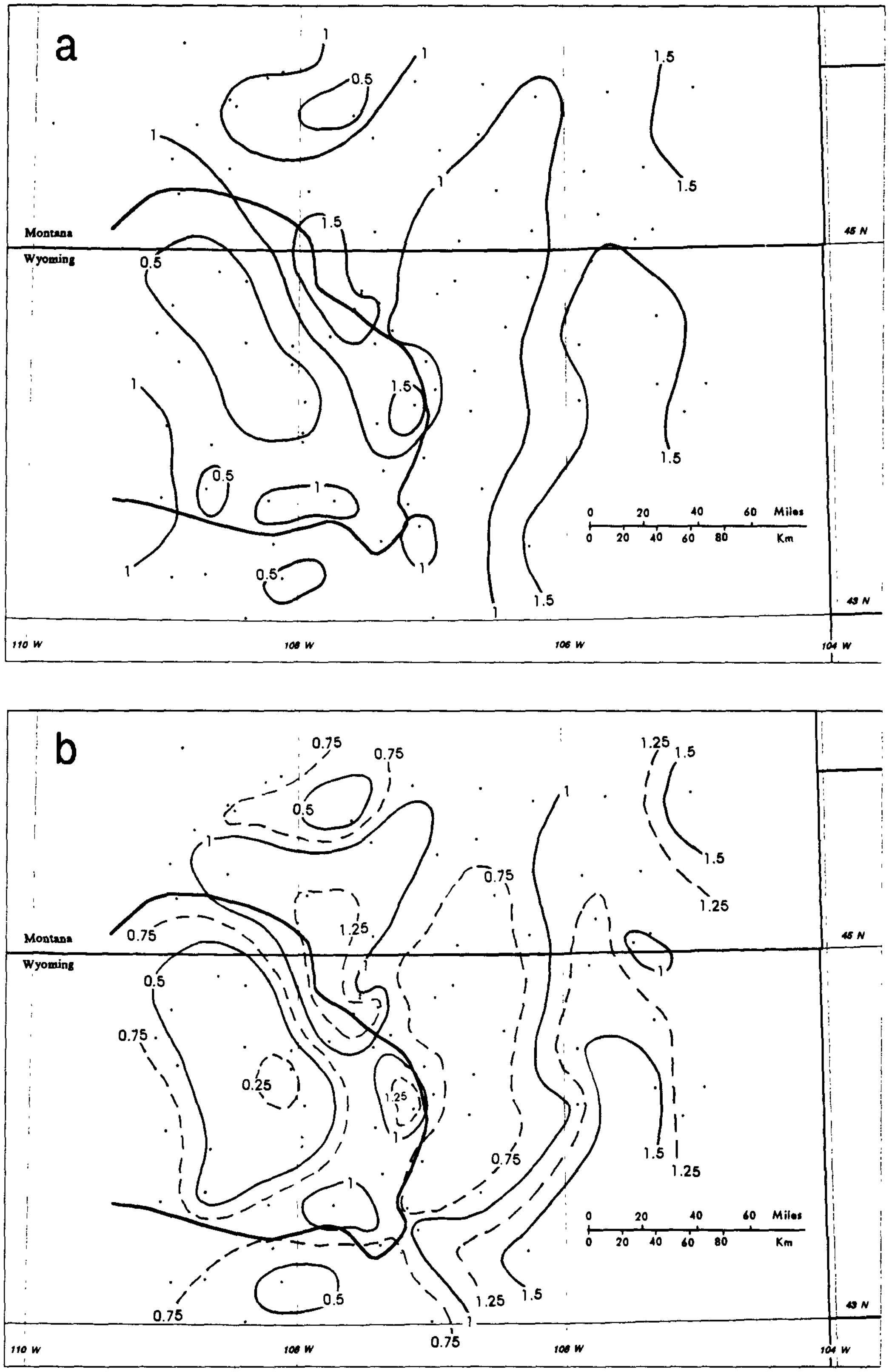

Figure 23. *Type 4: a) average precipitation and b) average orographic factors.*

eastern part of the study area, in the interior valley, and on the eastern rim of the interior valley. Interestingly, less than 10% of all the precipitation was recorded on the eastern crest of the Big Horns with Type 4. Figure 23b shows the spatial pattern of orographic factors under Type 4. Although the factors are not particularly high, they are concentrated along the northeast ridges of the Big Horns. The highest values are only about 1.25, but a distinct minimum is found in the interior basin in that area sheltered from east to northeast flow.

7.5 Storm Type 5

The upper-air flow of the May 16, 1987 analog storm for Type 5 is characterized by light winds and a broad ridge over most of the southern two-thirds of the United States (Fig. 24). The polar jet stream and high winds aloft are restricted to the northern tier of the United States and southern Canada, a synoptic pattern characteristic of summer. This precipitation type occurs when a short-wave trough moves along the southern part of the faster flow, passing over the Big Horn mountains and provides some upper-level divergence. The surface pattern shows a cold front or a stationary front stretched from some point on the West Coast to a surface low north of the Great Lakes. This front frequently lies over or in the vicinity of the Big Horn mountains (Fig. 25a).

The upslope component of these storms comes either from the east or the northeast. Consequently, the heaviest rains occur in the northern part of the area, just north of the Montana border, or along a northeast-southwest axis from Montana toward the crest of the Big Horn mountains. The precipitation generally decreases or stays the same with elevation in these storms, primarily owing to the lack of organized moisture inflow which can be lifted by the terrain. The precipitation associated with these storms is generally light; these seven events only contributed 5% of the total precipitation. The spatial pattern of average precipitation (Fig. 25b) shows a significant precipitation reduction in the interior basins of the Big Horns, with a minima of less than 0.25 inches (6.4 mm). Much of this reduction may be due to the mean frontal position location north of the Big Horns. There is simply less mechanism for precipitation production further south. Again, the reduced orographic effect is reflected in the precipitation maxima at lower elevations northeast

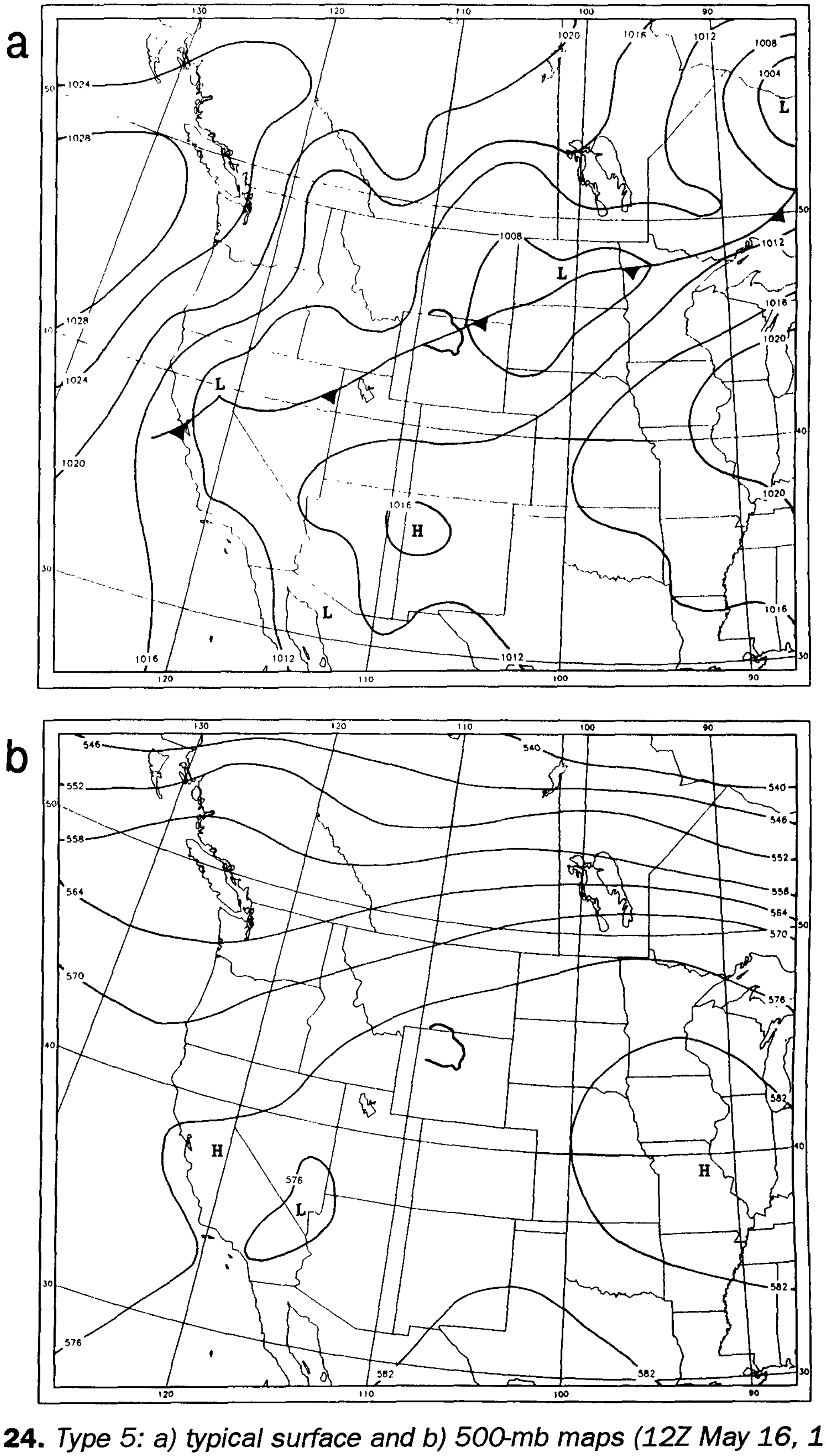

Figure 24. *Type 5: a) typical surface and b) 500-mb maps (12Z May 16, 1987).*

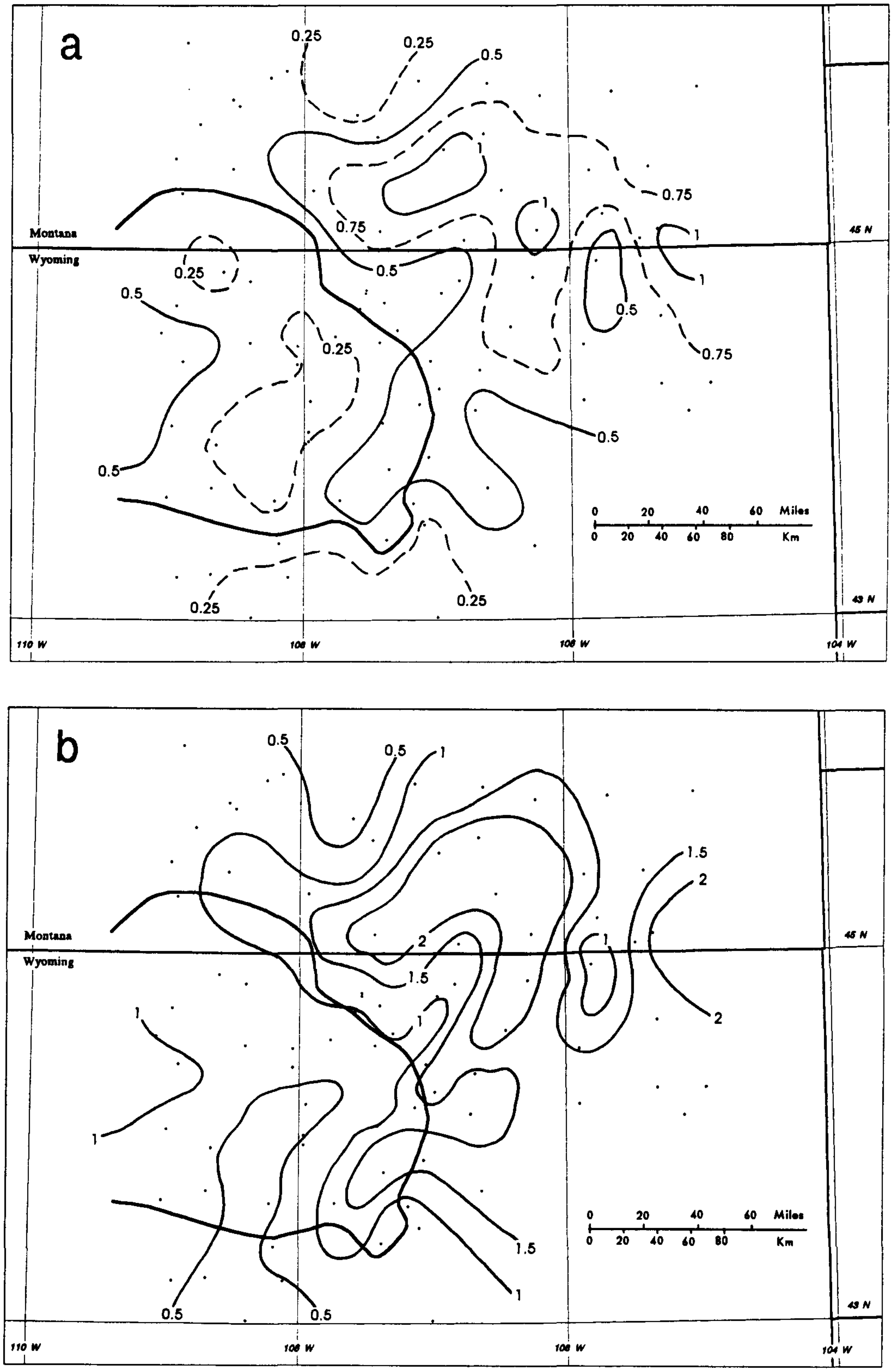

Figure 25. *Type 5: a) average precipitation and b) average orographic factors.*

of the main crests of the range and relatively lower orographic factors along the ridges and in the interior basin.

7.6 Storm Type 6

The Type 6 storms represent a well-developed cyclone with strong upper-level support quite similar to the Type 4 storm. The major difference between these two types in terms of surface and upper-air patterns is in the pressure gradients. The Type 6 tends to be a better developed storm than the Type 4. These storms are associated with a strong cut-off low over or east of the Big Horn mountains (Fig. 26). Winds aloft over the region are from the southwest ahead of the upper low but become east to northeast as the low moves eastward. Such storms produce strong pressure gradients with winds well in excess of 50 knots at 500 mb, indicating strong upper-level divergence. The surface low-pressure area passes south of the Big Horns moving from the southwest to the northeast. Surface and low-level winds are also quite strong from the south or the southeast, drawing moisture northward from the Gulf of Mexico. Polar air from Canada is advected south behind the surface low along the Rockies. This is a strong upslope condition and the May 6-8, 1988 (classified as a Type 6 storm) event shows that this storm type can on occasion occur outside the normal season for upslope storms, which runs from September or October through April (Reinking and Boatman, 1986; Whiteman, 1973; Hansen, et al., 1988).

This storm was shown to be a prolific precipitation producer in the Big Horn range. Only four storms were identified as Type 6, but these four storms account for 15% of all the precipitation that occurred during the three years that were examined (Table 1). Unlike the Type 4 which showed only minor differences between the precipitation below and above 7500 feet (2286 meters), Type 6 displays a marked difference in the magnitude of the lower- and upper-level average precipitation. There is a difference of 1.15 inches (29.2mm) between the low- and high-level average precipitation. This disparity underscores the effectiveness of the orographic precipitation mechanism in these storms. These storms occurred during April, May, and November so they can be considered as transitional storms between summer and winter.

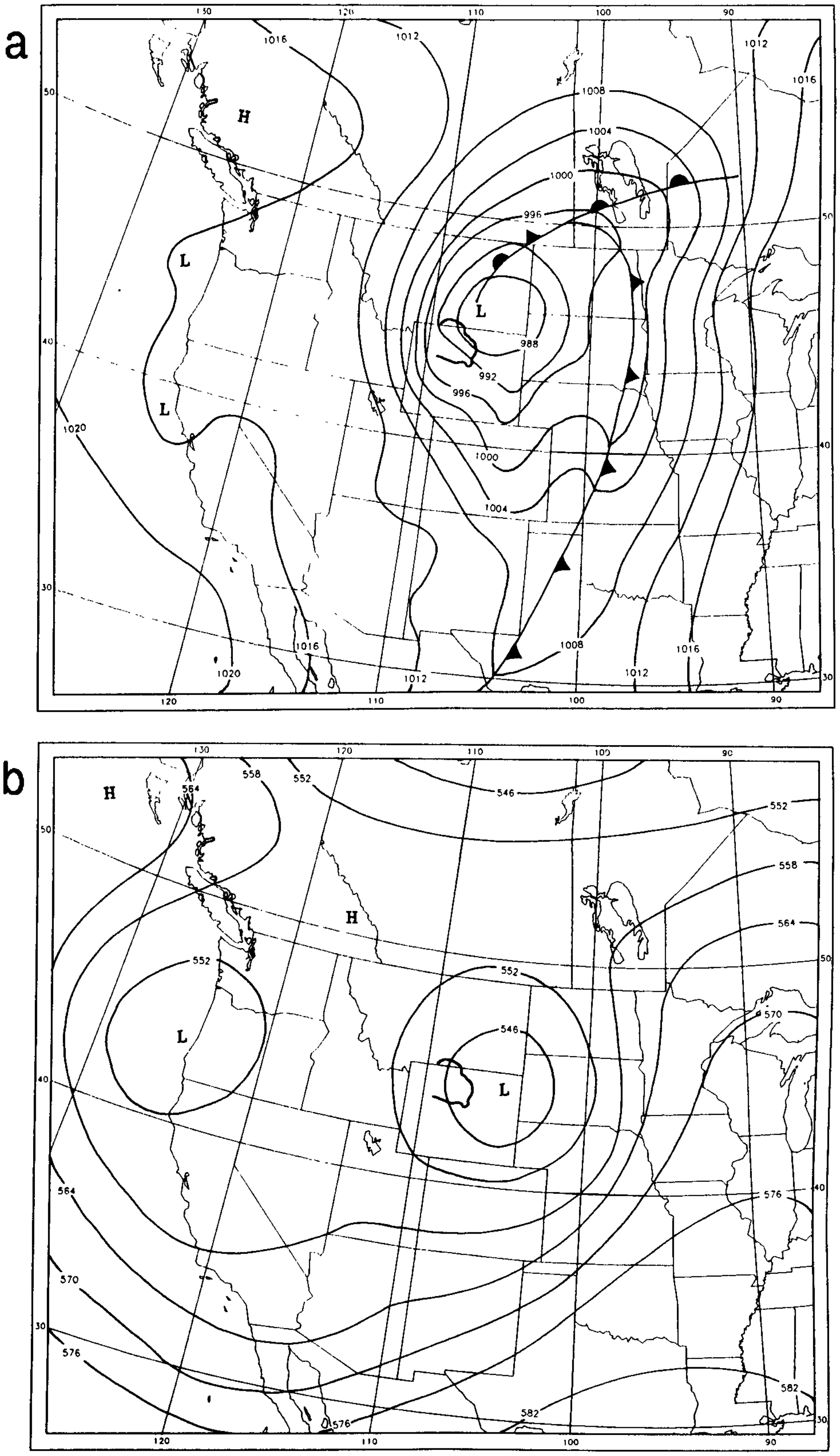

Figure 26. *Type 6: a) typical surface and b) 500-mb maps (12Z May 7, 1988).*

These four storms account for 15% of all the precipitation for the 108 storms. To the east of the Big Horns the percent of precipitation ranges from about 10 to 15% with a few rain gauges obtaining as much as 20% of all their precipitation from Type 6. In the interior valley and along the crest of the Big Horn mountains the percent of total precipitation ranges from 15 to over 30%, with the highest percent of precipitation being noted at northern valley stations. The spatial distribution of average precipitation (Fig. 27a) shows maximums of 2.5 to 3+ inches (63.5 to 76+ mm) concentrated along the eastern crest of the Big Horn mountains, and generally one inch (25 mm) or more of precipitation at the lower elevations. A secondary maximum of 2 inches (51 mm) is found in the eastern base region. The magnitude and the pattern of the average orographic factors parallel the pattern found in the average precipitation (Fig. 27b).

Cross sections for two of the four storms comprising Type 6, the previously discussed May 6-8, 1988 storm, and another similar, albeit less intense storm that occurred from May 24-30, 1987 were constructed to compare with the average for all storms of this type (Figures 28a and 28b). The figure shows some of the significant variation in the orographic factors that can also occur among storms of the same type. The base precipitation for both these storms is the areal average precipitation for stations less than 3050 feet (930 meters). The two cross sections in parts a and b of this figure represent trajectories that approximate the 700-mb windflow in these two storms. Figure 28a (see insert map) shows a trajectory through the eastern portion of the basin and demonstrates the large variation in orographic enhancement possible between two individual storms. The second storm (May 24-30, 1987) more closely approximates the average orographic factors for storm Type 6 than does the May, 1988 storm and the orographic factors are considerably less as well. This emphasizes the individual differences between storms even within the same type.

Along the second trajectory (Fig. 28b), to the immediate northeast of the crestline, each storm followed the average orographic factors for Type 6 closely both in pattern and magnitude. This again points toward the individual signatures that can be anticipated during single storm events. The various maxima and minima are a function of the general- and meso-scale dynamics and are not necessarily adequately described by an average set of

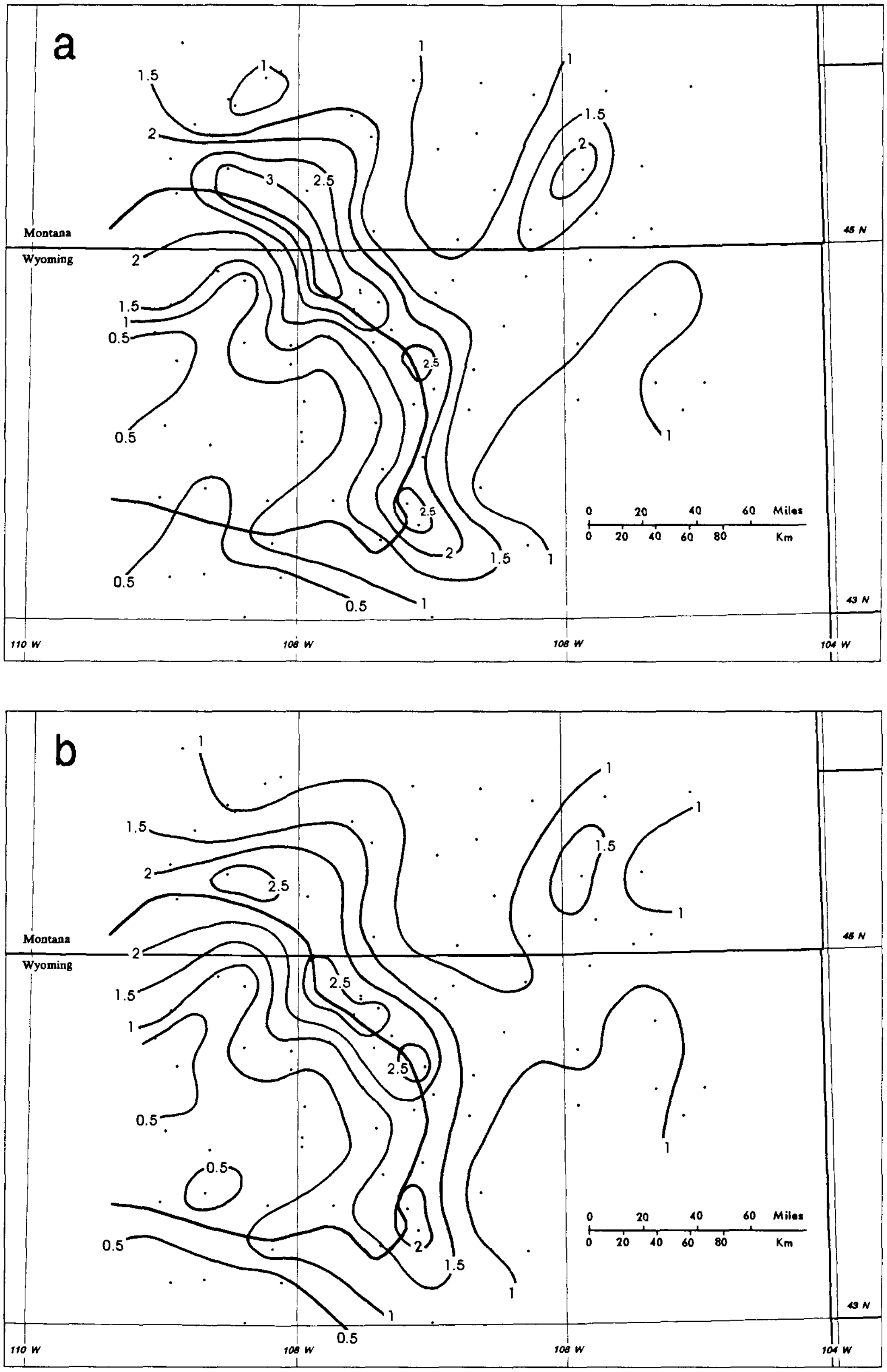

Figure 27. *Type 6: a) average precipitation and b) average orographic factors.*

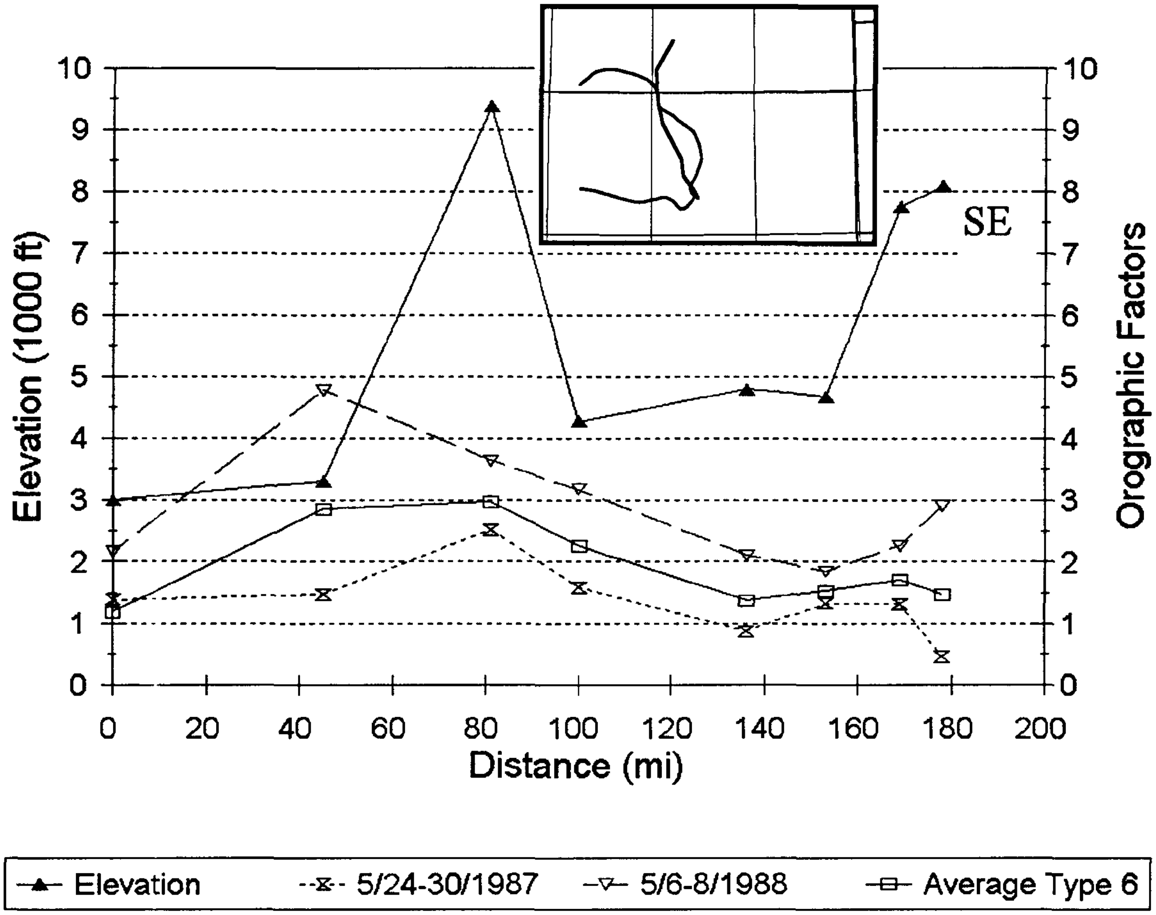

Figure 28a. *Cross sections of elevation and orographic factors for May 6-8, 1988 and May 24-30, 1987 storms and the average orographic factors for all Type 6 storms along trajectories (see inset).*

orographic factors. The wide variation in the orographic factors between individual storm events and monthly or seasonal averages makes the development of a catalogue of analog synoptic events associated with precipitation valuable.

7.7 Storm Type 7

There were only four occurrences of Type 7 storms, from January through September. The analog selected was a March 10, 1988 storm. They accounted for 4% of the occurrences and 4% of the total precipitation. The average precipitation below 7500 feet (2286 meters) was 0.36 inches (9 mm), and above 7500 feet (2286 meters) 0.68 inches (17.3 mm). Thus,

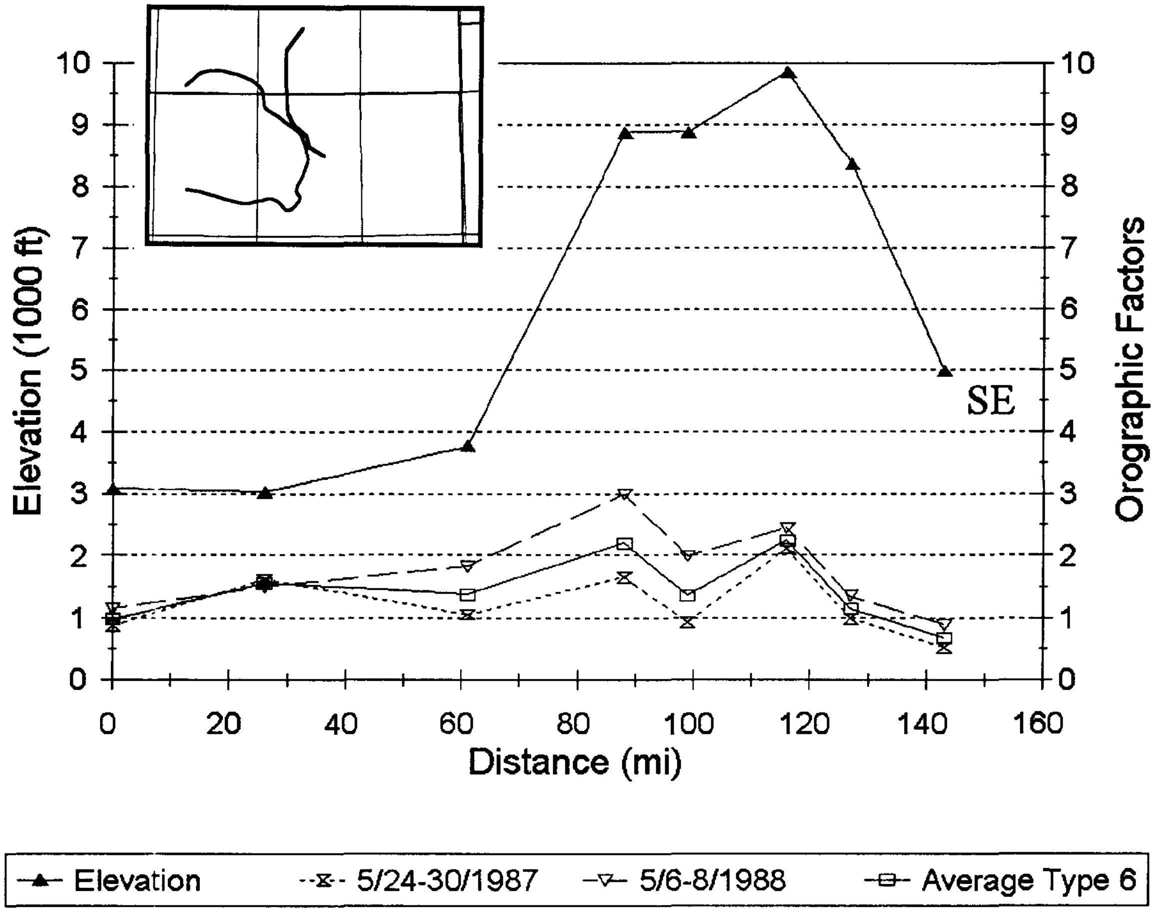

Figure 28b. *Cross sections of elevation and orographic factors for May 6-8, 1988 and May 24-30, 1987 storms and the average orographic factors for all Type 6 storms along trajectories (see inset).*

these storms exhibited some orographic effect, but were not major contributors to the precipitation over the region.

At 500 mb a strong short wave passes from west to east over the Big Horn region, which is similar to many of the other types (Fig. 29). However, at the surface the low pressure forms well south of the Big Horn region, and the northern portion of the cold front is located east of the Big Horns. This weather type is associated with strong southern and southeasterly winds at the surface and low levels of the atmosphere with strong upslope conditions. With the surface front as far east as the Dakotas, only a portion of this moisture is realized in the form of precipitation over the Big Horns.

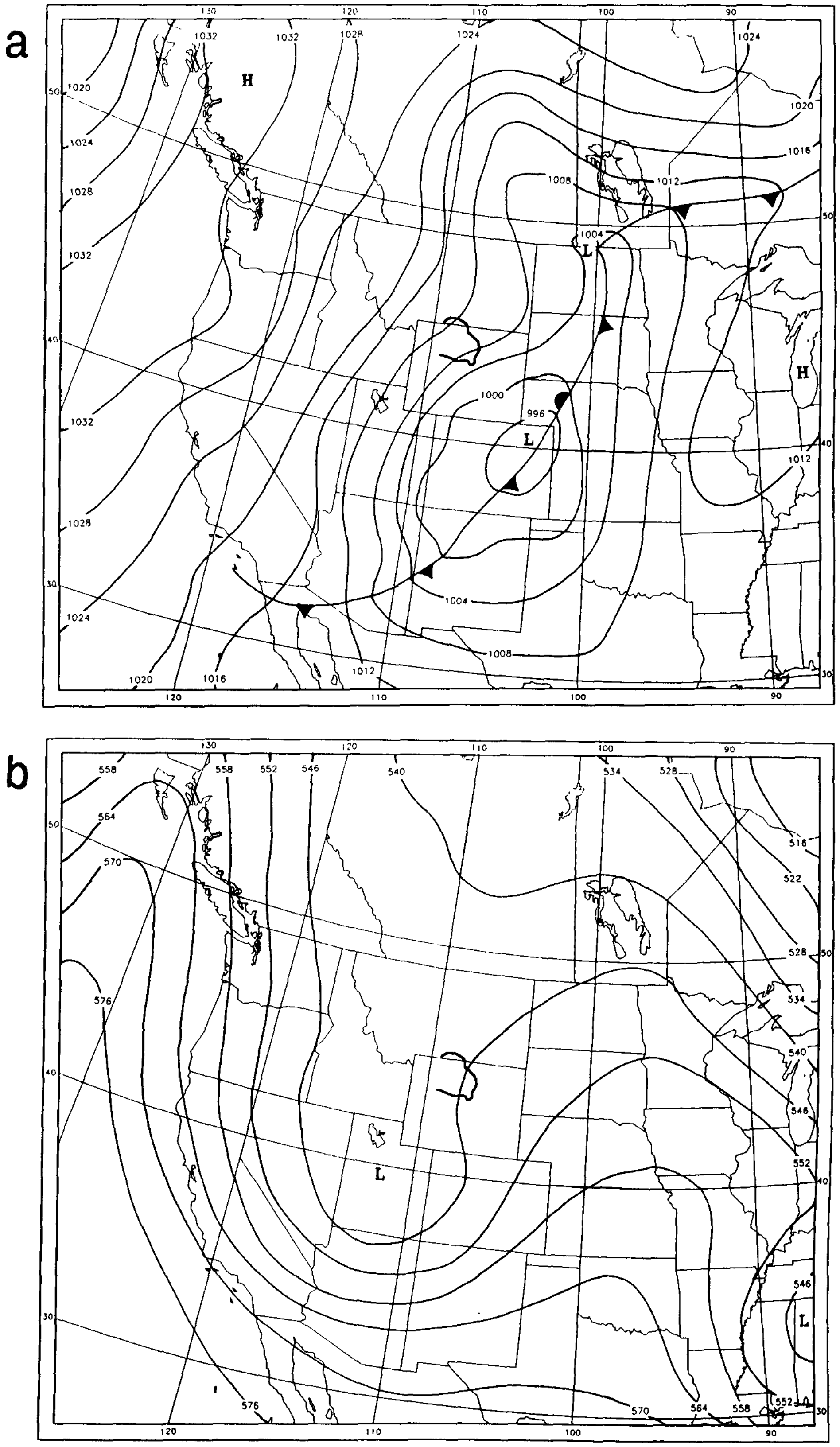

Figure 29. *Type 7: a) typical surface and b) 500-mb maps (12Z March 10, 1988).*

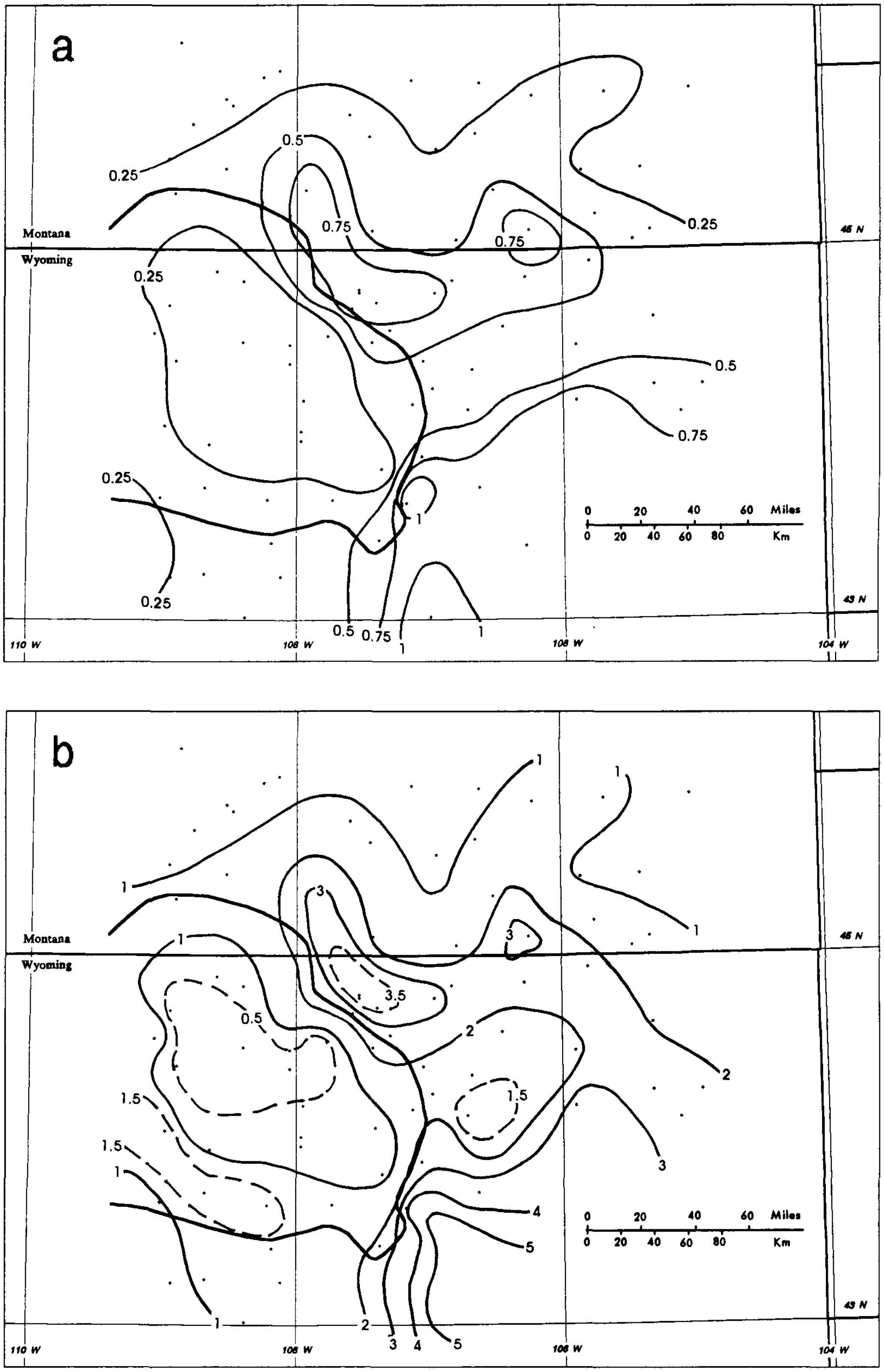

Figure 30. *Type 7: a) average precipitation and b) average orographic factors.*

The percent of precipitation associated with this storm type is flat across most of the region varying from near zero to about 10%. The average precipitation pattern (Fig. 30) shows a maximum over the northeast crest of the Big Horns which extends east into the lower elevations of Montana and Wyoming. The interior value shows a minimum of less than 0.25 inches (6.4 mm). The average orographic factors associated with this storm show a generalized maximum of 3 over and east of the crest of the Big Horns. Values up to 5 are found over lower elevations in the southeast part of the study area. Within the interior basin the orographic factors are less than 0.5.

7.8 Storm Type 8

Type 8 only occurred two times during the study period; one of the two occurrences, April 22, 1988, is shown in Fig. 31. The upper-air is characterized by a weak anticyclone over the region, and southwest flow to the south and southeast of the Big Horns. At the surface a low forms to the lee of the Rockies over Colorado usually along a stationary front, and moves slowly eastward. The low-level flow is characterized by southerly flow over the central portions of the Great Plains which turns clockwise and comes from the northeast over the Big Horns.

In the low-lying areas, this weather type accounts for 1 to 2% of all the precipitation, but along the crest and in the central and southern interior valley from 5% to as much as 20% of the total precipitation comes from this weather type. The spatial distribution of precipitation from Type 8 shows a 2-inch (51-mm) center on the east side of the interior valley with precipitation less than 0.10 inches (2.5 mm) in the low area north of the Big Horns (Fig. 32a). This is the only storm type that maximizes over the interior valley. The average rain in the base precipitation area is only 0.07 inches (1.8 mm), but the average precipitation for the region below 7500 feet (2286 meters) is 0.57 inches (14.5 mm), which is the third highest average precipitation for these elevations. Above 7500 feet (2286 meters), the average precipitation is the second highest amount with 1.17 inches (29.7 mm). The precipitation south of the base area rapidly increases to 0.5 inches (12.5 mm) and more as it approaches the crest of the Big Horns. The average precipitation from these storms are about one-third of the total annual precipitation at some of the interior valley stations.

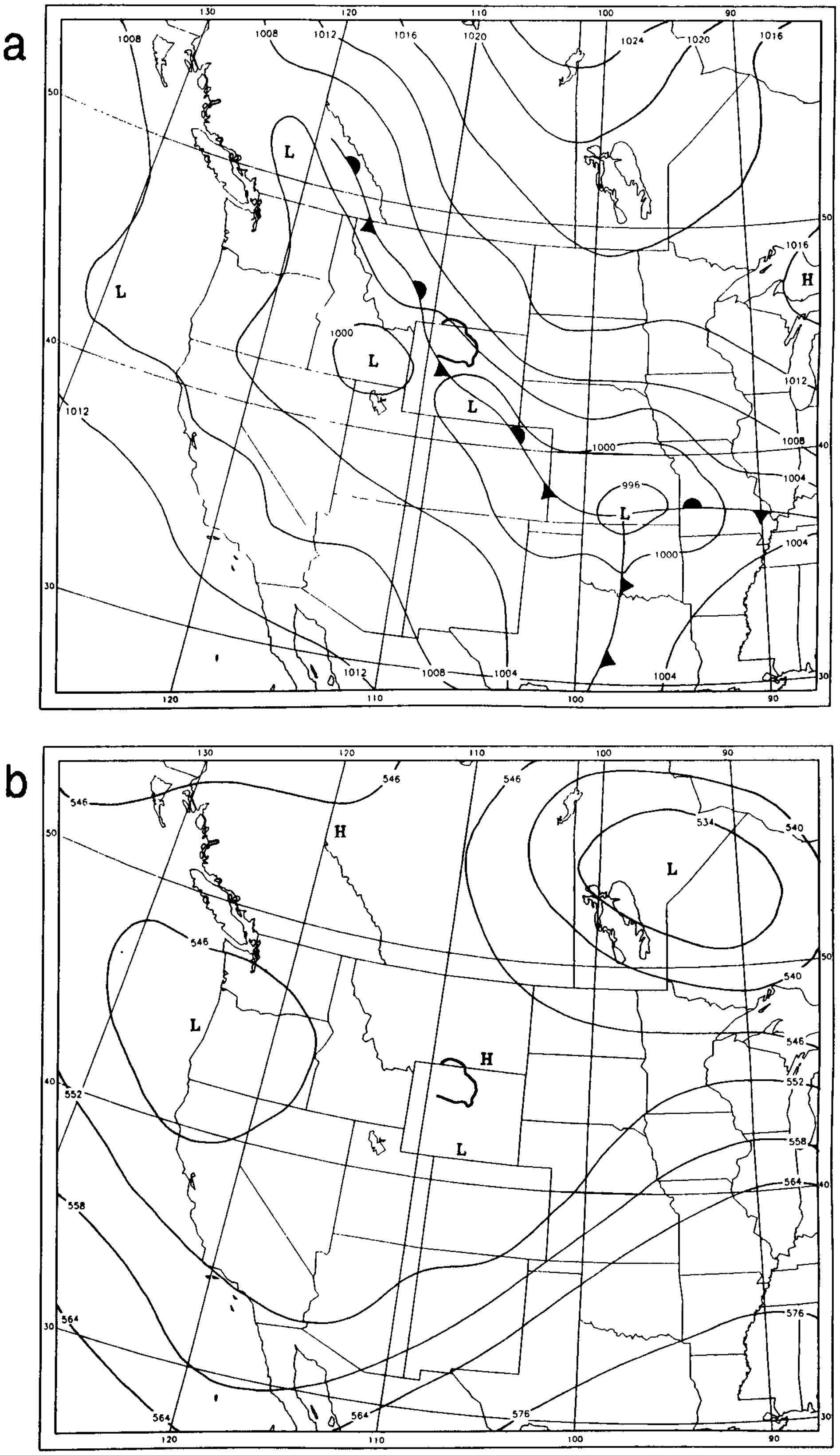

Figure 31. *Type 8: a) typical surface and b) 500-mb maps (12Z April 22, 1988).*

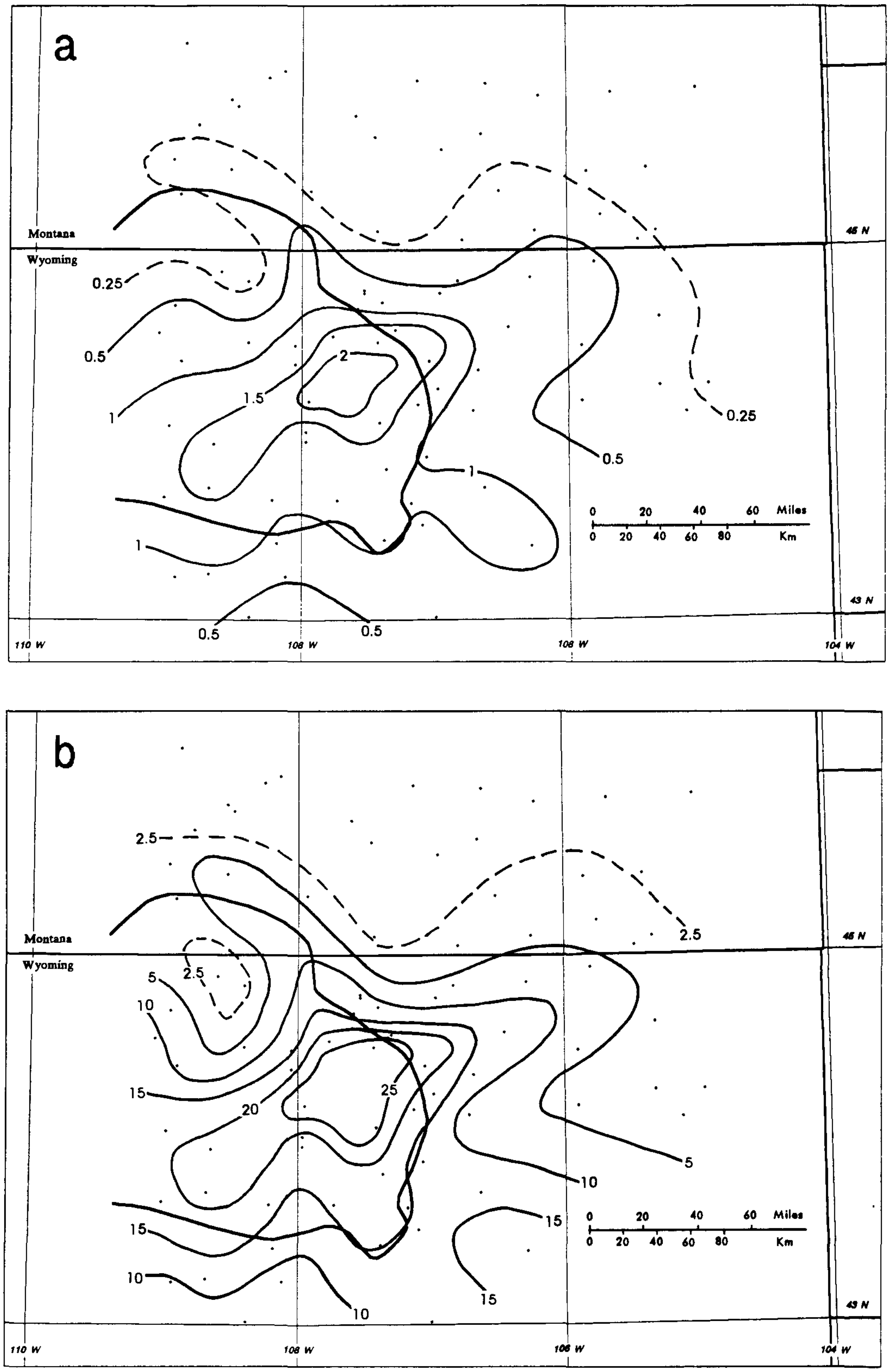

Figure 32. *Type 8: a) average precipitation and b) average orographic factors.*

The low-level winds in this situation are from the northeast and represents upslope flow, which means that the orographic components are about 90 degrees counterclockwise from the normal upslope flow. As could be expected with the very low base-precipitation amounts the orographic factors over the southern two-thirds of the region rise rapidly (Fig. 32b). The average orographic factor below 7500 feet (2286 meters) is 7.85, and above 7500 feet (2286 meters) it is 16.73. Maximums of over 25 were found in the eastern portion of the interior valley, both at higher elevations and at the lowest points of the interior valley. However, this is because the base precipitation is so low, at 0.07 inches (1.8 mm). Overall, this is a rather rare event, but when it occurs the precipitation amounts can be relatively heavy and in regions which normally do not receive much precipitation. An event such as this could dramatically alter the monthly precipitation values, when compared to monthly or seasonal averages.

8. SUMMARY AND CONCLUSIONS

Two of the major objectives of this study were to develop a precipitation climatology for the Big Horn mountains, and to establish the effect that topography has on precipitation from a climatic and storm perspective. One of the tools used in this work was the development of orographic factors. These are calculated from either "base" precipitation data using stations located in the adjacent, essentially non-orographic areas, or by using a single station at the starting point of a cross section. Orographic factors represent simple multiples of either the base precipitation value or the starting station. The period from 1980 through 1990 was used to take advantage of raingauge data from the SNOTEL network, which provides daily precipitation data from high elevations that are not available from stations in the cooperative network. Most of the SNOTEL sites were above 7500 feet (2286 meters), while the cooperative stations were below this level. In all, 83 stations were used in this analysis over nearly 40,000 square miles.

The precipitation climatology examined the annual, seasonal, and monthly patterns within the Big Horn basin and the surrounding area. On an annual basis, precipitation varied from over 30 inches at the highest elevations, down to about 5 inches in the interior lowlands. The most obvious find-

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The precipitation climatology examined the annual, seasonal, and monthly patterns within the Big Horn basin and the surrounding area. On an annual basis, precipitation varied from over 30 inches at the highest elevations, down to about 5 inches in the interior lowlands. The most obvious finding was the clear dominance of the cool-season on the effectiveness of the orographic precipitation process. The precipitation transitional seasons approximated the annual average variation of precipitation with elevation. The summer season showed the least orographic effect over the Big Horn mountains. This is in substantial agreement with the findings of Hanson (1982) using measurements from a dense raingauge network in western Idaho. Various cross sections of precipitation from least orographic regions into the Big Horn mountains showed that the average precipitation and average orographic factors followed the elevation gradients when winds were perpendicular to the slopes. Elevational differences within these time frames were also explored by analyzing cross sections taken through various traverses across the mountains.

A second objective of this work is to provide information that can be used to define the precipitation associated with individual events, or to develop seasonal patterns of precipitation in near real time. From our analysis it became obvious that a storm or two can dominate the precipitation totals and pattern for a particular month or season. Seasonal normals tend to dampen the effects of individual storms, rather they take on the character of the ensemble of storms over the years. In an effort to define the differences that could be attributed to individual storms, storm types were developed to characterize the individual events. Three years were chosen on the basis of annual precipitation over the region. One year typified a dry year (1988), one a near normal year (1987), and the third was typical of a wet year (1982). From these three years of data, 108 storms were drawn to define the synoptic climatology of the Big Horn mountains according to surface and 500-mb maps. Eight synoptic types were identified. Nearly two-thirds of the storm occurrences were comprised of only two types (1 and 2), but these two accounted for less than 40% of the total precipitation. By contrast, two other types together (4 and 6) made up less than 10% of the occurrences, but produced nearly 30% of the total precipitation. The orographic factors varied considerably among the storm types as well. The largest orographic factors were associated with Type 8, which was only observed four times in the three years. Orographic factors of 25 and more were observed over the interior valley stations, and this was the only storm type for which a precipitation maximum east of the main ridge of the Big Horns was observed. This was primarily because the "base" precipitation stations averaged less than 0.07 inches (1.8 mm) of precipitation. Some of the average precipitation amounts from this storm type were about one-third of the average annual precipitation.

Other high orographic factors were observed with Type 1, but the "base" and high elevation precipitation was relatively low. The two major precipitation producing storm types, 4 and 6, had very different orographic "footprints", the latter being much more effective in inducing high elevation precipitation. Synoptically, the surface and the 500-mb flows were similar, however, the major difference was in the intensity of the storms; Type 6 was much more intense than Type 4. These findings suggest that storm types can be used to provide estimates of the variation in precipitation within the mountains, where observations are scarce. Using the storm types and surface observations of precipitation, estimates of the magnitude of precipitation in the mountains can be made. These estimates can be used to provide information about individual storms, or they can be accumulated to provide information about the current seasonal precipitation for use in flood prediction or the management of water resources.

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