Patterns of Orographic Uplift in the Sierra Nevada and Their Relationship to Upper-Level Atmospheric Circulation

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ABSTRACT: We examine monthly and seasonal patterns of precipitation across various elevations of the eastern Central Valley of California and the Sierra Nevada. A measure of the strength of the orographic effect called the "precipitation ratio" is calculated, and we separate months into four groups based on being wet or dry and having low or high precipitation ratios. Using monthly maps of mean 700-mb height anomalies, we describe the northern hemisphere mid-tropospheric circulation patterns associated with each of the four groups. Wet months are associated with negative height anomalies over the eastern Pacific, as expected. However, the orientation of the trough is different for years with high and low precipitation ratios. Wet months with high ratios typically have circulation patterns favoring a west-southwest to east-northeast storm track from around the Hawaiian Islands to the Pacific Northwest of the United States. Wet months with low precipitation ratios are associated with a trough centered near the Aleutians and a northwest to southeast storm track. Dry months are marked by anticyclones in the Pacific, but this feature is more localized to the eastern Pacific for months with low precipitation ratios than for those with high ratios. Using precipitation gauge and snow course data from the American River and Truckee-Tahoe basins, we determined that the strength of the orographic effect on a seasonal basis is spatially coherent at low and high elevations and on opposite sides of the Sierra Nevada crestline.

The majority of precipitation in the Sierra Nevada results from the passage of mid-latitude cyclones from November through March. Since the range is oriented north-south and the storms normally have a strong west-east component, a significant orographic effect generally results in increases in precipitation with elevation. Although spatial distribution of precipitation anomalies is fairly uniform throughout the range (Aguado 1990), the strength of this orographic effect can vary considerably.

The elevational distribution of precipitation has some important ramifications to water managers. If a larger than normal orographic effect is experienced, there will likely be more precipitation in the form of snow as opposed to rain, leading to a delay in the hydrograph response. Moreover, it has been shown (Aguado *et al* 1992; Cayan *et al* 1992) that the relative importance of temperature and precipitation to the timing of melt varies with elevation. The timing of runoff is important for two reasons:

- It influences the allocation of water for the conflicting purposes of water retention and flood control.
- Timing of runoff is likely to be significantly altered if any of the hypothesized climatic warming scenarios are realized (*eg*, Gleick 1987, 1989; Lettenmaier and Gan 1990).

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The primary objectives of this paper are to examine underlying patterns of orographic uplift across a transect of the Sierra Nevada and to relate variability in these patterns to synoptic-scale circulation patterns in the mid-troposphere. We also examine on a seasonal basis whether higher or lower than normal orographic effects tend to occur simultaneously on the windward and leeward basins of the range. Finally, we examine whether seasonal low or high orographic effects are consistent for different elevation bands across the windward and leeward slopes of the Sierra.

Data

Determination of the strength of the orographic effects and their relationship to middle tropospheric circulation patterns was based on precipitation data from November through April for 9 stations, 5 from the eastern part of the California Central Valley and 4 from the Sierra Nevada. These data, from 1949 through 1988, were obtained from the National Climate Data Center.

A second set of precipitation and snow-course data from the American and Truckee River basins were used to test spatial consistency of the monthly orographic effects for the cool season (November through March). Nine precipitation gauges and two snow courses were used for the American River basin; three precipitation and five snow-course sites were employed for the Truckee. These precipitation and snow data were obtained from the Centralized Data Exchange Center (CDEC) of the California Department of Water Resources and the Centralized Forecast System (CFS) of the U.S. Soil Conservation Service for water years 1949 through 1991. The snow-course data were used as surrogates for cool season precipitation due to the limited number of precipitation gauges at high elevation and the fact that standard rain gauges are unreliable when precipitation occurs as snow. In most instances, however, these snow courses observe snow cover on only a monthly basis during the snow season. This means any melting of snow cover or occurrence of significant rainfall could cause the snow-course measurements to underestimate the true seasonal precipitation. By comparing April 1 snow-water equivalents to the net cool season snowfall measured by daily, automated snow sensors (pillows), we determined that courses above 2450 meters elevation accurately represented net cool season precipitation. Procedures used to make this determination are detailed in Reece and Aguado (1992).

Methodology

The first step in determining intensity of the orographic effect for each month was to obtain the precipitation gauge values for the five Central Valley and four Sierra Nevada locations. Thus, for each month from November through April, the regional mean precipitation for both the Central Valley and the Sierra Nevada was determined. The ratio of Central

Valley to Sierra Nevada regional mean precipitation was then calculated as a measure of the orographic effect we call the "orographic ratio". Separate datasets were assembled for the 40 years of record for each month (*ie*, individual datasets consisted only of data for November, December, *etc*). We then stratified the datasets into terciles of wet, normal, and dry months and plotted them for each of the six months.

We examined the middle tropospheric circulation patterns associated with months that fell into four categories of precipitation and precipitation ratios (*ie*, wet/high, wet/low, dry/high, dry/low). For this portion of the analysis we restricted our data to December through February, since those months contribute the greatest amount of precipitation and would yield the most meaningful composites. The categories were delineated by the following procedure:

For each of the months, December through February, the 14 wettest and driest were selected. These were subdivided into those with the seven highest and lowest precipitation ratios. The result was that for each of the three months, seven cases were included in each of the four categories. Finally, the seven cases for each of the three months were merged into larger datasets containing 21 cases with wet/high ratio, wet/low ratio, dry/high, and dry/low events. For each of the categories, the average monthly 700-mb height anomalies across the Northern Hemisphere were determined and mapped.

Spatial consistency with regard to windward versus leeward sides of the Sierra and low versus high elevations were examined using the precipitation and snow-course data from the American and Truckee basins. First, the ratio of precipitation at each site to the lowest in the basin was calculated for each cool season. A 42-year mean ratio was then calculated for each site.

For each cool season, each site's ratio of precipitation to that of the lowest site was compared to the 42-year ratio (*ie*, the ratio for each cool season was compared to the mean ratio). The mean ratio was calculated for each cool season for each basin, from which ordinal rankings were determined for the seasonal mean ratios. The same procedure was also performed separately for the precipitation gauges and the snow courses so their mean ratios for each cool season could be compared.

Central Valley / Sierra Nevada Precipitation Transects

Figure 1 depicts the precipitation ratios (*ie*,the ratio of mean precipitation for the four Sierra Nevada precipitation gauges to the mean of the five from the eastern Central Valley) for the wettest and driest months. For all months considered, there is a considerable range of ratios, with the greatest range occurring for the tercile of dry years.

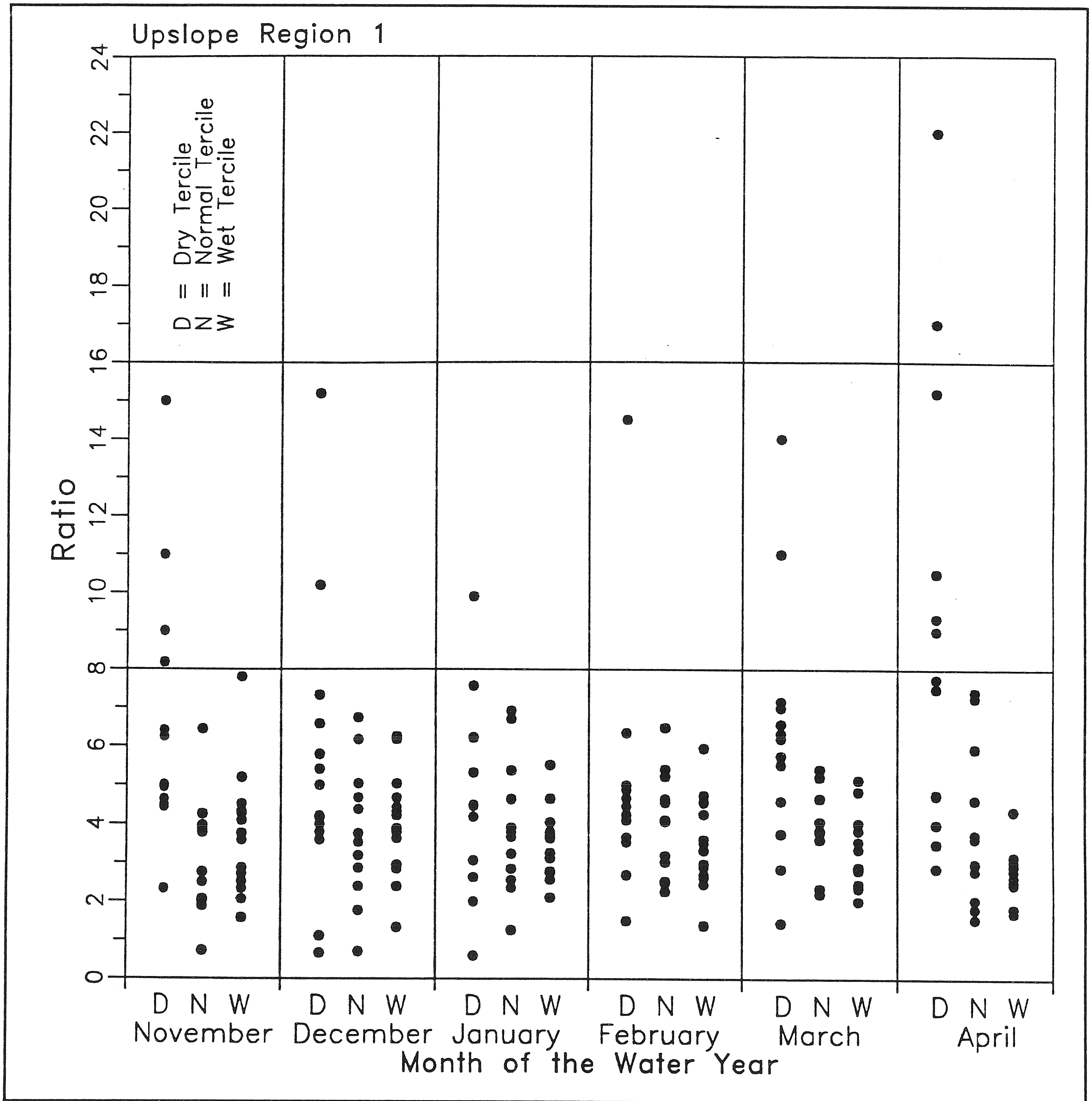

Figure 1. Precipitation ratios observed for the wet, normal, and dry terciles of monthly precipitation.

Extratropical cyclones may traverse a wide range of differing paths across the Pacific Ocean. It has been shown in other areas (*eg*, Williams and Peck 1962) that the direction of wind relative to the mountain orientation can influence the magnitude of the orographic effect. Moreover, the mean paths of the storms on a monthly basis can be related to middle tropospheric circulation patterns. We therefore composited maps of 700-mb Northern Hemisphere anomalies associated with wet and dry years with low and high precipitation ratios (Figures 2 and 3).

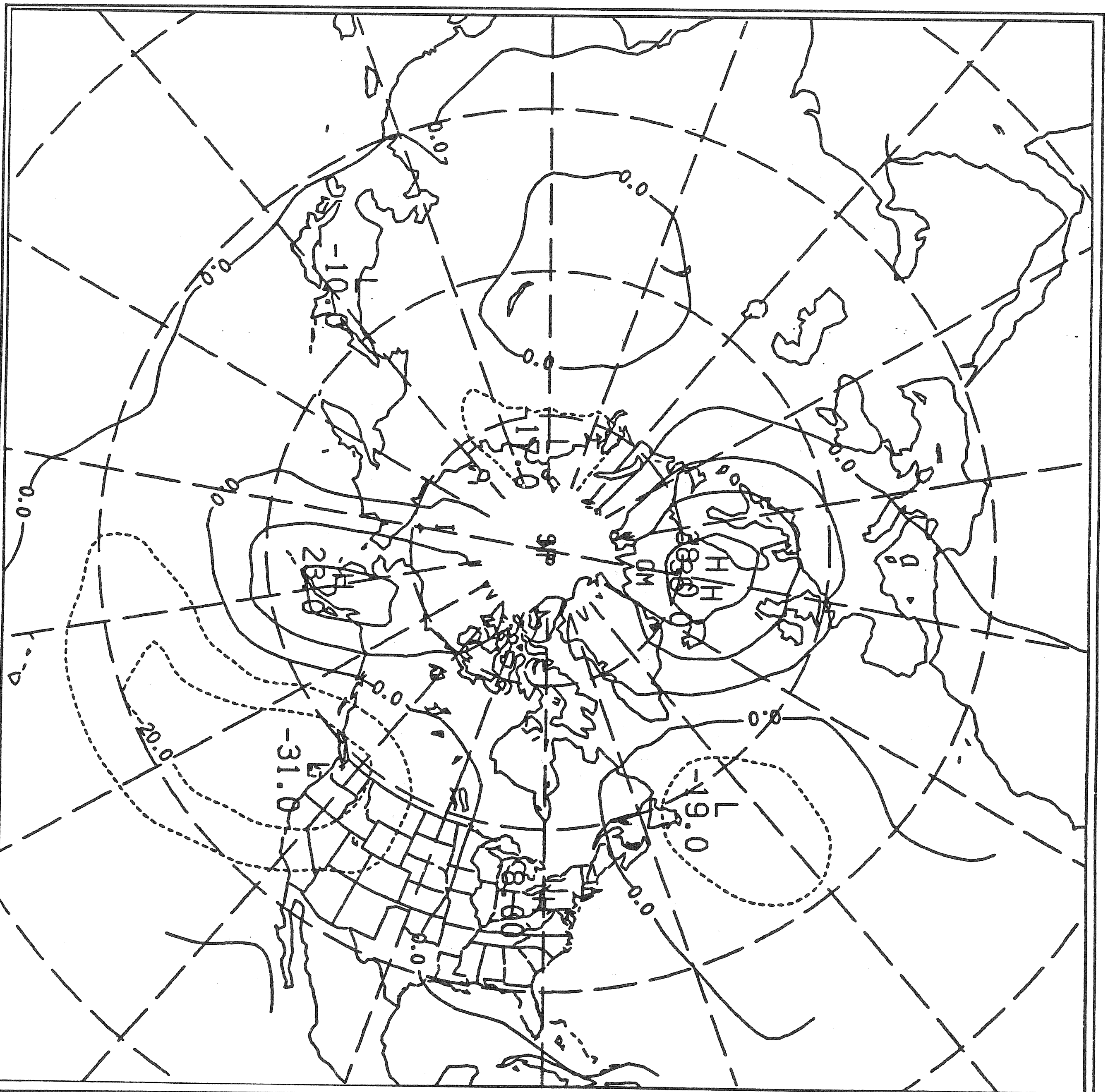

Figure 2. Mean 700-mb height anomalies (in meters) for the wet months with high precipitation ratios.

For the wet months, as expected, a mean low pressure is present in the eastern Pacific. However, the configuration of the troughs is different for months with high (Figure 2) and low (Figure 3) precipitation ratios. In the case of the high ratios, the trough assumes a west-southwest to east-northeast elongation, consistent with a zonal storm track. In contrast, the wet years with low precipitation ratios are marked by a deeper trough centered in the Gulf of Alaska. The trough line stretches southward along the west coast of North America and indicates a more southward progression of the storms. The result here is that the storm path is more oblique to the orientation of the Sierra Nevada, thus lowering its orographic influence on precipitation. All the high and low pressure systems

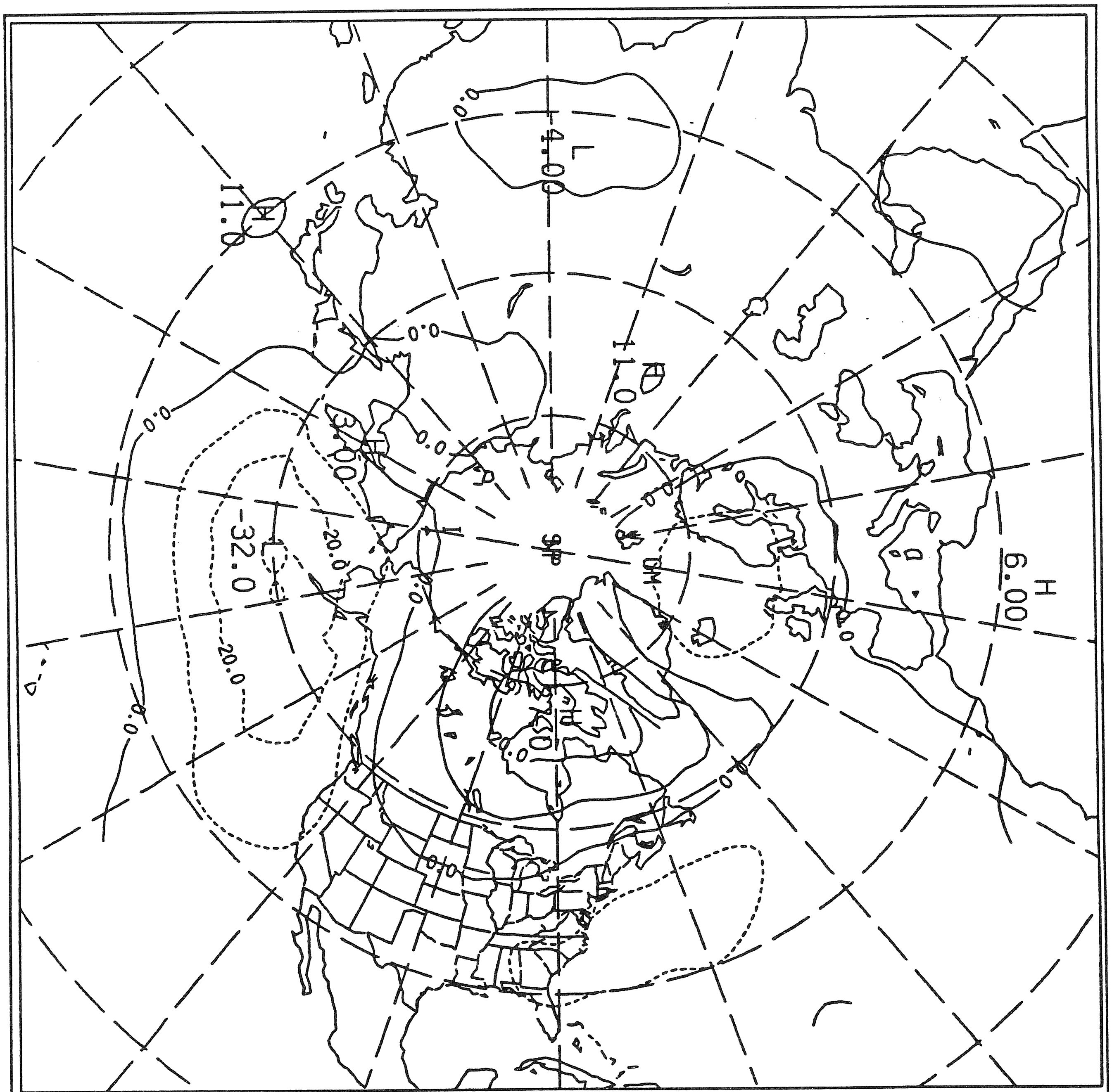

Figure 3. Mean 700-mb height anomalies (in meters) for the wet months with low precipitation ratios.

described contained observation points with anomalies that exceeded the 90 percent confidence level using a 2-tailed t-test. This in fact proved true as well for all the systems described in the following paragraphs.

The average middle tropospheric height anomalies are mapped for dry years with high and low precipitation ratios in Figures 4 and 5, respectively. While both show blocking highs in the Pacific Ocean, there is a major difference in the size and shape of these features. In the case of low-ratio months, the high pressure is more localized and occupies a position over the eastern Pacific and the west coast of North America. To

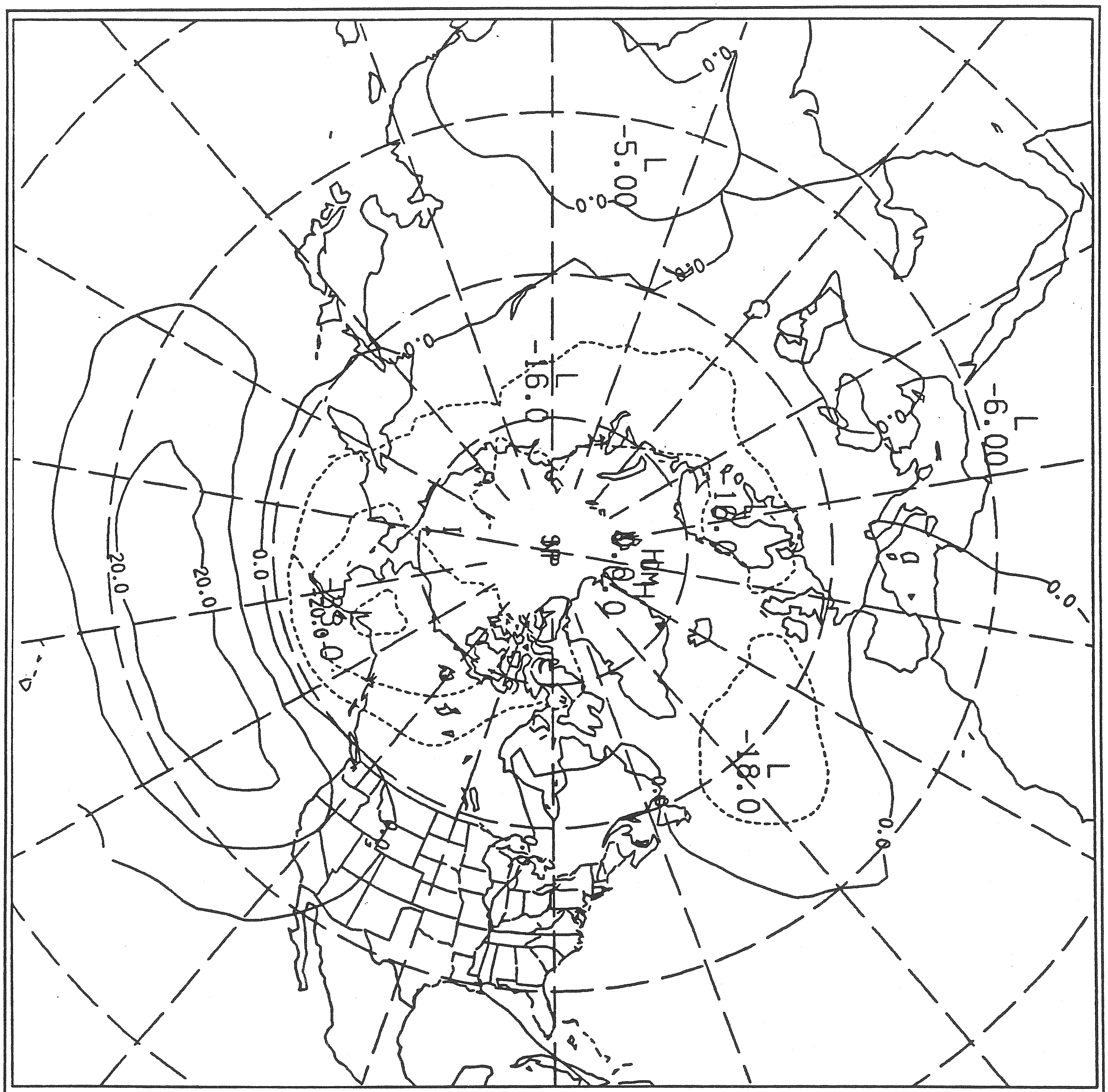

Figure 4. Mean 700-mb height anomalies (in meters) for the dry months with high precipitation ratios.

the west of the anticyclone is a large area of negative height anomalies over much of the central Pacific. This pattern suggests a mean cyclone path from west to east over much of the Pacific, with a northward deflection around the high pressure over the eastern Pacific. This pattern could allow for some storms to pass obliquely over the Sierra Nevada.

In the case of dry years with low precipitation ratios (Figure 4), a large high pressure system occurs with an west-east elongation over most of the Pacific. To the north of the anticyclone is a region of negative height anomalies from eastern Siberia to northwestern Canada. Such a pattern

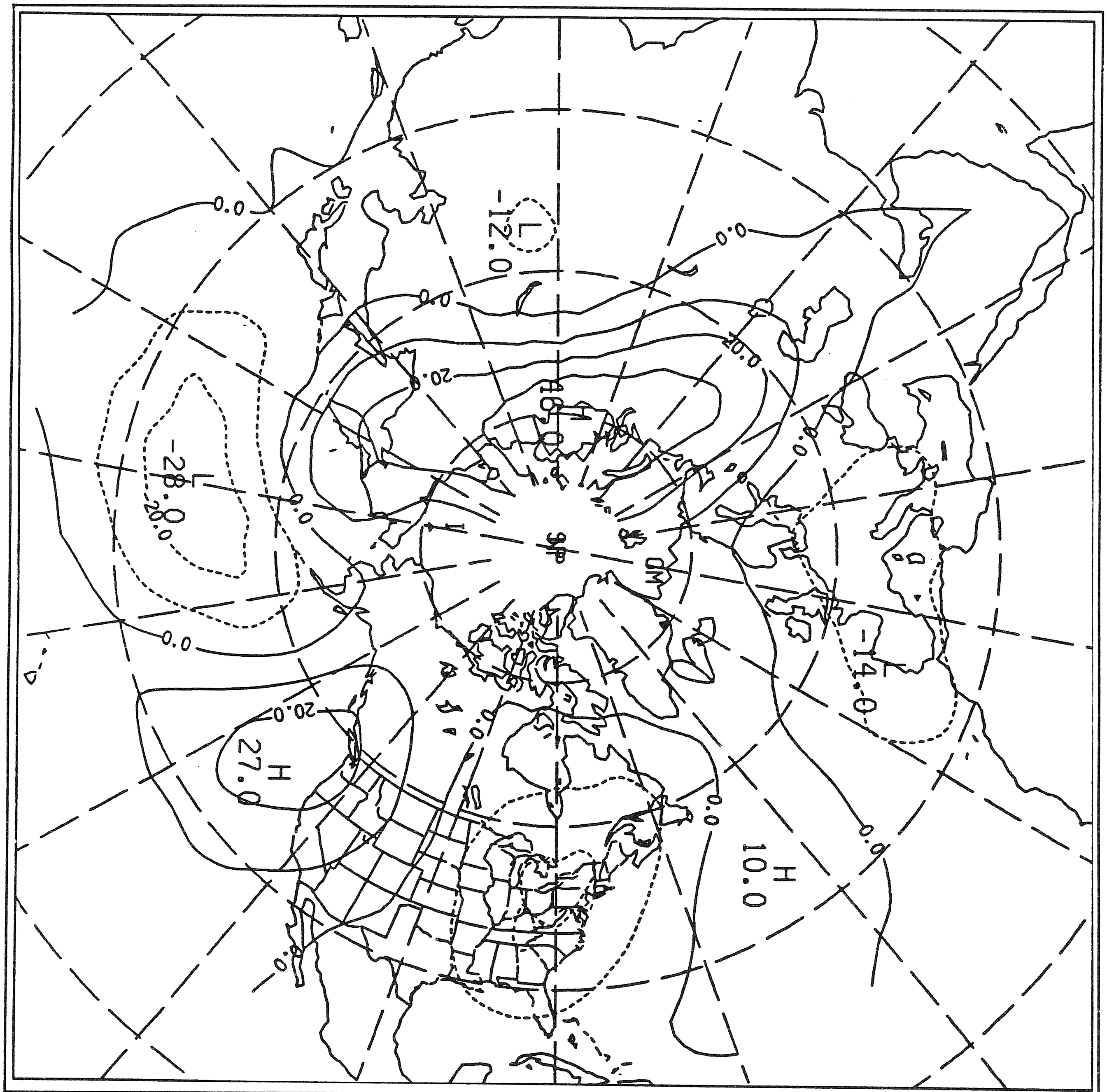

Figure 5. Mean 700-mb height anomalies (in meters) for the dry months with low precipitation ratios.

is consistent with a westerly storm track displaced northward. Under such a scenario, the Sierra Nevada could be receiving some precipitation from the tail end of cold fronts passing across the range.

In summary, Figures 2-5 indicate substantial differences in the middle tropospheric circulation with each of the four categories of precipitation and precipitation ratios. It also appears that those patterns favoring a more west-east storm track tend to enhance the ratio of high- to low-elevation precipitation.

Spatial Consistency of Orographic Effects

Figure 6 plots annual percentage change from normal of orographic effects for the American and Truckee-Tahoe basins. It is evident that for most years the mean orographic effect as a percentage of normal is similar on either side of the Sierra. Correspondence between orographic effects on the east and west slopes was further illustrated by a time-series plot (not shown) of the ordinal rankings of annual orographic effects on the American and Truckee-Tahoe basins. In most cases the ordinal ranking of orographic effect was the same or nearly so in both basins.

Figure 7 illustrates the similarity of the annual orographic effects at low and high elevations. In most cases there is a strong similarity in the percentage change from the annual ratios using datasets consisting only of the precipitation gauges (representing lower elevations) and the snow courses (high elevation). A time-series plot (not shown) simultaneously depicting ordinal rankings of the annual precipitation gauge and snow-course values further supports the spatial consistency of annual orographic effects at a wide range of elevations.

Conclusions

We have used several decades of data to determine elevational patterns of precipitation from the eastern Central Valley of California to the Sierra Nevada. We used monthly precipitation gauge data to determine "precipitation ratios" representing precipitation on the windward slopes of the Sierra Nevada relative to that in the Central Valley. Individual months were categorized as wet or dry and as having low or high precipitation ratios. Months with the four possible combinations of wetness and precipitation ratios were then associated with maps of the corresponding mean middle tropospheric circulation.

As expected, wet months were associated with the presence of mean low pressure over the eastern Pacific Ocean. However, the shape of the low pressure was different for high- and low-precipitation ratio months. High precipitation ratios tend to occur when the trough over the eastern Pacific is oriented from the west-southwest to east-northeast, suggesting movement of storms from around the Hawaiian Islands. For wet years with low ratios, the low is centered near the Aleutians and the stormtrack assumes a northwest to southeast track.

Dry months were characterized by the presence of positive height anomalies for the corresponding mean 700-mb maps. For those with high precipitation ratios, the region of positive anomalies was large and oriented with a west to east elongation. For dry years with low ratios, there tended to be a smaller region of positive anomalies over the extreme eastern Pacific with a region of negative anomalies to the west. As was the case with wet years, high precipitation ratios seemed to be favored by a more zonal pattern of mean air flow.

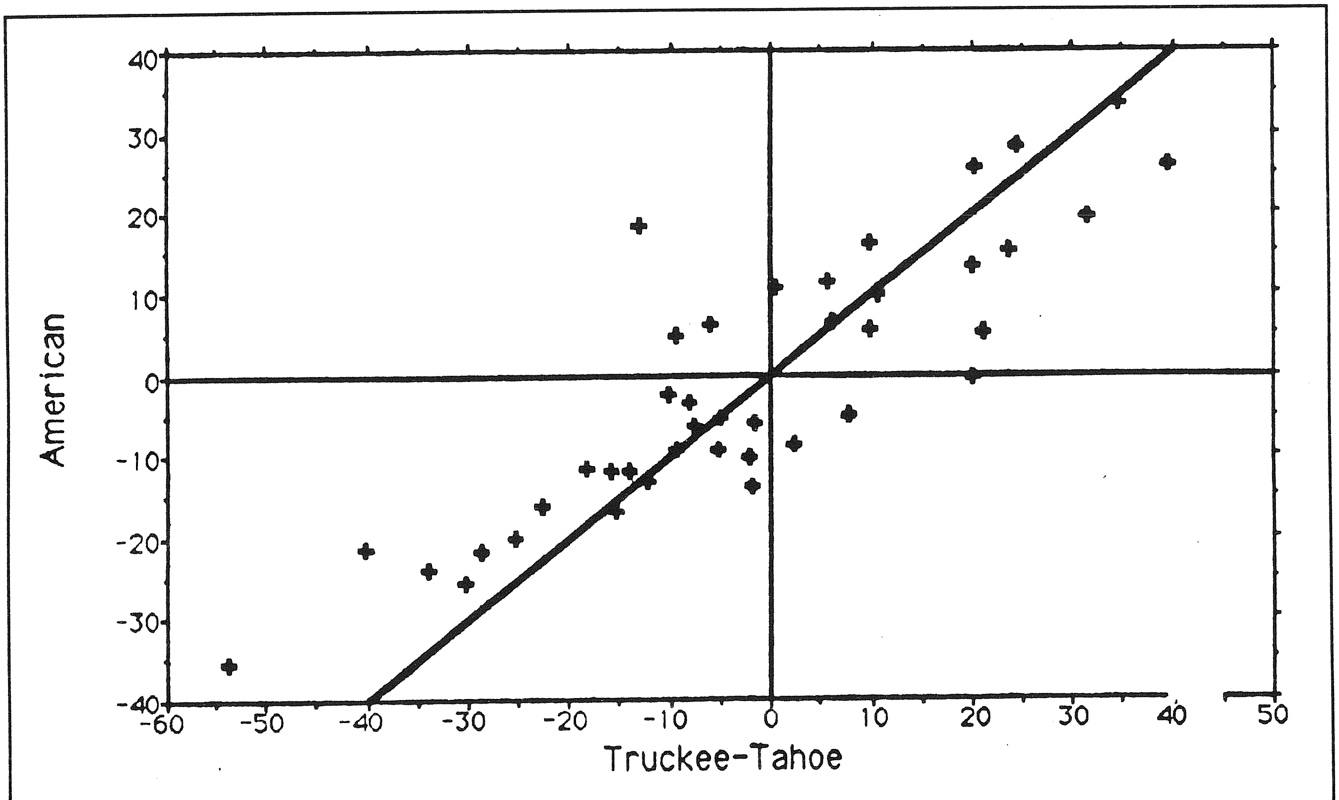

Figure 6. Comparison of east versus west annual mean orographic departures from normal (percentage change from normal ratios).

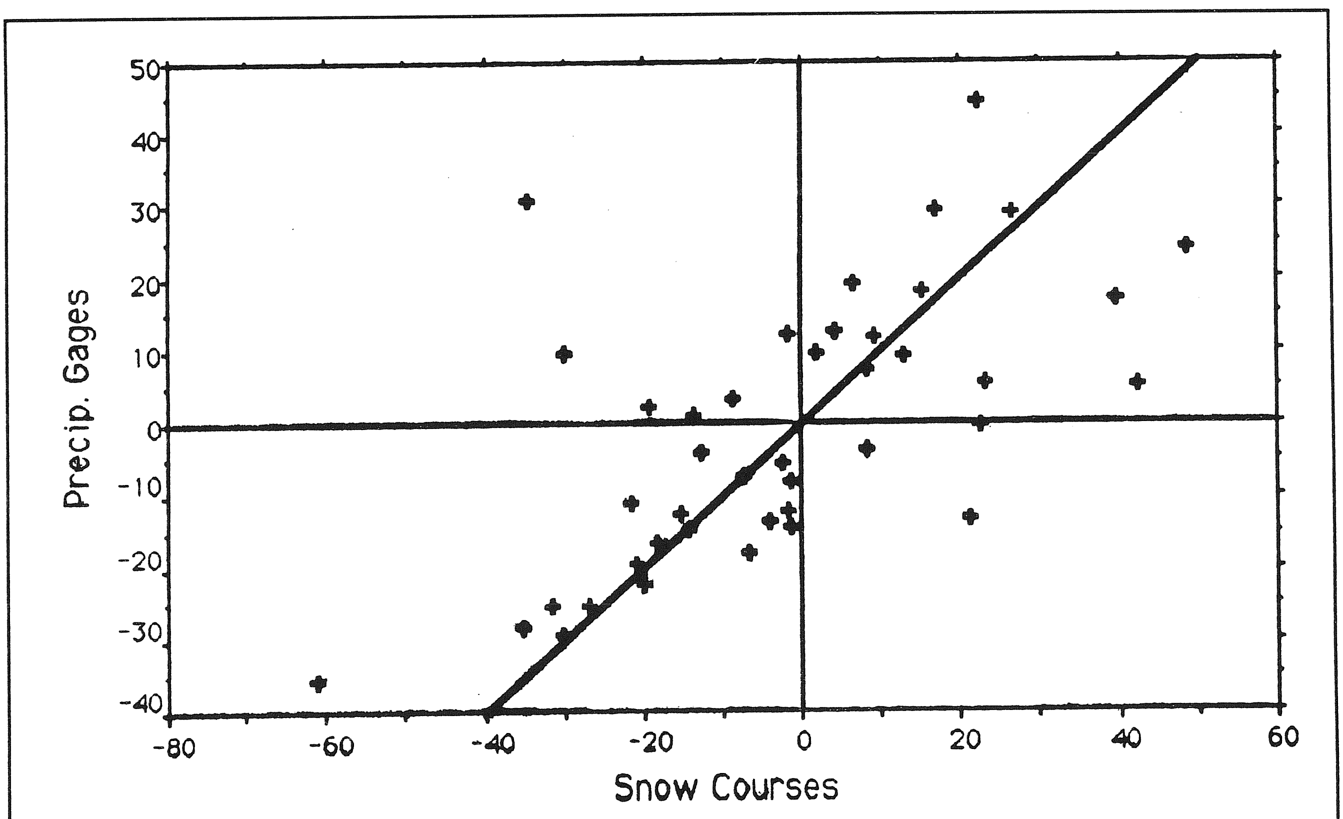

Figure 7. Comparison of precipitation versus snow course annual mean orographic departures from normal (percentage change from normal ratios).

We also examined the spatial coherency of high or low orographic effects at a seasonal level using precipitation gauge and snow-course data. It was found that basins on either side of the Sierra crest usually have greater or less than normal precipitation gains with elevation simultaneously on a seasonal basis. It was also found that the precipitation gauge data representing lower elevations and the snow-course data for higher elevations normally show similar seasonal patterns of enhanced or reduced orographic effects. We thus conclude there is considerable spatial coherency with regard to enhanced or reduced orographic effects across the Sierra.

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