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ATMOSPHERIC CIRCULATION AND PRECIPITATION IN THE SIERRA NEVADA

Dan Cayan[1] and Larry Riddle[1]

ABSTRACT: Hydrologic fluctuations in the Sierra Nevada are linked to winter-spring atmospheric circulation. Most of the precipitation in California occurs during the winter wet season (November through March) from North Pacific storms, but these storms vary considerably in frequency, intensity, and trajectory. The most important storm characteristic is the amount of precipitation, but other hydrologically important aspects are the timing during the water year, the distribution of precipitation over a watershed, the amount received as snow, and the duration of storms and dry spells. While the above characteristics are caused by local atmospheric conditions, those conditions are controlled by atmospheric circulation over the North Pacific and western North America. Circulation patterns associated with specific hydrologic characteristics exhibit definite teleconnections to remote anomalies, particularly upstream over the North Pacific. The development of the circulation patterns producing the most persistent storms and dry spells exhibits some systematic evolution several days in advance. Winters characterized by cool storms have substantially more spring snowpack and peak runoff is typically 1-2 months later than that of winters dominated by warm conditions.

KEY TERMS: Atmospheric Circulation; Precipitation; Temperature; Snow Water; Streamflow; Sierra Nevada.

INTRODUCTION

To understand the surface hydrology in the Sierra Nevada, it is important to link the watershed conditions to the atmospheric circulation. Our focus here is mainly upon precipitation, which is the primary control of the water balance. Since precipitation in California is highly seasonal, we concentrate mainly on winter wet season conditions.

Three aspects of the precipitation in the Sierra Nevada are touched upon. These are: (1) the distribution of different duration precipitation events and the evolution of circulation patterns that produce persistent wet and dry spells, (2) the elevational distribution of precipitation and its relationship to the circulation, and (3) the variation of temperature with precipitation events, the associated atmospheric circulation, and the effect on snowpack and runoff.

The approach we use to diagnose the precipitation mechanisms is inferential. In each of the following exercises, we begin with certain properties of the precipitation and go on to examine what larger scale conditions caused them or what were their effects on the hydrology. Previous studies have used this approach to determine the circulation patterns that cause wet or dry conditions in a particular region (Klein and Bloom, 1987; Weare and Hoeschele, 1983; Cayan and Peterson, 1989; Knox and Lawford, 1990). Another approach, which provides a better climatologic view of conditions in California with respect to conditions elsewhere in the Northern Hemisphere, is to identify frequently occurring circulation patterns (e.g., Barnston and Livezey, 1987). These patterns, then, can be related to local climate variations (e.g. Dettinger and Cayan, this volume) or the spatial distributions of climate variables over a broader region (e.g. Redmond and Koch, 1991).

Past studies have shown that atmospheric circulation is the key influence in driving winter season conditions (precipitation and temperature) along the West Coast, but for California, these conditions appear to have strong regional dependence. While some of the prominent Pacific circulation modes such as the Pacific-North American Pattern (PNA) have strong impacts upon climate variability over the United States (Wallace and Gutzler, 1981; Barnston and Livezey, 1987), the patterns, particularly for precipitation, are not consistent over California (Cayan and Peterson, 1989). The reason for this sensitivity is that fairly subtle shifts in the quasi-stationary long waves (e.g., 10° of longitude) are sufficient to realign the storm tracks that deliver precipitation to the Sierra Nevada. There is a similar weakness in the relation between precipitation in California and the El Niño-Southern Oscillation (ENSO) phenomenon (Ropelewski and Halpert, 1986; Cayan and Peterson, 1989; Redmond and Koch, 1991), although there is a suggestion that precipitation in California during these events is influenced by the type of El Niño (Livezey and Mo, 1987; Schonher and Nicholson, 1989). The following analyses indicate that there are an abundant variety of winter precipitation patterns, including lack of precipitation. When wet vs. dry

[1] Research Climatologists, Climate Research Division, Scripps Institution of Oceanography, La Jolla, CA 92093-0224

atmospheric circulation patterns near the West Coast taken are taken as one unit, only the regional signal is strongly discernable. But, as will be shown, the individual categories may have distinct hemispheric anomaly expressions.

DATA

This study uses daily and monthly precipitation and temperature, and monthly snow cover and streamflow from watersheds in the central Sierra Nevada region of California. Most of the analyses are drawn from the most recent four decades (1948-1988), but a few of the analyses are from longer data sets beginning in 1913.

The precipitation and temperature data used in this study are mainly from National Weather Service cooperative stations within or near these watersheds. Several of the analyses employ daily averages of 6 stations in the central Sierra Nevada region. These stations are Blue Canyon (1609 m), Calaveras Big Trees (1433 m), Lake Spaulding (1573 m), Nevada City (847 m), Salt Springs (1128 m), and Twin Lakes (2438 m). Annual mean precipitation at these stations ranges from about 120 to 180 cm/year. The 6-station average was constructed as in Aguado, et al., (1992), and had a mean annual precipitation of about 150 cm. In analyzing the elevational distribution of precipitation in the central Sierra Nevada, different station aggregates were chosen to contrast low and high elevations. The low elevation aggregate, "EV", was from 6 stations in the eastern San Joaquin-Sacramento Valley: Colusa (15m), Davis (18m), Lodi (12m), Sacramento (24 m), Stockton (6 m), and Woodland (21 m). The high elevation aggregate, "HM", was from 4 relatively high elevation stations in the central Sierra Nevada: Blue Canyon (1609 m), Bowman Dam (1637 m), Lake Spaulding (1573 m), and Strawberry Valley (1161 m). The stations were selected on the basis of length of record, location, elevation, compatibility with surrounding stations, and the absence of any apparent "step-function" changes in long-term trends. In one analysis, longer time series of monthly precipitation and temperature were needed, and we used the National Climate Data Center (NCDC) climate division averages (Karl and Knight, 1985) for the mean of the Sacramento Drainage and San Joaquin Drainage climate divisions.

Streamflow is from a middle elevation central Sierra Nevada stream, the Cosumnes River at Michigan Bar (1388 km^2, mean elevation 1121 m, USGS gage number 11335000), for the period 1907-1985. Snow water content is from a long series of once per month samples at the Donner Summit snow course (2103 m) for the period 1910-1988. In addition, we employ an array of many (over 300) long snow course records from USDA snow courses beginning as early as 1910.

THE CLIMATOLOGY OF SIERRA PRECIPITATION

Table 1 December-January-February Precipitation Frequency
Central Sierra Nevada (1948-1988)

Precipitation (mm)	*n*	Total	Percent
1 - 10:	816	2969	9.7
11 - 20:	295	4152	13.6
21 - 30:	183	4496	14.7
31 - 40:	133	4544	14.9
41 - 50:	88	3857	12.6
51 - 60:	53	2892	9.5
61 - 70:	32	2045	6.7
71 - 80:	17	1261	4.1
81 - 90:	17	1440	4.7
91 - 100:	8	760	2.5
101 - 110:	3	315	1.0
111 - 120:	5	584	1.9
121 - 130:	3	372	1.2
131 - 140:	3	396	1.3
141 - 150:	0	0	0.0
151 - 160:	2	313	1.0
161 - 170:	1	168	0.5

Total DJF days: 3701
Days with precipitation: 1659

Table 2 December-February Sierra Winter Storms 1948-1988

	Duration (Days)				
Precipitation (mm)	1-2	3-5	6-8	9-11	12+
1-10	70	31	12	8	1
11-20	8	24	15	12	15
21-30	1	12	4	6	10
31-40	1	3	1	2	4
41-50		2			
51-60		1			
Total Storms	80	73	32	29	30
Mean Daily Precip (mm)	6.3	14.7	14.4	18.1	22.2
Total Number of Days	127	276	228	282	530
Accumulated Precip (mm)	806	4067	3292	5095	11743
Percent of Total Precip	3.2	16.3	13.2	20.4	46.9

Note: A storm is defined as an *n* day period with no zero precipitation interludes longer than one day (from the 6 station central Sierra Nevada average).

Even in winter, precipitation is an unusual weather feature, as measurable precipitation (as an average of the 6 central Sierra Nevada stations) occurs on only about 45% of the days, and many of these events are light (49% were 10 mm or less). The frequency of daily precipitation during winter (December, January, and February) is presented in Table 1 in 10 mm precipitation intervals. Although heavy precipitation events are infrequent (only 22% of them were 31 mm or greater), they account for a major proportion of the winter precipitation (62% from the 31 mm and greater events). To further clarify this process, the precipitation was stratified according to the duration of a precipitation event (a "storm"). A storm is defined as a period of days in which the regional (6 stations) average precipitation is greater than zero at the beginning and end and not interrupted by more than one day of zero precipitation. The storm ends on the first day of a two or more day period in which average precipitation is zero. Table 2 gives the distribution of precipitation by storm duration in 5 categories from 1-2 days to 12 days and greater. These statistics are from all days of December, January, and February (DJF) from 1948-1988. One feature of this distribution is that the longer duration storms tend to have more precipitation (per day) than the shorter duration storms. For example, the mean daily precipitation for 1-2 day storms is about 6 mm/day, while the mean for the 12+ day storms is about 22 mm/day. Furthermore, although the longer duration storms occur fairly infrequently, because of their long duration and relatively heavy precipitation rate, they contribute a large fraction of the total winter precipitation. Storms of 9 days and longer account for about two thirds of the total winter precipitation. The statistics of "interstorm" dry periods, categorized by duration, are given in Table 3. In keeping with the above definition of storms, an interstorm is defined as a zero precipitation period of 2 days or longer. Dry days (when the 6 station average was less than 0.5 mm), including the one day dry events not included in the interstorm events in Table 3, account for about 55% of all winter days. Approximately 58% of dry spells are relatively short (2-5 days duration). On the other hand, only 77 of the 223 interstorms episodes are 9 days and longer, but they account for 37% of the dry days (including the 1-day dry events not categorized in Table 3). In summary, some of the most hydrologically important events during winter are persistently wet or dry, with durations of a week or more. The circulation regimes of these events, including their temporal evolution, are discussed below.

Table 3 December-February Sierra Winter Interstorms 1948-1988

	Duration (Days) 2	3-5	6-8	9-11	12+
Total Events	44	73	29	33	24
Total Number of Days	88	276	206	329	435
Percent of Dry Days	4.3	13.5	10.1	16.1	21.3

Note: There are 2042 dry days in the DJF 1948-1988 record. This includes the one day-duration dry days, which were not included in the interstorm events given above.

The link between temperature and precipitation is important because it determines the partition of precipitation as snow vs. rain, and it affects the timing of snowmelt. The distribution of DJF daily mean temperature on days with precipitation and on days without precipitation is shown in Figure 1. Days with precipitation (middle panel of Figure 1) tend to have lower mean temperatures. The average temperature of days with precipitation for the central Sierra Nevada aggregate is about 3° C less than that of days with no precipitation (bottom panel of Figure 1). Precipitation ("Mean Ppt" in the upper panel of Figure 1) tends to be highest on days with the highest mean temperatures; inspection shows that this is because extremely heavy precipitation tends to have high daily minimum temperatures. The non-zero and zero precipitation day mean temperature distributions are both approximately normally distributed with a spread of greater than 15° C, and have similar standard deviations (3.3° C and 3.9° C, respectively). The correlation between monthly precipitation and monthly temperature (maximum, mean, and minimum) for the 6 station aggregate is shown in Table 4. In non-winter months, the temperature relation is strongly weighted by the lower maximum and minimum temperature during precipitation, probably owing to increased cloudiness and cool air advection. In winter, precipitation is negatively correlated with maximum temperature (ρ=0.4 to 0.5), but not with minimum temperature. In fact, the correlation with minimum temperature is slightly positive due to the occurrence of high minimum temperature and heavy precipitation. This relation probably results from the effect of clouds moderating winter nighttime temperature and from warm moist Pacific air masses common to large precipitation events.

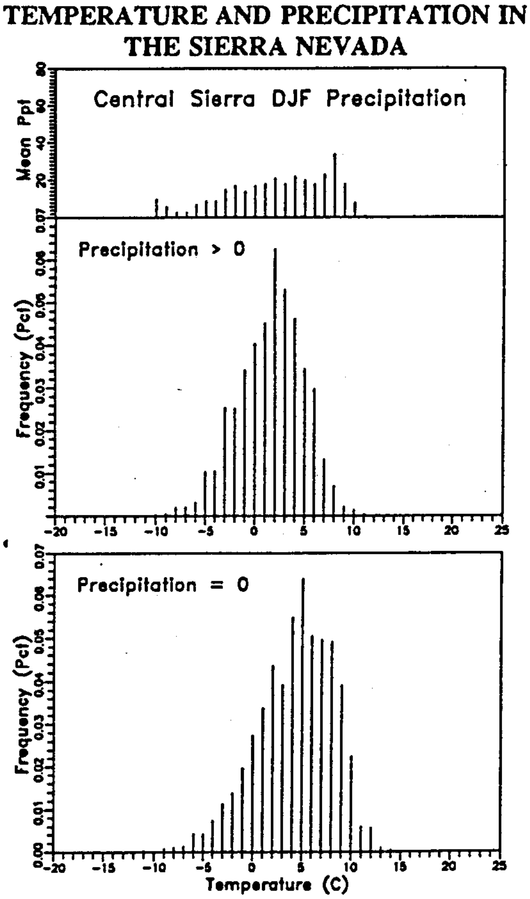

Figure 1. Above: The distribution of daily mean temperatures on winter days when the central Sierra six station average precipitation is greater than zero. Upper panel gives the average amount of precipitation according to daily mean temperature. From December, January, and February of 1948-1988. Below: As above, but daily mean temperature on days with zero precipitation.

Table 4 Correlation of Monthly Precipitation vs. Temperature (1948-88)
An average of six stations in the central Sierra Nevada

	J	F	M	A	M	J	J	A	S	O	N	D
T_{Max}	-.40	-.47	-.59	-.74	-.67	-.71	-.20	-.59	-.73	-.57	-.63	-.50
T_{Mean}	-.20	-.21	-.36	-.68	-.59	-.63	-.11	-.46	-.63	-.52	-.48	-.31
T_{Min}	.08	.17	-.10	-.52	-.39	-.47	0	-.25	-.37	-.37	-.08	.01

ATMOSPHERIC CIRCULATION AND THE DISTRIBUTION OF PRECIPITATION WITH ELEVATION

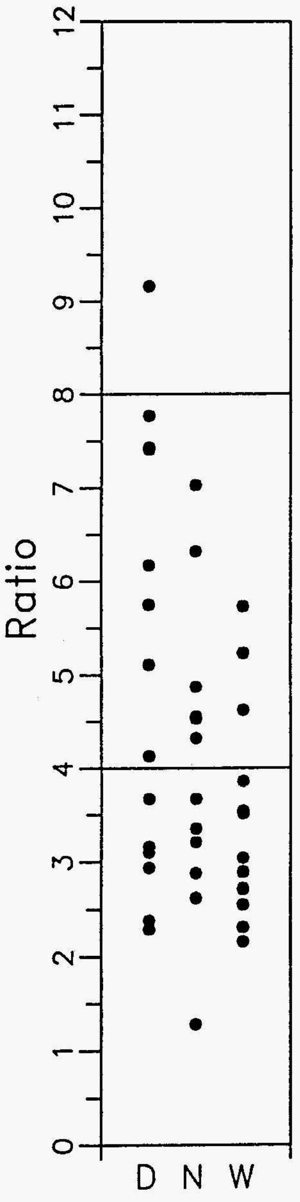

Figure 2. Ratio of January precipitation at high (HM) vs. low (EV) elevations in the central Sierra Nevada region. Ratios are shown for three tercile categories of the EV precipitation: light (D), moderate (N), and heavy (W). From 1948-1988.

Another aspect of precipitation that is related to atmospheric circulation is the distribution of precipitation with elevation. Of greatest benefit to the water supply are cases in which there is strong orographic amplification of storms. That is, when it is wet at low elevations, it is very wet in moderate to high elevations of the Sierra Nevada. To investigate this relation, we used monthly precipitation averaged over several stations from two regions, the east San Joaquin-Sacramento Valley (EV) and high elevations of the central Sierra Nevada (HM). Using the corresponding HM precipitation for a given month, we also formed the ratio of HM to EV precipitation. Using EV precipitation as an indicator of the amount of precipitation, each month's EV precipitation time series (e.g., all Januaries) was then ranked and divided into terciles (heavy, moderate, and light), with the corresponding HM/EV ratio carried along. Then, for the 14 cases within the heavy EV precipitation tercile, two subsets were formed: one with the 7 highest HM/EV ratios and one with the 7 lowest HM/EV ratios. As shown by the graph in Figure 2, these ratios can vary considerably, ranging from about 2 to 5.5 for the heavy January EV precipitation tercile and from about 2 to 9 for the light January EV precipitation tercile. The associated atmospheric circulation is shown in Figure 3 by composite monthly 700 mb height anomalies for the low and high ratios of the heavy terciles of December, January and February, all taken together. Each composite contains 21 individual cases. These patterns indicate greater westerly to west-southwesterly anomalous geostrophic winds in the high ratio cases, a condition that would produce greater orographic lifting over the north-northwest to south-southeast aspect of the Sierra Nevada range. The low ratio pattern has a strong anomalous southerly wind component, which would tend to produce heavy precipitation in all elevations, but not produce exceptional orographic enhancement because it is parallel to the range. Similar ratios and circulation patterns are typical of precipitation in different transects (both north and south) across the Sierra Nevada, and by using foothill as opposed to east valley stations in the high-to-low elevation precipitation ratio.

ATMOSPHERIC CIRCULATION ASSOCIATED WITH PERSISTENT WET AND DRY EVENTS

Previous studies have often assumed that atmospheric flow patterns responsible for heavy and light precipitation along the West Coast are mirror images (e.g. Weare and Hoeschele, 1983; Klein and Bloom, 1987). Specifically, anomalously low atmospheric pressure to the northwest of the California coast enhances westerly or southwesterly flow which makes for active storms, stronger winds, and greater moisture flow into the state, while anomalously high pressure in this region is symptomatic of a lack of storms and dry conditions. This description generally applies to most near-coastal basins along the Pacific Coast of North America, as was shown by correlations of winter sea-level pressure (SLP) with December-August streamflow anomalies (e.g., Cayan and Peterson, 1989). However, it is well known that various synoptic patterns result in precipitation (Weaver, 1962; Enzel, et al., 1989), and similarly, substantial differences between the flow patterns result in light precipitation episodes in California in winter.

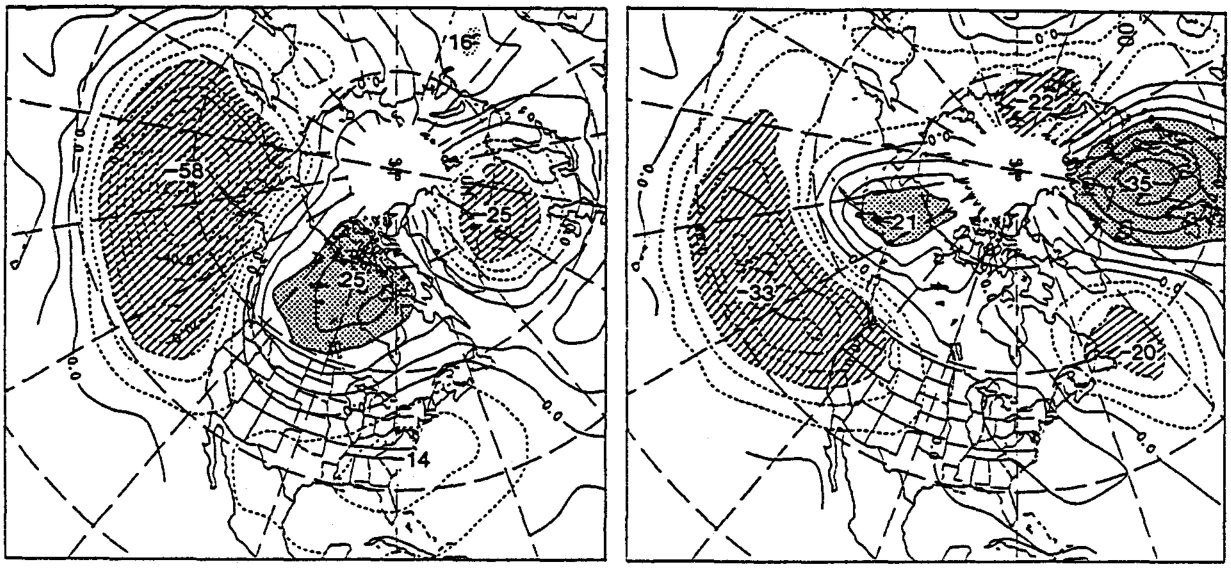

Figure 3. Composite 700 mb heights (meters) for winter months (DJF) with heavy low elevation (EV) precipitation and small high to low elevation (HM/EV) precipitation ratios (left), and months with large HM/EV ratios (right). Each composite is an average of 21 months, from 1948-1988.

To begin, we categorize the winter precipitation events into "warm" and "cool" groups, on the basis of regional temperature anomalies. There are two major reasons for considering the temperature in association with the precipitation. The first is that the anomalous temperature may provide a means for better identifying distinct precipitation-bearing atmospheric circulation types. The second is that the temperature has an effect on surface hydrology; when storms are cool they deposit more precipitation as snow than when they are warm.

Atmospheric circulation patterns for the most persistent wet and dry precipitation events are shown in Figure 4. These maps are composites of the 700 mb height anomalies for two subsets of the 10-day and longer storms and interstorms that were summarized in Tables 2 and 3. The two subsets were constructed on the basis of the average daily mean temperature for each event, where the warm wet cases have temperatures above the median of all 10+ day storms, and the cool wet cases have temperatures below the median. Similarly, the warm dry cases have temperatures above the median of all 10+ day interstorms, and the cool dry cases have temperatures below the median. The composites are averages of the daily anomalies (calculated from a 41 year long term daily mean) for 22 cases. A few of the 10+ day cases included in Tables 2 and 3 are not included in the composites because the 700 mb daily data set ends in mid-1987.

To examine the evolution of this pattern, maps are shown for day -7, day -4, and day +3. Days are referenced to day 0, which is the beginning day of the storm or interstorm sequence.

During the persistent storms and interstorms (day +3) there are, of course, tremendous differences between the wet and dry composites, but also marked differences between the warm and cool composites (see also: Dettinger and Cayan, this volume). As anticipated from previous work specifying precipitation and runoff from the atmospheric circulation (Klein and Bloom, 1987; Cayan and Peterson, 1989), both wet categories are associated with negative 700 mb height anomalies (lower than normal pressure) in the eastern North Pacific. However, for the warm wet case, there is an extensive negative anomaly in low mid-latitudes. This feature extends westward beyond the International Date Line, and is located to the south of a strong positive height anomaly (high pressure) at higher latitudes extending from Kamchatka through Alaska. This pattern represents a southerly displaced storm track, and the position of the positive anomaly indicates that the coldest air is confined to the north of California. Of the four weather types, the warm wet pattern has the largest wavelength and the largest anomaly center in the North Pacific sector. For the cool wet case, the negative anomaly in the eastern North Pacific has a center that is farther north and more regionally confined than its warm wet counterpart. Also, the cool wet pattern has a positive anomaly center to the west, just south of the Aleutian Islands. This latter center is prevalent in cool storm cases of all durations that we have examined, and is responsible for injecting cold air into the eastern North Pacific. It is interesting that the cool wet pattern is nearly the negative of the stronger warm dry composite located just below the cool wet series in Figure 4. The scale of the anomalies in the cool wet pattern and its three counterparts is much larger than the Sierra Nevada or even California. These anomalies are associated with spatially coherent surface temperature, precipitation, and snowpack patterns over much of the western United States. Downstream anomalies of opposite sign produce out-of-phase teleconnections in these surface features over the eastern half of the United States.

Both warm dry and cool dry cases contain similar anomaly centers (positive 700 mb heights) over the eastern North Pacific-West Coast sector as shown in the day +3 composite maps. This feature is symptomatic of dry conditions; the circulation deflects storms from the West Coast during these events. However, the major difference between the warm dry

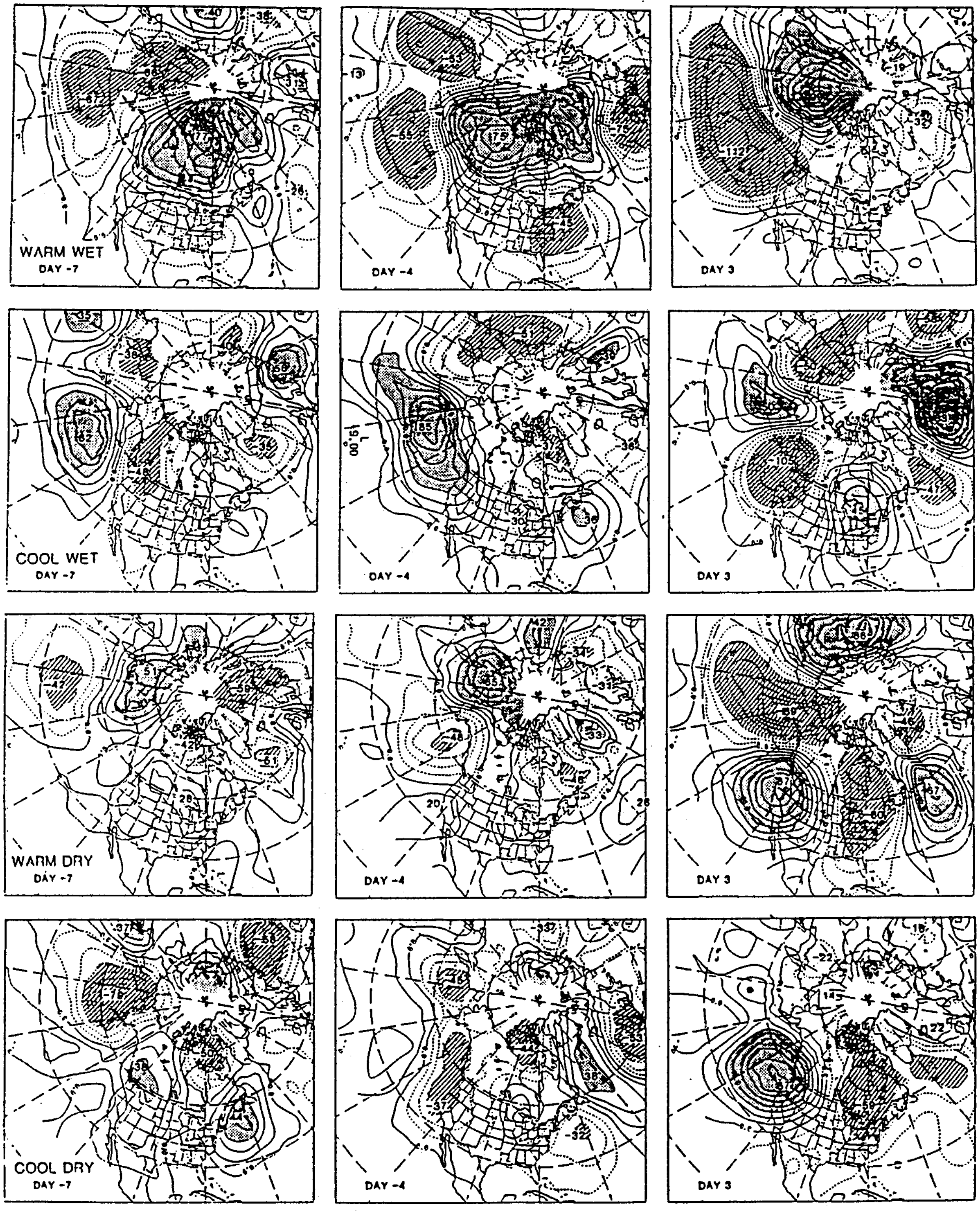

Figure 4. 700 mb height anomalies (meters) for highly persistent (10 days and longer) storms and interstorms in the central Sierra Nevada. Broken into warm and cool categories by dividing at the median daily mean temperature of the (a) storm and (b) interstorm events. Day -7 (left), day -4 (center), and day +3 (right) refer to the beginning day of an event, which would be day 0. Data 1948-1988.

and cool dry patterns is that the warm dry map has a chain of alternating sign anomalies from Asia through the Atlantic sector. In particular, this high amplitude pattern contains a large negative anomaly centered over the Aleutian Islands, while the cool dry map does not. Also, the cool dry negative anomaly center is stationed farther west, offshore from the West Coast, than its warm dry counterpart. The attendant circulation for the cool dry case has strong anomalous northerly winds over California, which would advect cold winter continental air into the Sierra Nevada. In contrast, the position of the positive anomaly center in the warm dry case produces a more stagnant circulation in central California, and would favor warming due to subsidence. Such a case was the warm dry conditions of the great drought of Winter 1976-1977 (Namias, 1978).

Some insight into the evolution of these cases is provided by the day -7 and day -4 composite maps in Figure 4. There appears to be a systematic organization in the precursors to the persistent wet cases, especially for the warm wet case. The warm pattern develops as a negative anomaly (storm track) approaches the West Coast across North Pacific mid-latitudes, while the cool wet pattern evolves "in place" in the eastern North Pacific, following the development of the strong positive anomaly to the west. The incipient warm wet patterns have an Arctic high pressure (positive anomaly) over high latitudes of North America, and lows (negative anomalies) in Kamchatka and to the south of the western Aleutians. The warm wet pattern takes hold in the Sierra Nevada as the Arctic high apparently migrates west and the low progresses towards North America. The circulation pattern preceding the cool wet case is quite different. Here, the early stages of the circulation exhibit a positive anomaly center in the Gulf of Alaska with negative anomalies to its west, north, and east. By day +3, the circulation exhibits a train of 6 alternating-sign anomaly centers that circumscribe the Northern Hemisphere. The remnant of the incipient positive anomaly center is now positioned south of the Aleutians. The precursory patterns to the persistent dry episodes have some upstream features that appear significant, but they are neither as spatially extensive nor as stationary as those for the wet cases. Day -7 and day -4 composite anomalies over the Sierra Nevada are nearly zero, indicating that persistent dry periods may be preceded by wet or dry, cool or warm circulations.

PRECIPITATION, TEMPERATURE, SNOWPACK, AND STREAMFLOW

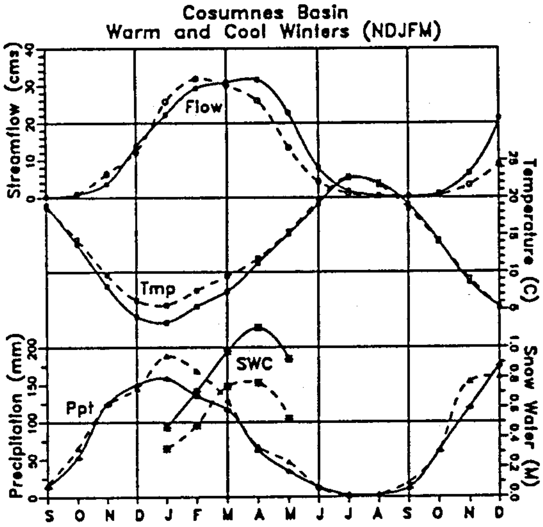

Figure 5. Composite monthly Cosumnes River streamflow, divisional temperature and precipitation, and Donner Summit snow water content for years with warm (dashed) and cool (solid) winter months. Temperature is from NDJFM average temperature for the mean of NCDC Sacramento and San Joaquin Drainage divisions.

The response of streamflow to the warm and cool November-March (NDJFM) conditions is illustrated by composite hydrographs for 25 warm and cool winters in the Sierra Nevada. To focus exclusively upon temperature, these groups are *not* further divided according to wet and dry categories. Composites are shown in Figure 5 for the intermediate elevation Cosumnes River basin (average basin elevation 1121 meters), where the runoff timing is quite sensitive to temperature anomalies.

The Cosumnes River exhibits an unmistakable delay of about two months in cool NDJFM water years relative to the warm NDJFM water years. This temperature effect is most apparent in late winter-early spring (Riddle, et al, 1990; Aguado, et al, 1992; Cayan, et al, 1992; Cayan and Peterson, 1992; Riddle, et al, 1992, this volume). The effect of temperature and the timing of precipitation is exhibited when the monthly temperature and precipitation is composited according to the fraction of annual streamflow during spring-early summer at Cosumnes River (Figure 5). Years with a relatively late peak in streamflow typically have above normal winter and spring precipitation and cool winter and spring temperatures, but a low fraction of spring-early summer streamflow is produced by heavy early winter and light spring precipitation and warm winter and spring temperatures. This effect varies with elevation. Lower basins are more immediately affected by winter climate anomalies and have relatively little sensitivity to spring temperature in comparison to middle and high elevation basins (Riddle, et al, 1990; Cayan, et al, 1992). The involvement of lighter (warm NDJFMs) and heavier (cooler NDJFMs) snowpack in producing these streamflow anomalies is shown by the Donner Summit snow water composite which has about 150% more snow water content in cool April 1st vs. warm April 1st.

The effects of these winter weather types is regional (not local) in scale (Cayan, 1991). For example, May 1st snow depth anomalies (U.S. Soil Conversation Services snow courses over the western United States) were composited for years of the four winter precipitation and temperature categories (warm wet, etc.). These categories were divided according to conditions in California, based on the NCDC Sacramento Drainage and San Joaquin Drainage climate division averages described above. Although the years in each are based on local conditions in the Sierra Nevada, May 1st snow water content exhibits significant anomalies over most of the western United States (Figure 6). Furthermore, since we have chosen May 1st snow, this analysis indicates how affects of these conditions persist beyond the winter. This is particularly important because the spring snowpack is a substantial portion of the spring and early summer water supply. The warm wet case and

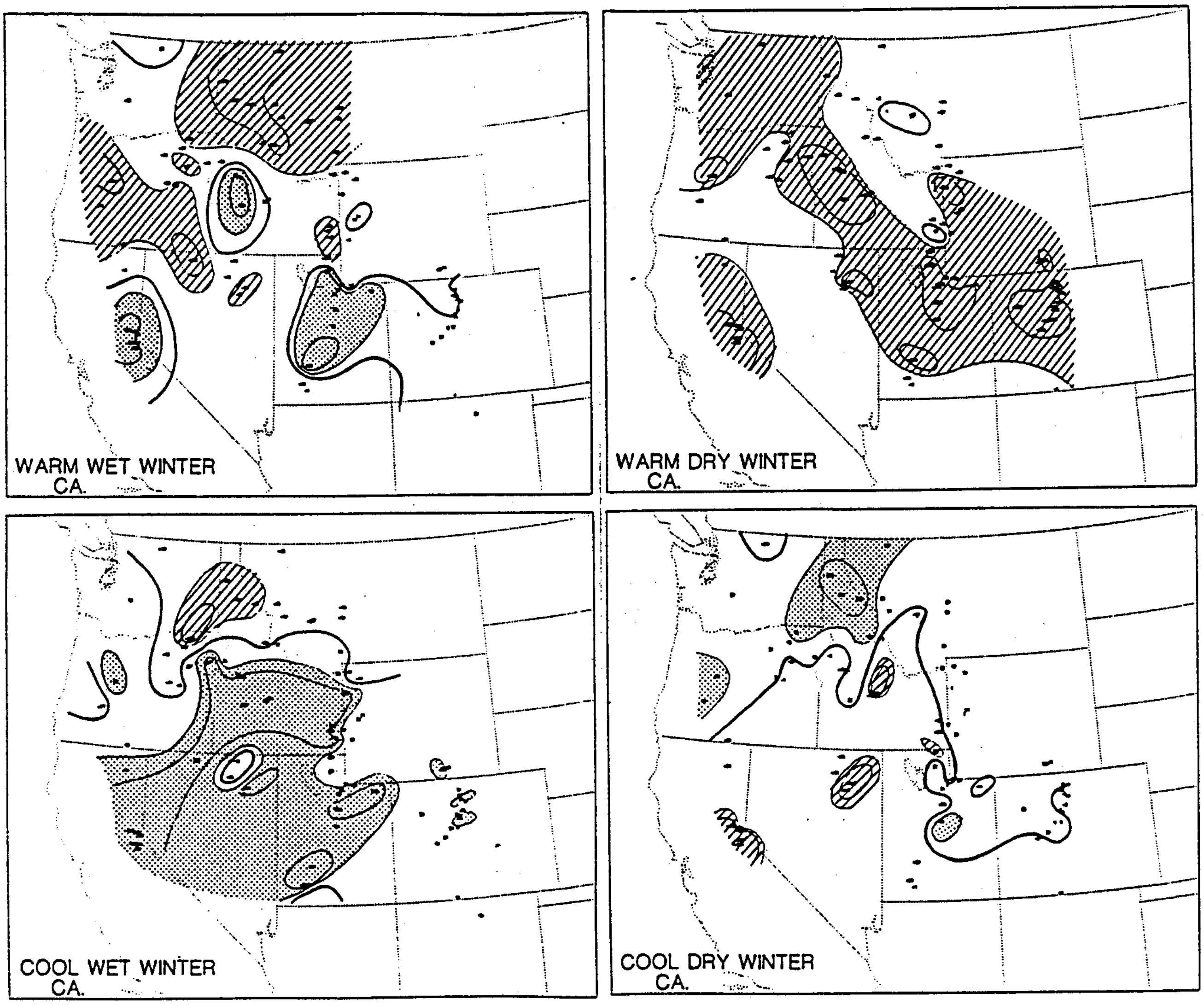

Figure 6. Composite May 1st snow water content anomalies from the USDA snow course network. These composites are based upon the DJF Sacramento and San Joaquin Drainage climate division average precipitation and temperature (Karl and Knight, 1985). Contours are at 10 inch intervals. Regions with greater than 5 inch anomalies or less than -5 inch anomalies are denoted by stippling and hatching, respectively.

the cool dry case exhibit a tendency for snow water content to be out of phase between the northwestern and the southwestern United States. Large scale persistence of the snowpack excess and deficit is strongest in the cool wet and especially in the warm dry cases.

CONCLUSIONS

To appreciate the variability of precipitation (rain and snow) and runoff from the Sierra Nevada, it is helpful to consider the linkage to the atmospheric circulation. Precipitation is produced by local physical processes, but these local processes are initiated by larger scale patterns that extend upstream into the North Pacific. Some pertinent aspects of the hydroclimatology-circulation linkage were described here.

Heavy precipitation, although infrequent, accounts for a large fraction of total winter precipitation in the Sierra Nevada of California. In addition, "long" storm regimes tend to produce higher daily precipitation rates than do "short" storms. While they are relatively infrequent, the long storms account for a major fraction of total seasonal precipitation. Similarly, long, dry "interstorm" spells contribute a significant fraction (number) of the total dry days.

The effect of temperature fluctuations on the timing of runoff is an important aspect of the natural hydrological variability and also lends insight into possible future climate changes. Significant temperature variability is evident in synoptic and seasonal scales, in both wet and dry spells. The different precipitation/temperature regimes are driven by atmospheric circulation, which are characterized by markedly different anomalies between these weather types. Resulting from this weather variability is a substantial difference in the hydrology. At typical snow courses, April 1st snow water content following cool winters is 120-150% of April 1st snow water content following warm winters, and peak streamflow in warm winter years is two months earlier than in cool winter years.

There is a substantial spread in the distribution of precipitation with elevation. Using as an index the ratio of precipitation accumulated in modest-to-high elevations of the Sierra Nevada to precipitation in the eastern San Joaquin-Sacramento Valley, precipitation ratios of about one to more than twelve have occurred. In part, these differences result from the direction of flow across the Sierra Nevada, which is associated with distinct large scale anomalies in the atmospheric circulation.

Local watershed variability is partly controlled by the large scale structure of the atmospheric circulation. Dry-vs.-wet patterns, temperature characteristics, and the distribution of precipitation with elevation are all associated with a definite atmospheric circulation signature. The Sierra Nevada surface weather characteristics are strongly affected by the regional circulation in the eastern North Pacific-western North America. For example, the greatest orographic precipitation enhancement arises during months with circulation patterns containing west-southwesterly winds. Strong southerly winds still produce wet patterns, but the orographic enhancement is less. In many cases, the circulation patterns also contain important teleconnections. Cold storms in the Sierra Nevada tend to occur when there is a high pressure anomaly south of the Aleutians injecting cold air into the eastern North Pacific. The most persistent storms, though infrequent, contribute a substantial amount of the winter precipitation. Distinct anomaly centers tend to develop upstream several days in advance of a wet episode. The pattern of this upstream development differs substantially in warm storms as opposed to cool storms.

The observed hydroclimatology in the Sierra Nevada has important implications for modeling efforts. First of all, realistic atmospheric model simulations have a challenging set of attributes that are essential to the realistic functioning of the surface hydrology. These include a rich spectrum of precipitation (amount, frequency and duration), its spatial and elevational dependence, and the associated temperature. The key in replicating this precipitation is to realistically simulate the atmospheric circulation, which has both regional and hemispheric anomaly signatures, depending on the particular surface feature. Of particular importance to the California water supply is that approximately two-thirds of the winter precipitation in the Sierra Nevada is received in the relatively infrequent long storm regimes.

Concerning global change issues, the observations suggest that increased temperatures, even by 1-2° C, will significantly shift peak runoff earlier in the spring and diminish the spring snowpack. Variations have occurred naturally via fluctuation in the regional/hemispheric circulation flow. However, it is not clear if the circulation-induced fluctuations in temperature constitute natural analogs to Greenhouse warming, in that the future changes in temperature may or may not be accompanied by significant precipitation changes. Furthermore, climate changes in storm persistence (and/or their causal patterns), the precipitation distribution with elevation, and the mix of warm vs. cool storms could have effects as significant as "simple" temperature changes.

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