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AN ORGANIZED SIGNAL IN SNOWMELT RUNOFF OVER THE WESTERN UNITED STATES[1]

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ABSTRACT Daily-to-weekly discharge during the snowmelt season is highly correlated among river basins in the upper elevations of the central and southern Sierra Nevada (Carson, Walker, Tuolumne, Merced, San Joaquin, Kings, and Kern Rivers). In many cases, the upper Sierra Nevada watershed operates in a single mode (with varying catchment amplitudes). In some years, with appropriate lags, this mode extends to distant mountains. A reason for this coherence is the broad scale nature of synoptic features in atmospheric circulation, which provide anomalous insolation and temperature forcings that span a large region, sometimes the entire western U.S. These correlations may fall off dramatically, however, in dry years when the snowpack is spatially patchy.
(KEY TERMS: hydroclimatology; surface water hydrology; water management; snow hydrology.)

INTRODUCTION

Climate, the major source of variability in our nation's water resources, poses major challenges for water-resource and ecosystem management programs. In the western United States, a realistic assessment of water availability must accommodate linkages between climate, water, and energy along river corridors extending from mountain ranges to the coastal ocean. No segment within each corridor is independent of the others. That is, impacts and responses to climate variability and change in one segment cannot be assessed separately from others. Further, in the west, nearly half or more of the fresh water discharge is snowmelt (Serreze *et al.,* 1999). The snowmelt/discharge process is complex (Hartman *et al.,* 1999) and needs to be studied at all scales.

In general, large-scale regional studies of climate-river basin connections have focused mostly on monthly to interannual to decadal time scales (Cayan, 1996), while atmospheric/hydrologic processes at shorter time scales are generally studied at the catchment scale (c.f., Hardy *et al.,* 1998). The problem of connecting atmospheric conditions to river discharge on a regional scale is simplified by focusing on a major mode of variability. In this study we investigate variations in air temperature as a large-scale control on runoff fluctuations during the critical spring snowmelt season. Solar insolation, the important driving variable behind snowmelt discharge (Leavesley *et al.,* 1983), and which covaries with air temperature, is not considered because radiometer records are not sufficient to form a high elevation network.

In this paper we describe an observationally based study that examines a simplified snowmelt/discharge cycle, highly correlated daily-weekly fluctuations in snowmelt discharge among river basins in the upper Sierra Nevada and their strong correlation with air temperature, and the possible extension of such correlations to distant mountains. We conclude with a discussion of the implications of our study that are relevant to the management of water resources. Our study area includes ten stream-flow gaging stations (Figure 1) with primary focus on the Merced River at Happy Isles, Yosemite National Park, California.

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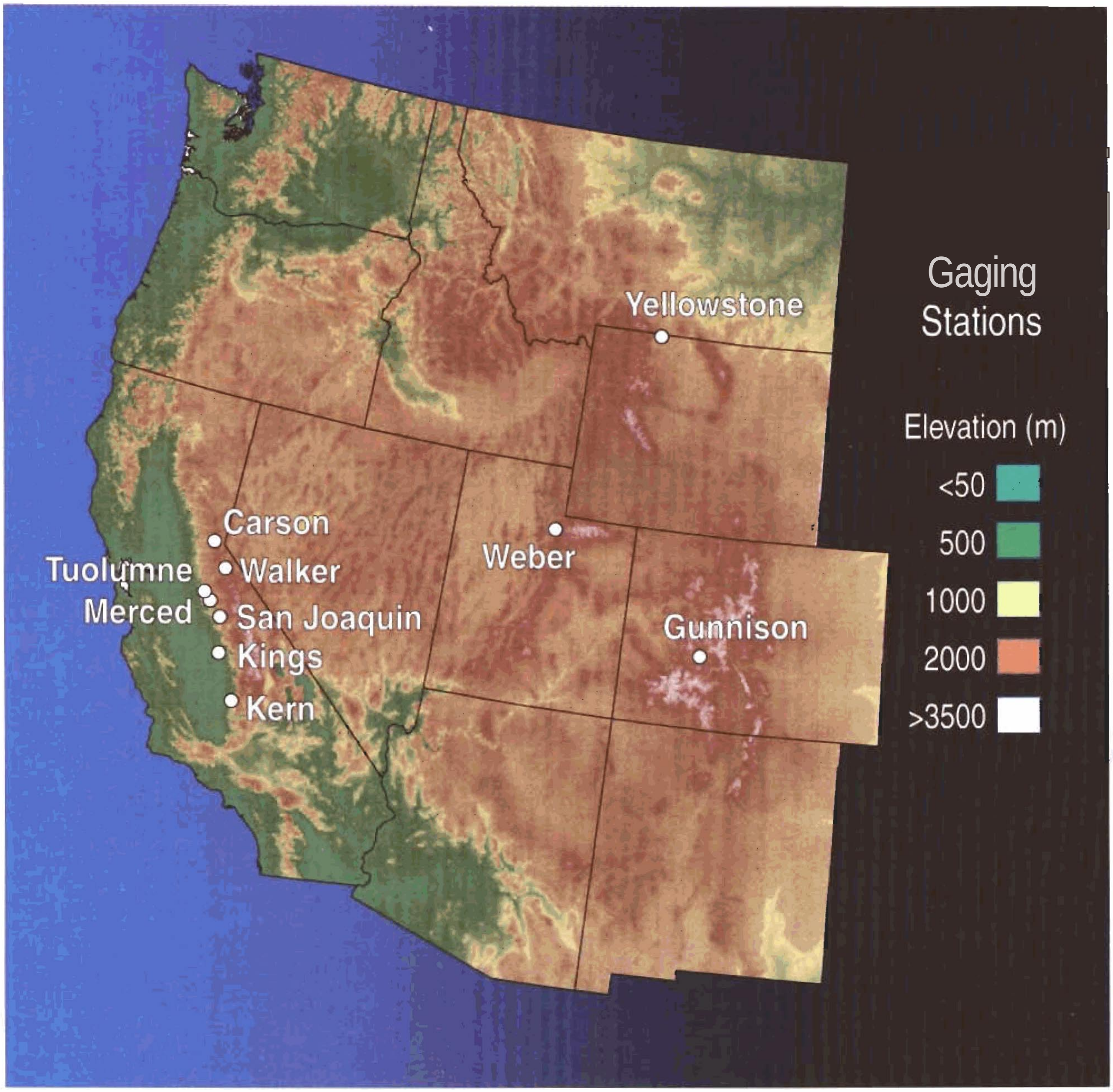

Figure 1. Snowmelt Caging Stations.

DATA AND METHODS

To carry out this study we used air temperature observations from the National Climate Data Center cooperative station data, and stream discharge measurements from climatologically suited gages (Slack and Landwehr, 1992) from the hydroclimate discharge network (HCDN) of the U.S. Geological Survey (Tables 1 and 2). Seasonal temperature and discharge cycles of four distant watersheds are in Figure 2. Seasonal cycles were estimated from daily discharge observations (for the period of record), using a 15-day boxcar filter applied twicc (forward and backward to preserve phase). To be consistent, the 15-day filter was used for both discharge and temperature, although our results show that a longer filter (i.e., 25-day) would be more appropriate for temperature.

A Hypothetical Spring Snowmelt Cycle

For purposes of this analysis of the linkages between air temperature and snnwmelt discharge, the seasonal snowmelt cycle is simplified into four phases

TABLE 1. Snow Melt Discharge Stations.

Station Name	Number	Longitude DD	Latitude DD	Elevation (m)	Area (km^2)	Mean Flow (cms)	Distance (km)
MERCED R AT HAPPY IS	11264500	119.5578	37.7317	1224	469	10.05	0
SAN JOAQUIN R AT MIL	11226500	119.1964	37.5105	1393	645	16.62	40
NF KINGS R BL DINKEY	11218400	119.1278	36.8797	315	1002	9.06	104
KERN R NR KERNVILLE	11186000	118.4767	35.9453	1103	2191	12.63	224
TUOLUMNE R NR HETCH	11276500	119.7972	37.9375	1045	1046	25.26	24
W WALKER R BL L WALK	10296000	119.4492	38.3797	2009	469	7.48	73
W F CARSON R AT WOOD	10310000	119.8319	38.7694	1754	169	8.21	119
WEBER RIVER NEAR OAK	10128500	111.2458	40.7361	2024	420	6.23	786
GUNNISON RIVER NEAR	09114500	106.9514	38.5411	2333	2621	21.75	1097
CLARKS FORK YELLOWST	06207500	109.0667	45.0111	1215	2989	26.65	1190

*Between gages from the Merced.

TABLE 2. Air Temperature Stations.

Name	Station	Elevation
1. Yellowstone*	LAKE YELLOWSTONE	2367
	WEST YELLOWSTONE USFS	2030
	YELLOWSTONE NATL PARK	N/A
	HEBGEN DAM	1978
	ISLAND PARK	1917
	TOWER FALLS	1910
2. Salt Lake City**	SALT LAKE CITY	1286
3. Gunnison*	CORTEZ	1893
	DURANGO	2095
	GRAND JUNCATIO	1476
	GUNNISON	1764
	MONTROSE	1764
	OURAY	2390
4. Merced*	SACRAMENTO WSO CITY	8
	HETCH HETCHY	1179
	NEVADA CITY	869
	TAHOE CITY	1899

*The temperature weighting scheme is in Cayan and Webb, 1992.
**For the Weber River watershed.

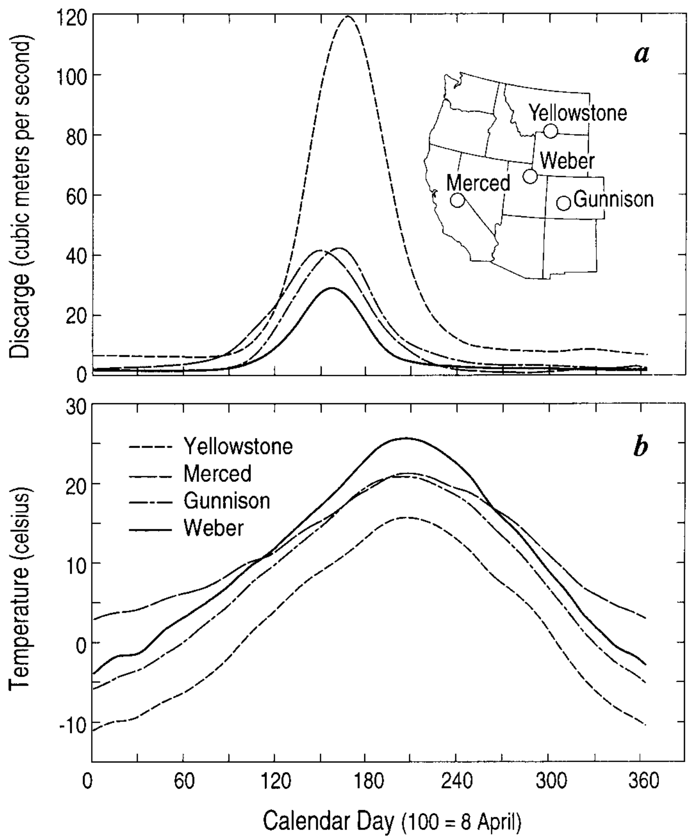

Figure 2. Upper Panel, Seasonal Climatology of Discharge. Peak value day, Merced 149; Weber 157; Gunnison 162, and Yellowstone 168. Lower panel, climatology of air temperature, all values peak after day 200. Low-pass mean daily observations using a 15-day boxcar filter (applied twice, forward and backward, to preserve phase).

(Figure 3). In the first phase discharge shows little response to changes in temperature because the snowpack is too cold. The second phase (spring rise, Cayan *et al.,* 1999) occurs after the snowpack has accumulated sufficient heat (i.e., when snowpack is locally at or near zero degrees centigrade with depth). At this point the snowpack is ready to respond more strongly to an increase in temperature that, in turn, initiates the spring snowmelt pulse and the increase in the discharge. In the third phase, the system is near temperature saturation (i.e., when snowpack temperatures at or near zero degrees centigrade are widespread, and the discharge response to temperature is nearly linear). In this condition, the snowpack is warm enough throughout the basin to melt, and solar insolation becomes the limiting factor. In the fourth phase, air temperature continues to rise, discharge declines, and air temperature is replaced by snowpack size as the major controlling factor.

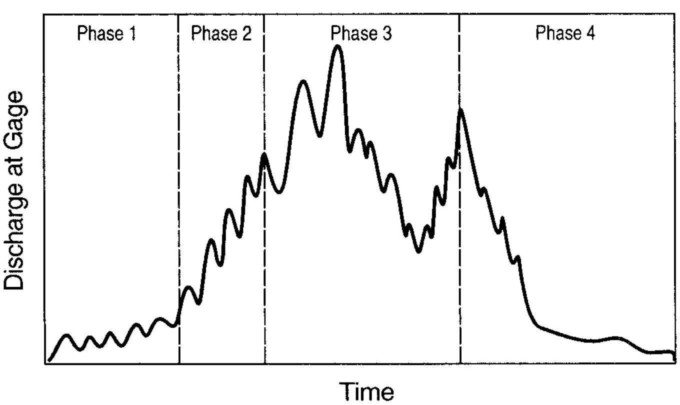

Figure 3. Schematic of the Life Cycle of Spring Snowmelt Discharge. Air temperature is the controlling variable in Phase 2 and 3 and size of the snowpack is the controlling variable in Phase 4.

Considering only the first three phases of the cycle, the discharge response to air temperature is at first small (1st phase), then increases (2nd phase), and finally is nearly constant (3rd phase). To illustrate this, we use a linear statistical model with constant parameters. For response parameter estimation (air temperature as input, discharge as output) we used the instrumental variable method (Ljung, 1988, 1989) that gives the average of response coefficients over the length of record. For example:

$$q(t) = b_1T(t) + b_2T(t_{-1}) + b_3T(t_{-2}) + b_4T(t_{-3}) \qquad (1)$$

where $T(t)$, $T(t_{-1})$, $T(t_{-2})$, $T(t_{-3})$ are today's and the past three days average air temperature (degrees centigrade); q is today's average discharge, and b_1, etc., are each day's constant response coefficient. If discharge lags air temperature by one day then b_1, equals zero. In general, b_2 is greater than b_1, indicating the expected lag in full response (the response is not instantaneous). Also the response coefficients typically span three or four days.

As expected, this method initially overestimates and then underestimates the discharge when applied to the first three snowmelt phases (Figure 4), because at first the snow is too cold (1st phase), and later (3rd phase) is at zero degrees centigrade throughout the basin, permitting a full response. The modeled response, averaged over all three phases, gives estimates that are artificially high in the beginning of the cycle and low during peak runoff.

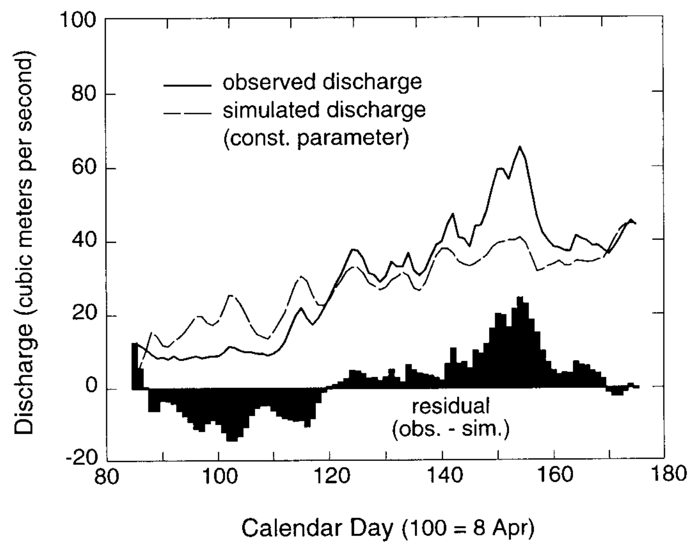

Figure 4. Observed and Simulated Discharge Using Constant Response Parameters to Air Temperature, Gunnison River, Colorado.

The temperature/discharge response is commonly observed to encompass several days of air temperature history (Morris, 1985; Gray and Prowse, 1992), and the response is nonlinear over the seasonal cycle, as in the simplified snowmelt cycle described above. Perhaps less well recognized is that daily observed temperature-driven discharge simulations are consistently in phase even when using simple statistical methods such as Equation (1). As a refinement, time-varying parameters can be used to approximate the nonlinear response in amplitude. Time varying response coefficients can be estimated using a Kalman Filter scheme, for example as illustrated in a simulation using time-varying coefficients (Figure 5).

Work in progress on the Merced River basin and other watersheds using this method is beyond the scope of this paper, but has shown that it can be used in a forecast mode, driven by daily temperature forecasts from the National Center for Environmental Prediction, NOAA.

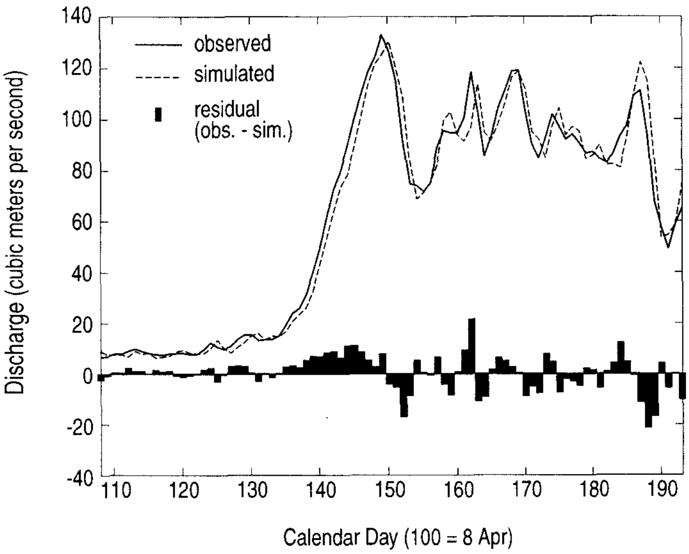

Figure 5. Observed and Simulated Discharge Using Variable Response Parameters to Air Temperature, Merced River, Happy Isles, Yosemite National Park.

Spring Snowmelt Discharge

Each watershed has unique characteristics of topography, soils, and vegetation. Therefore, it might be assumed that high elevation watersheds would yield different sequences of discharge. What is unexpected is that high elevation watersheds on the same mountain range, and to a lesser extent distant mountain ranges, often display very similar discharge fluctuations, down to the level of a few days. The reason for this result is the broad scale nature of synoptic features in atmospheric circulation, with anomalous temperature forcings that often span the entire western U.S.

The Merced River at Happy Isles, Yosemite National Park, is our focal point for illustrating the large-scale nature of variations in snowmelt discharge along the High Sierra Nevada mountain range. We initially present correlations between the river discharge in the Merced and that of other rivers on the western, high-precipitation side of the range, then correlations for rivers on the eastern, low-precipitation side.

The first major watershed south of the Merced is the upper San Joaquin River, with gages that are 40 km apart (Table 1). The San Joaquin gage elevation is only 553 feet higher than the Merced, the area above the gage is 1.38 times that of the Merced, and the estimated peak discharge is 1.5 times that of the Merced. The seasonal peak discharge is four days earlier for the Merced and there maybe a small difference in their percentage of watershed area as a function of elevation. On average, snowpack per unit area maybe slightly less for the Merced as indicated by the difference in peak discharge and drainage area ratios. The long-term discharge for the Merced is $0.0214\ m^3/s/km^2$ and for the San Joaquin is $0.0270 m^3/s/km^2$. Despite these differences in setting and in seasonal discharge amount and timing, the timing in daily fluctuations are essentially the same.

The average correlation (see remarks, Table 3) between the two is high ($R = 0.982 + 0.012$). To make these correlation computations, we have included the period bracketed by calendar days 105 to 195 unless stated otherwise. This window minimizes the number of major rain-on-snow events in the correlations. However, it should be mentioned that the daily correlations between the Merced and San Joaquin discharges remain strong over the entire year. If we assume for this analysis that the Merced River discharge is the forcing function in Equation (1) (instead of air temperature) and San Joaquin River discharge is the response function, the Merced appears to simulate the daily San Joaquin discharge record, including rain spikes, over the entire year. For the 30 years of record the "R" correlation coefficient is 0.986 + 0.013. Thus the hydrologic characteristics of the two watersheds must be closely related.

In essence, even though their major directions of flow differ by about 90 degrees (Merced – drains NW; San Joaquin – SW), the persistently high correlations show the two basins are almost identical in discharge variability. Their close match also indicates the field observations are of high quality. Although their air temperature fields are not known in detail because high elevation observations are sparse, similar air temperature forcings are expected. Thus, we did not attempt to estimate a different air temperature time series appropriate for each Sierra watershed. In fact the Merced air temperature is considered accurate in phase but only a close approximation in amplitude, as is the case for the distant mountain watershed temperatures. For the Sierra Nevada it could be difficult to resolve the differences in watershed temperatures based on sparse sampling, but they are expected to be small.

The Kings River gage (Table 1), 104 km to the south from the Merced gage, shows that the daily average correlations between the Merced and the

King discharges (Table 3) have weakened considerably between these more distant locations (R = 0.709 + 0.163). This low average correlation is misleading, however, because it misrepresents the rate of decorrelation with increasing distance from the Merced. The poor correlations are observed largely in dry years [Figure 6(a)], and therefore are mostly due to an effect of snow patchiness rather than watershed differences and distances. In these analyses, we use discharge summed over days 105 to 195 as a simple index of initial snowpack water volume rather than an estimate of the actual snowpack water volume (which is a linear transform of the water volume index). Above a water volume index of 1,500, the correlations hold up well and increase in years with increased snowpack. The outlier, 1982, appears to be caused by an unusually early warming in the Kings River watershed relative to the Merced [Fig. 6(b)]. The fact that elevation of the Kings watershed is somewhat lower (the elevation at 50 percent of the cumulative area above the gage on the Kings River is 290 meters lower than the elevation at 50 percent of the cumulative area for the Merced) is a factor in ending the snowmelt season earlier than in the Merced. This effect is apparently less important in years with heavier snowpack.

TABLE 3. Daily Discharge and Air Temperature Correlations* with Merced River, Happy Isles, Yosemite National Park for Watersheds in this Study.

Name / (Years)		Discharge	Air Temperature
San Joaquin	(1956-1990)**	0.982 ± 0.012	N/A
Kings	(1952-1990)	0.709 ± 0.163	N/A
Kern	(1961-1992)	0.884 ± 0.012	N/A
Tuolumne	(1916-1922)	0.94 ± 0.02	N/A
Walker	(1939-992)	0.897 ± 0.056	N/A
Carson	(1939-1992)	0.745 ± 0.129	N/A
Weber	(1949-1988)	0.730 ± 0.162	0.802 ± 0.096
Gunnison	(1935-1987)	0.619 ± 0.188	0.775 ± 0.0112
Yellowstone	(1939-1992)	0.347 ± 0.376	0.774 ± 0.092

*Over calendar days 105 to 195.

**The correlation does not include years with large data gaps in the San Joaquin discharge record: 1957-1958, 1966-1967, and 1982.

Discharge from the Kern River, 224 km to the south (Table 1) correlates more strongly with the Merced discharge (R = 0.884 ± 0.012, Table 3) than the Kings River. Interestingly, this correlation also decreases dramatically in dry years when the snowpack water volume index falls below 1,500 (Figure 7). This stronger correlation at a greater distance from the Merced than the Kings River is probably due to a higher watershed elevation accompanied by a more extensive snowfield. We did not examine correlations in rivers further to the south.

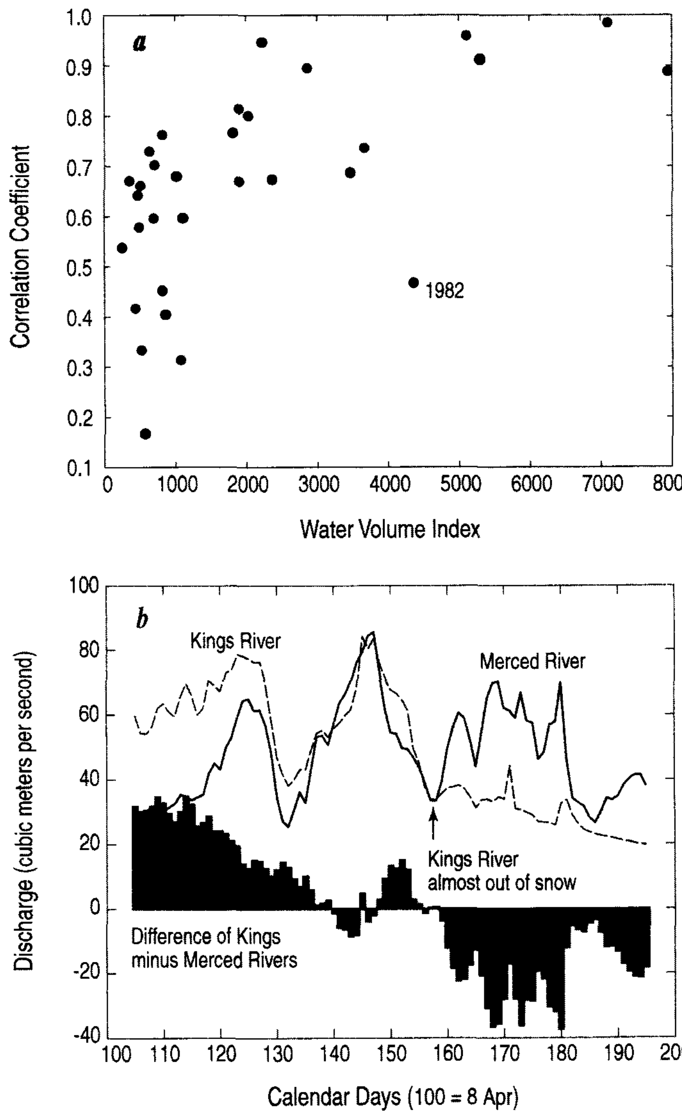

Figure 6. (a) Merced and Kings River Discharge Correlations for Days 105-195 vs. Initial Snowpack Water Volume Index (sum of Kings River discharge over days 105 to 195). Note the reduced correlations when the initial snowpack water volume index is small. (b). Merced and Kings River Discharge, 1982.

The discharge correlation between the Merced River and the Tuolumne River, just to the north, is R = 0.94 ± 0.02 (Table 3). This might be somewhat low because of the short record of overlap (1916-1922) before the Hetch Hetchy reservoir was built. Also, there is a slight difference in the percentage of area above the gage as a function of elevation (Figure 8) that appears to be reflected in the seasonal discharges averaged over the seven years (Figure 9). A comparison of the residuals in the two figures shows similar variations (one in time the other in space).

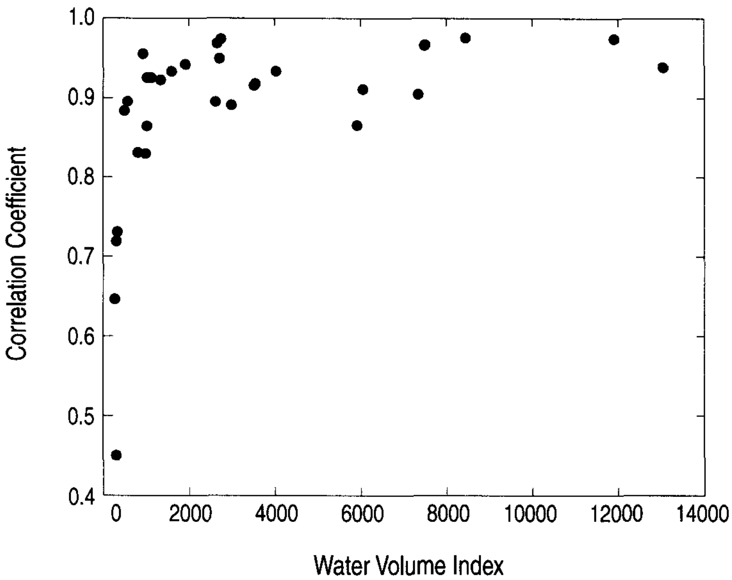

Figure 7. Merced and Kern River Discharge Correlations for Days 105-195 vs Initial Snowpack (initial snowpack is indexed as the sum of Kern River discharge over days 105 to 195). Note the reduced correlations when the initial snowpack is small.

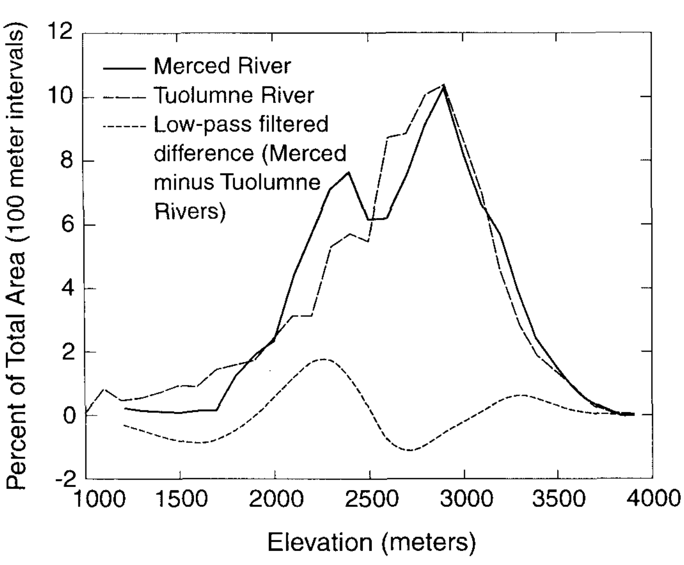

Figure 8. Percent of Total Area Above the Merced and Tuolumne Gage Sites as a Function of Elevation.

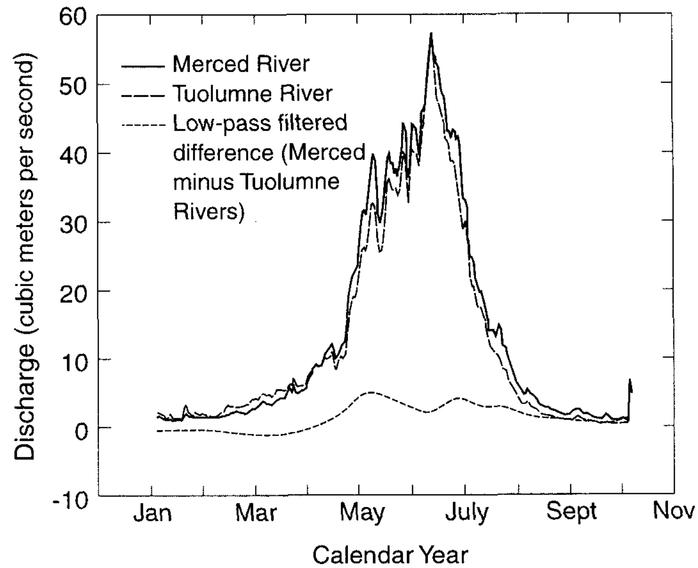

Figure 9. Average of Daily Discharge Over the Annual Cycle for the Merced and Tuolumne Rivers, 1916-1922. Tuolumne River scaled by a factor of 0.43 for comparative purposes.

The next two watersheds north of the Merced are on the low-precipitation, leeward side of the Sierra Nevada. Discharge from the Walker River, the river closest to the Merced, strongly correlates with that of the Merced ($R = 0.897 \pm 0.056$, Table 3) even though river basin geomorphology is different in that the watershed slope is steeper in the Walker and the vegetation is probably different (a more arid flora). Furthermore, the river flow is opposite in direction to that of the Merced. Further northward (with about 119 km between the two gages, Table 1) the Carson River-Merced River discharge correlation is relatively strong ($R = 0.745$, Table 3) even though the quality of the record is considered poor (USGS, 1997:150).

Considering all of the rivers together, with few exceptions the effects of air temperature appears to be strongly reflected in the daily discharge correlations extending over a region of at least 340 km (the greatest distance between the gages to the north and south of the Merced). This is a larger scale, for example, than the 2°x2° resolution of most large-scale weather forecasting numerical models. These regional discharge correlations suggest that downscaling atmospheric numerical models to the catchment scale may be less of a problem for estimating snowmelt discharge than previously thought except in years following dry conditions and sparse snowpack.

BROADER SCALE IMPLICATIONS

How well do these correlations hold up over more distant mountains in the West? Several examples provide a good illustration of the correlation in temporal variability among the four distant watersheds selected (Figure 1). To examine these more distant relationships, we adjusted the daily hydrographs and temperatures for lead-lag relations for the same variable but not for cross variables. That is, no adjustment was made for the delay between air temperature and snowmelt. The Merced flow response is fixed so that it always leads those of the Weber and Yellowstone temperature/discharge observations by one day and the Gunnison by two.

The first of these examples, the year 1951 (Figure 10), was selected to show low frequency snowmelt "cycles" [from approximately day 140 (May 20) to day 170 (June 19)], that are obviously driven by two warm spells separated by an interlude of cool weather (between days 155-165) that invaded the west. Also evident is an early response for the Merced and fading snowmelt for the Gunnison, Weber, and Merced, with continued snowmelt at Yellowstone. The second example, the year 1979 (Figure 11), is similar, but with higher frequency temperature and discharge fluctuations. Again, the snow at Merced is probably preconditioned to a higher temperature (is warmer) giving an earlier and higher discharge response, and the Weber River snowmelt is fading before the other three. The third example, the year 1980 (Figure 12), is similar to the first (Figure 10) except that the second major peak is relatively lower for the Yellowstone presumably because the remaining area of snowpack was significantly diminished.

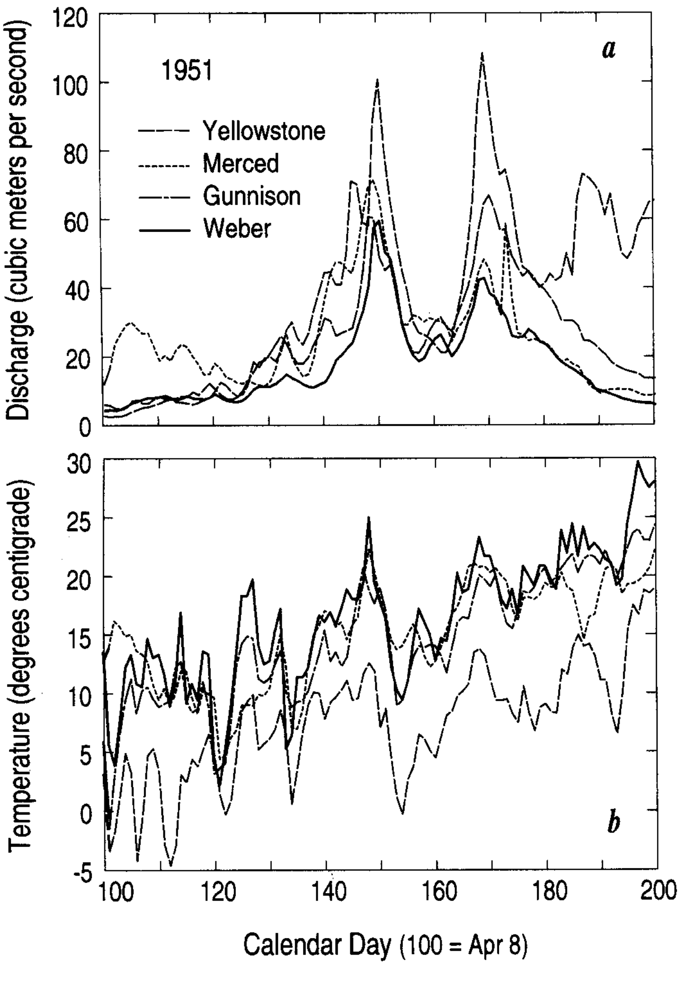

Figure 10. Daily Variations in Discharge (upper panel) and Air Temperature (lower panel) for the Yellowstone, Merced, Gunnison, and Weber Rivers, 1951. (Yellowstone discharge divided by two for comparative purposes.)

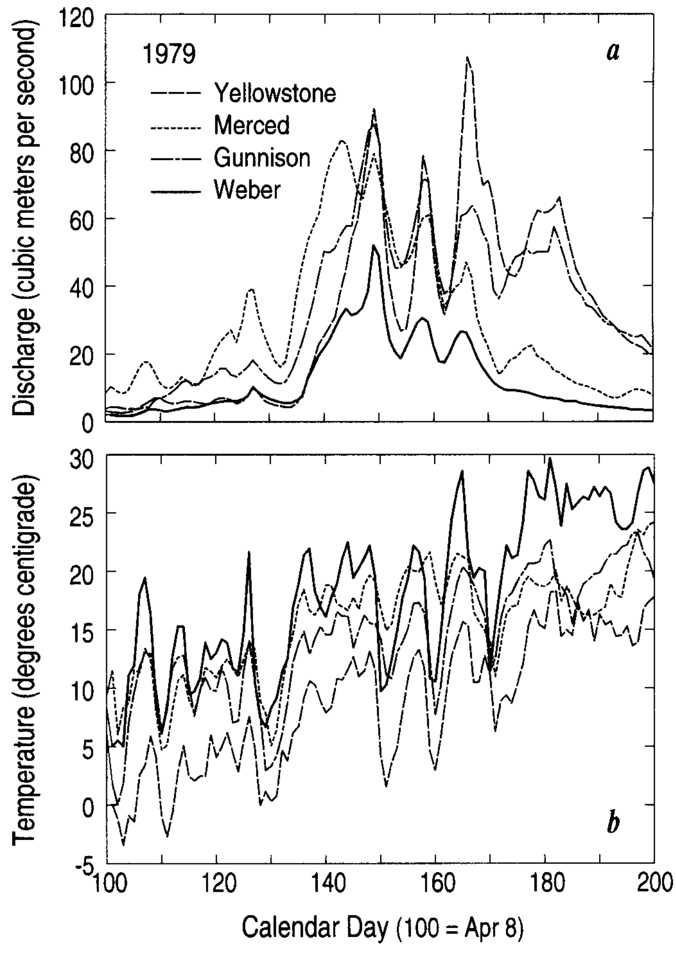

Figure 11. Daily Variations in Discharge (upper panel) and Air Temperature (lower panel) for the Yellowstone, Merced, Gunnison, and Weber Rivers, 1979. (Yellowstone discharge divided by two for comparative purposes.)

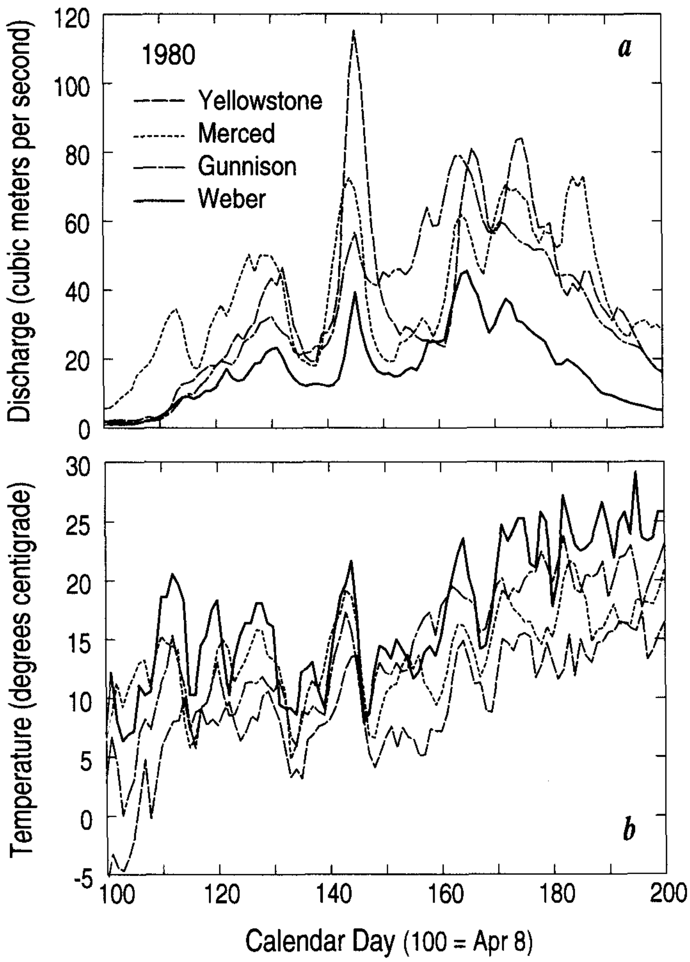

Figure 12. Daily Variation in Discharge (upper panel) and Air Temperature (lower panel) for the Yellowstone, Merced, Gunnison, and Weber Rivers, 1980. (Yellowstone discharge divided by two for comparative purposes.)

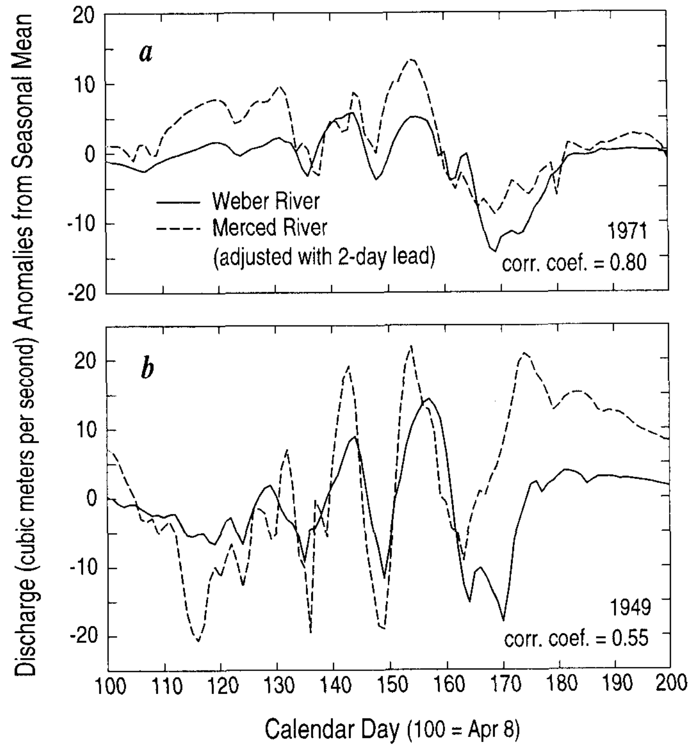

Figure 13. Daily Correlations in the Merced and Weber River Daily Anomalies from Seasonal Climatology (in Figure 2).

To examine seasonal cycles, (Figure 2) we filtered the mean-daily values with a 15-day boxcar filter applied twice (forward and backward). When daily values are normalized to the seasonal mean, fluctuations for the Merced and Weber Rivers (Figure 13) seem remarkably in phase (Merced plotted as a one-day lead) for such distant watersheds, and average temperature and discharge correlations for the period of record are relatively high (Table 3). Why the correlations from the more distant watersheds are stronger in some years than others is a subject of future research (note the increase in standard deviation with decrease in correlation). The problem is more complex than loss of correlation in dry years, and probably involves the influence of regional weather patterns affecting the Rocky Mountains that are different from those affecting the Sierra Nevada Mountains.

Implications of the Snowmelt Air Temperature Response

A ubiquitous characteristic of Spring-Summer streamflow in high elevation watersheds in the Sierra Nevada and throughout the west is the occurrence of large snowmelt fluctuations with time-scales of a few days to a few weeks. The fluctuations are often 10-20 percent of the peak spring flow, but can sometimes be much larger. Furthermore, they are coherent features enveloping the Sierra Nevada and Rocky Mountains. These fluctuations represent the response of western mountain watersheds to warming and cooling, a natural experiment that is repeated every year. While the focus here has been on intra seasonal fluctuations, there are longer term climate variability and change issues centered on precipitation and air temperature. Below are some research directions relevant to these issues and to hydrologic forecasting.

In the context of natural interdecadal climate fluctuations such as the Pacific decadal oscillation (Mantua *et al.*, 1997; Gershunov and Barnett, 1998; McCabe and Dettinger, 1999) and, perhaps, global warming, it would be useful to estimate the air temperature/snowmelt discharge response surfaces for high elevation snowmelt watersheds. At the very least this would provide empirical results for comparison with numerical simulations.

An example of warm vs. cool springs with similar initial snowpack is instructional. In West Coast winters, the day-to-day relative contributions of rainfall vs snowfall are determined by the general temperature within a storm and the rate of decrease in temperature with increase in elevation (temperature lapse rate). As a result, low elevation precipitation is most often rain (warm), high elevation precipitation is most often snow (cool), and at an intermediate elevation a mixture of the two (Cayan *et al.,* 1993). At high elevations, for similar snowpack (estimated here from cumulative discharge and direct measurements), the timing of snowmelt (early or late) is largely determined by seasonal air temperature variations (Cayan *et al..* 1999). *A* comparison of Merced River discharge between warm-wet (1986) and cool-wet (1967) years (Figure 14) shows that both discharge totals were higher than the long term mean, but importantly, the

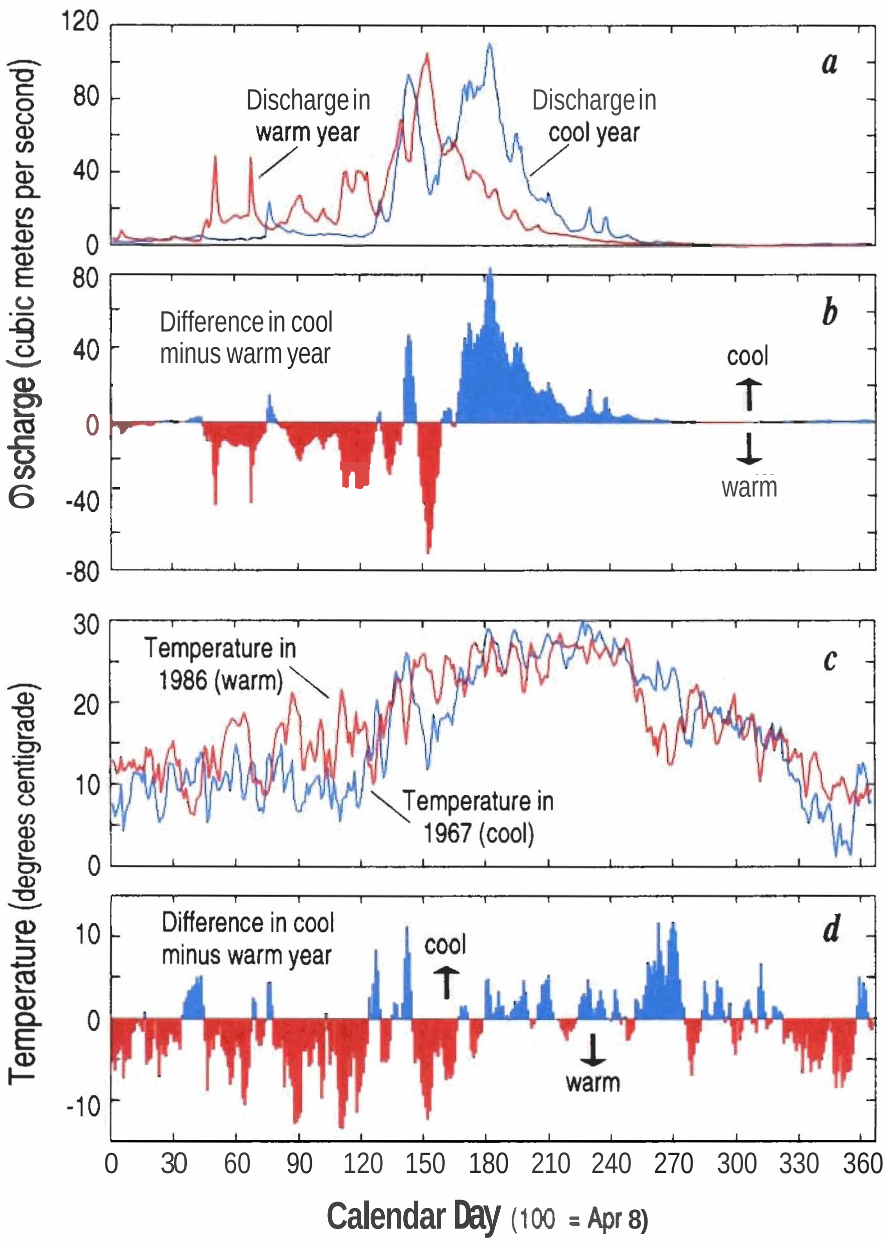

Figure 14. Comparison of Snowmelt Discharge Delay from a Cool Spring (1967)and a Warm Spring (1986). The mean day-100 to day-200 air temperature in 1967 is 13.9°C, and in 1986 it is 16.2°C; mean discharge for the same period in 1967 is 54.5 cubic meters per second, and in 1086 it is 39.5 cubic meters per second. Day for the start of the spring pulse in 1967 is 126, and in 1086 it is 108; day of peak discharge in 1967 is 182; and in1986 it is 152.

timing of peak discharge was 30 days earlier in 1986 in response to having a much warmer spring-early summer temperature. The mean day-100 to day-200 temperature difference between the two years was 2.3 degrees centigrade (Figure **14)** (see also Cayan and Peterson, 1993).

Water managers are concerned about differences in spring discharge timing because an early snowmelt shortens the season of natural water storage. In early snowmelt years, reservoir managers require more artificial reservoir volume to account for this loss of "free" storage capacity. There are also concerns about spring snowmelt floods in some watersheds. This temperature effect is at the heart of the long-term global warming issue (Jeton *et al.,* 1996; Gleick, 1987; Lettenmaier and Gan, 1990). It is probably an even more significant effect because over the last several decades, spring snowmelt at intermediate elevations has been declining (Roos, 1987) due to increasingly warmer winters (December, January, February, March; Dettinger and Cayan, 1995).

In northern and central California, early snowmelt also means that downstream summer discharge is less (all other things being equal). Salinity encroachment into the northern San Francisco Bay/Delta, a freshwater source for 20 million people, is exacerbated following warm versus cool springs (Cayan and Peterson, 1993). Therefore warm springs put even more pressure on water managers to balance agricultural, urban, and environmental water needs.

The results from this study suggest that improved spatial detail in air temperature, and especially solar irradiance observations at high elevations, would be helpful in understanding the physics behind the correlations presented. Solar irradiance is very sparsely observed and difficult to measure in the mountains, but is certainly involved in any hastening or retarding of the snowmelt runoff. Air temperature serves well as a snowmelt discharge forcing function, and the same or similar forcings apparently apply to multibasins, at least along the same mountain range, because temperature fields are large-scale. Also, preliminary results suggest that improved temperature forecasts will result in improved short-term discharge forecasts because the forecast error in discharge (output) correlates with the forecast error in air temperature (input).

In addition to improved observations, understanding the linkages will require complex physically based models. However, many of the forcing variables, and possibly the derived parameters in physically based models, may be assumed to covary to differing degrees with air temperature. A difficulty in using these more complex models in global warming scenarios will be to determine whether increasing air temperature is, or is not associated with cloudiness (solar insolation; see Jeton *et al.,*1996:23). That is, does the air temperature/solar insolation relationship that is implicit in the results presented here change with increasing global warming? To have the relationship remain constant would require a decrease in cloudiness with increase in air temperature. Even less is known about high elevation variations in solar insolation.

To conclude, it appears that there is a much stronger regionally organized signal in snowmelt runoff than has been heretofore appreciated. These coherent runoff fluctuations would seem to have application to water resource and hydropower management.

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