Air Temperature and Snowmelt Discharge Characteristics, Merced River at Happy Isles, Yosemite National Park, Central Sierra Nevada

David Peterson, Richard Smith, Stephen Hager, Daniel Cayan, and Michael Dettinger

Abstract

Although snowmelt discharge (SMD) is a function of many variables, only snowpack, river discharge, and air temperature have long-term records, which are the focus of this study. Solar insolation, an important variable, covaries with air temperature and, presumably, much of the air temperature-snowmelt discharge correlation includes solar insolation effects. Two features of the seasonal SMD cycle are the spring pulse, which defines the start of the rise in SMD, and the peak SMD, which defines the start of the decline in SMD. Air temperature leads SMD, throughout the snowmelt season, from zero to a few days. Apparently the lead/lag variations depend on the rates and durations of rising and falling air temperatures. On average, however, the lead time between air temperature variations and the SMD response is longer near the start of the snowmelt season and decreases as snowmelt progresses towards the peak SMD. This pattern is most likely caused by the seasonal increase in air temperature driven response as SMD progresses. Initially, the SMD response is slow as the snowpack takes time to ripen. Another, but likely smaller, contributing factor is the seasonal change in the air temperature variation which begins to decrease near day 150 (note: the range in maximum discharge extends beyond day 150 to 182). Further, the timing of the start of the SMD season (the spring pulse) depends more on air temperature (cool or warm) than winter snowpack (wet or dry). However, as the SMD season progresses towards maximum discharge, this pattern changes and the importance of differences in winter snowpack on SMD timing increases while the importance of differences in air temperature decreases.

Introduction

The stream gaging station on the Merced River at Happy Isles, Yosemite National Park, is an excellent location for expanding the effort to link large-scale atmospheric circulation to snowmelt discharge (SMD) and river chemistry. Although the advantages of this location are too numerous to list here, a few examples include: (1) the alpine river discharge record is long (1916 to present) and largely undisturbed, (2) the air temperature variations are large scale and strongly covary with SMD, and (3) more than 85% of the annual Merced River flow at Happy Isles is SMD. For all these reasons (and more), knowing the hydrologic response of this region to climate variability and change is important to scientists and park and water managers.

Variations of SMD correlate among many western watersheds because the correlation between air temperature and SMD is strong, and the air temperature variations are large-scale (Peterson and others 2000). The present paper focuses on characteristics of this air temperature-SMD linkage using daily Merced River discharges at Happy Isles and a regional average of daily air temperatures in the central Sierra Nevada. The SMD response to air temperature is increasingly important because air temperatures in central California have increased and are likely to continue to increase (Dettinger and others 2002).

Data and Methods

Data

The air temperature series used here is an average of air temperature from four long-term weather stations in the central Sierra Nevada (Cayan and others 1993), from 1931 to 1999 and a valley floor station from 1916 to 1999 (prior to 1931, only the valley air temperatures are available). The river discharge series is from the Merced River USGS gage at Happy Isles, Yosemite National Park (USGS site 11264500; Slack and Landwehr 1992), from 1916 to 1999.

Methods

The series were filtered with a box-car filter (backwards and forwards to preserve phase) (Matlab 1996) with a 25-day filter for air temperature and a 15-day filter for river discharge. Fewer filter days are needed for river discharge because air temperature-driven SMD is filtered by snowpack but air temperature is not. Two time-series modeling approaches were used: An instrumental variable method (Ljung 1988, 1989, function 'iv4') and an extended Kalman filter method (Ljung 1988, 1989, function 'rarx'). The annual date of the onset of major snowmelt, the spring pulse date (Cayan and others 1999), was defined by the objective method described in Cayan and others (2001).

Results and Discussion

A brief description of air temperature and SMD climatology is presented before discussing the SMD response characteristics to daily variations in air temperature.

Hydroclimatology

The mean annual cycles of air temperature and river discharge are estimated from the filtered 1916 to 1999 daily mean observations (Figure 1a), showing that the river discharge typically peaks during the springtime warming period from April through June, in response to the rapid snowmelt during that period. Thus, air temperature peaks almost two months (20.9 °C, day 209) after river discharge peaks (40.5 cubic meters per second [CMS], day 150). Standard deviations from those annual cycles differ substantially between air temperature (Figure 1b) and river discharge (Figure 1c). When air temperature is a maximum, the standard deviation of air temperature is a minimum; whereas when river discharge is a maximum, the standard deviation of river discharge is a maximum.

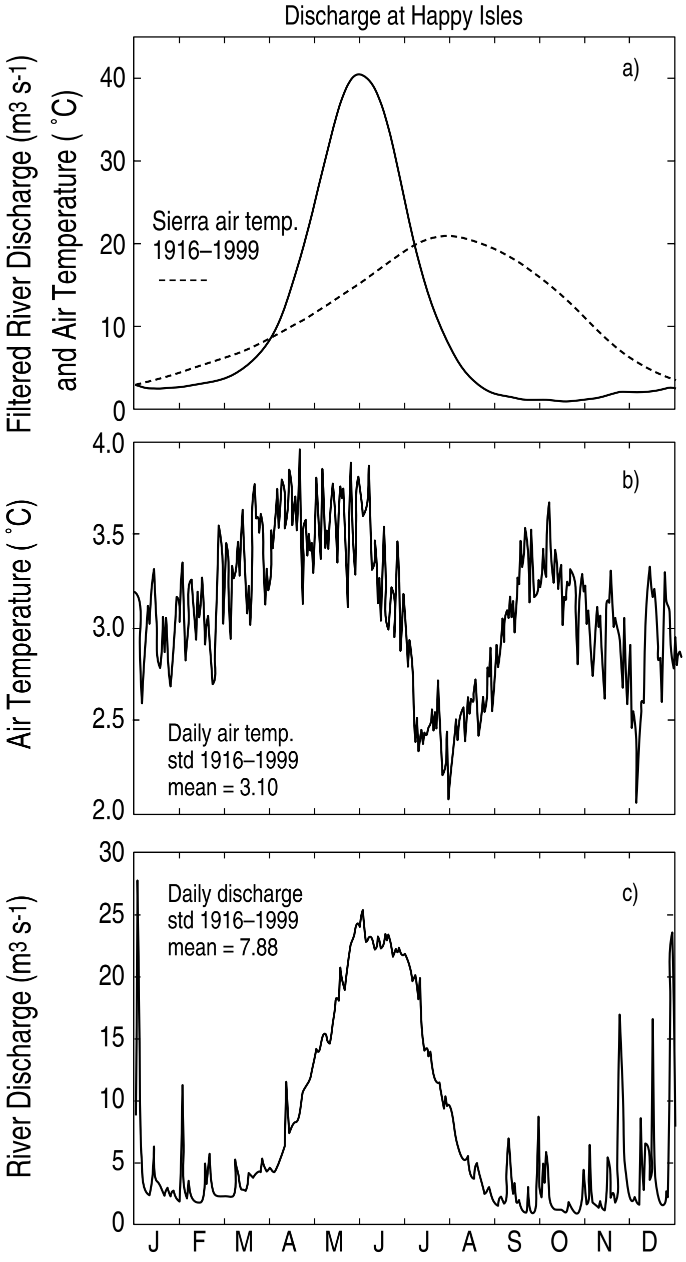

Figure 1 (a) Mean annual cycles of air temperature and river discharge; (b) Standard deviations of daily air temperature annual cycle from climatology; (c) Standard deviations of river discharge from climatology.

Snowmelt Discharge: Air Temperature Response

Snowmelt discharge (SMD) varies during the rise in the annual temperature cycle in response to the combination of temperature variation and the amount of water held in the evolving snowpack. The focus here is on the period of rising river discharge when SMD responds most strongly to air temperature. This interval is approximately bounded by the spring-pulse date and the time of SMD maximum (Figure 2a).

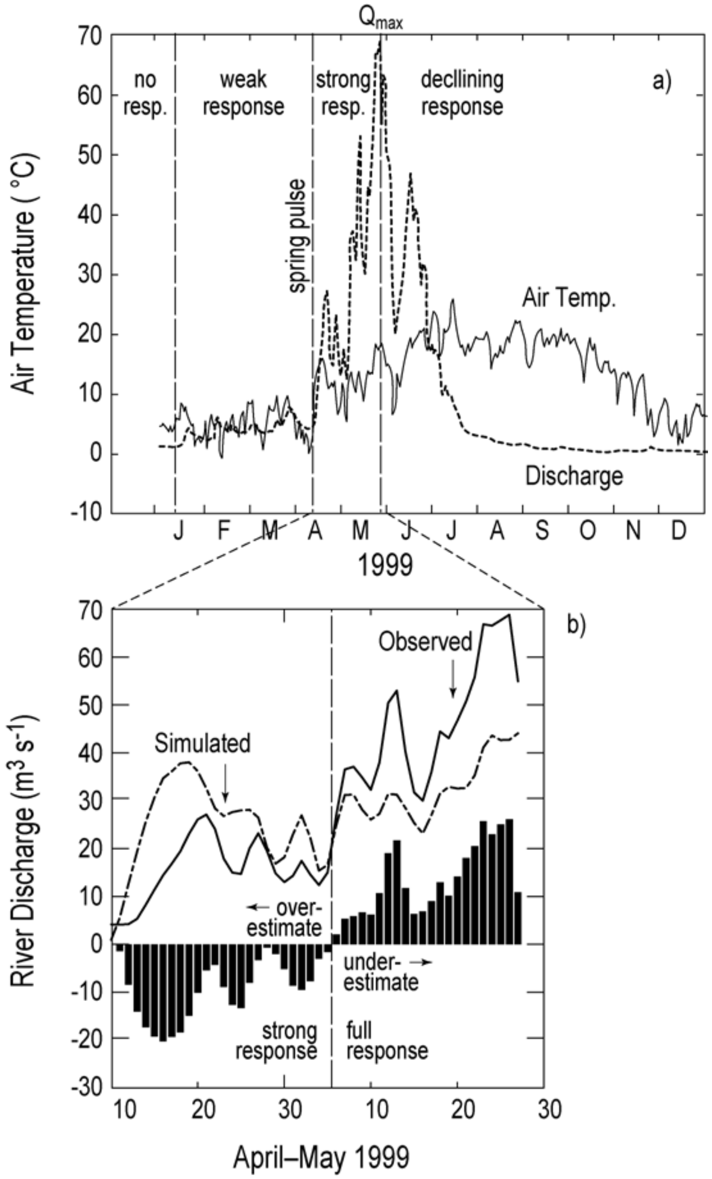

Figure 2 (a) Daily air temperature and river discharge during 1999; (b) Observed and simulated snowmelt discharge, 1999, from the spring-pulse date to the date of maximum in snowmelt discharge based on a constant parameter (iv4) model.

SMD responses to air temperature are not instantaneous. In 1999, for example, air temperature led SMD during the spring pulse (early April, Figure 2a). When air temperature leads SMD, we infer that it takes more than today's air temperature to produce today's river discharge. Snowpack, then, apparently has a memory of air temperature longer than one day. Notably, SMD responses to diurnal temperature fluctuations, which represent about 10% of daily mean SMD, are different. Diurnal air temperature fluctuations led diurnal SMD by many hours, but not by days (Lundquist and Cayan 2002; Lundquist and Dettinger 2003).

The multiple-day influence of temperatures on SMD is captured in a very simple model:
$Q_o = b_o T_o + b_{-1} T_{-1} + b_{-2} T_{-2}(1)$

Where three days of air temperature, T_o (today), T_{-1} (yesterday), and T_{-2} (the day before) contribute to today's river discharge, Q_o. How strongly the different air temperatures contribute to Q_o is estimated by fitting the weights of the response coefficients b_o, b_{-1}, and b_{-2} (instrumental variable method, Matlab function iv4, Ljung 1988, 1989). For example, past air temperature is more important to today's SMD than today's air temperature if b_o is less than b_{-1} or b_{-2}.

In the 1999 example (Figure 2c), when a single set of parameters is fitted for the entire rising limb of the SMD season, $b_o = 0.916 \pm 0.30$, $b_{-1} = 1.338 \pm 0.20$ and $b_{-2} = 0.1869 \pm 0.30$. In this example, yesterday's air temperature, on average, is more heavily weighted than today's (b_o) or the day before (b_{-2}). Also, the resulting simulated discharge is overestimated at first and underestimated later.

Fitting time-dependent response coefficients to the data, using the extended Kalman Filter (EKF) can eliminate this tendency toward over- and underestimation. The EKF not only estimates river discharge and response coefficients during the springtime SMD (Figure 3a) but throughout the annual cycle, even when the discharge is not air temperature driven because of its prediction-correction scheme. During the springtime SMD variations, the daily sum of the three response coefficients in this example ranges from about 1 to 4 CMS/°C (Figure 3c).

The 3-day EKF model closely simulates SMD and appears to be simply "curve fitting." For this reason, the results of a more widely used and straightforward correlation method are presented first. The mean daily correlation coefficient between today's SMD and today's, yesterday's, and the day before yesterday's air temperature were calculated individually. On average, yesterday's air temperature correlated most strongly with SMD over the period of interest (Figure 4a). Further, the day before yesterday's influence was generally stronger than today's, as shown by the difference between their associated correlations with discharge (Figure 4b).

In the EKF method, the response coefficient weights were estimated each day from 1931 to 1999. The maximum response coefficient was identified for each day of the 69 years and an indicator series was constructed depending on which coefficient was largest on each day, with the indicator set equal to 1 if today's coefficient was largest, 2 if yesterday's, and 3 if the day before yesterday's. Then, the indicator series was averaged by day of year. In the result, a mean value of 2 for a particular calendar day indicates that, on average, yesterday's air temperature elicited the strongest discharge response. In general (Figure 4c), discharge responds most to yesterday's temperatures in early April, or around the time of the spring pulse. After early April, the influence of yesterday's and the prior day's temperatures tend to decrease (relative to that of today's temperature) as SMD progresses and as the overall snowmelt response to air temperature (Figure 3c) increases. This seasonal pattern of the "memory" of temperatures in SMD variations largely parallels that found by the simple correlation analysis (Figure 4b). In essence, the EKF estimator of variable response parameters appears useful in defining the air temperature lead characteristics in the SMD process and therefore may also be useful in defining the response to differences in air temperatures and initial snowpack over the course of increasing temperature and SMD.

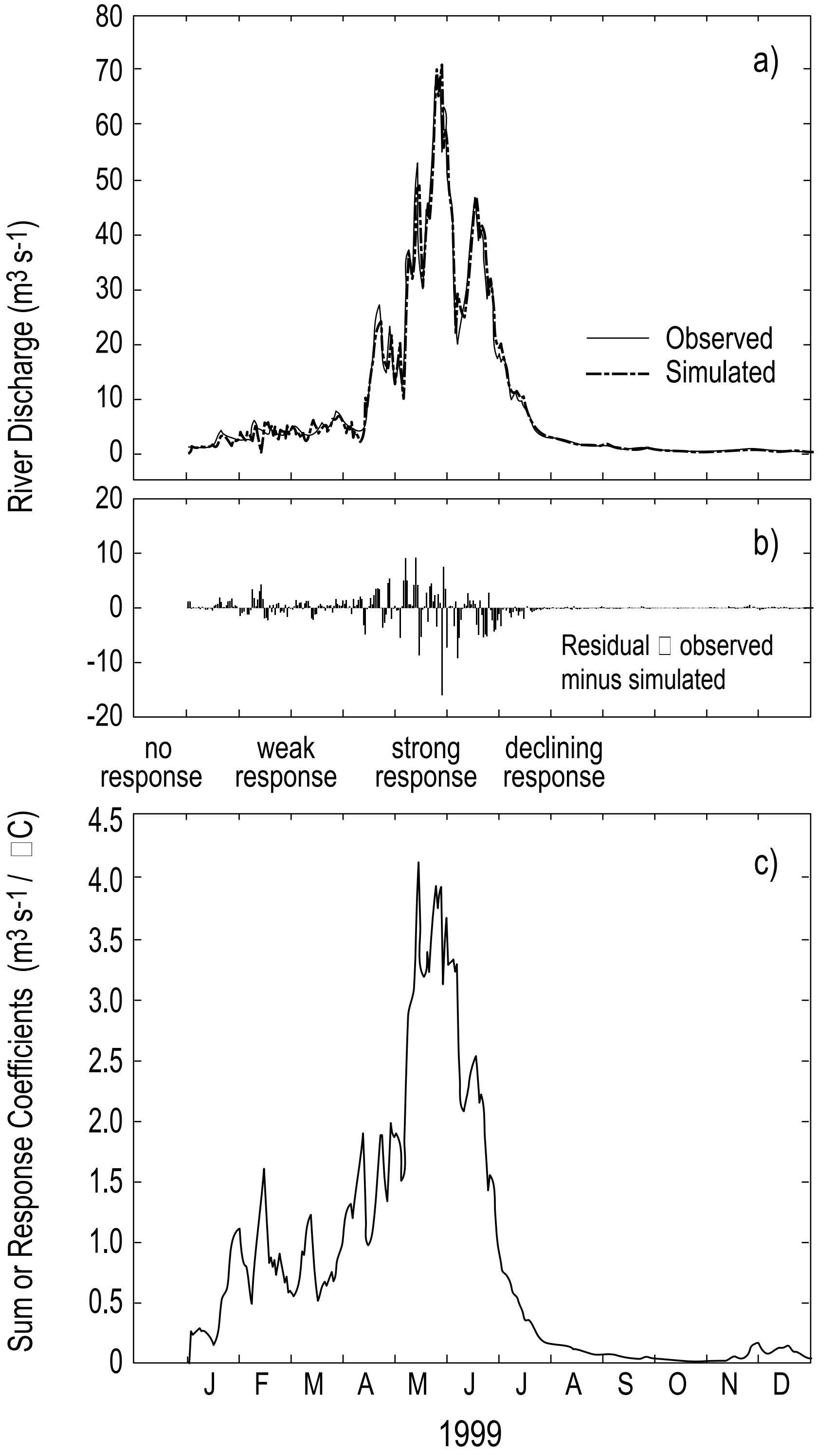

Figure 3 (a) Observed and simulated snowmelt discharge, 1999, based on a variable parameter model; (b) Sum of response coefficients.

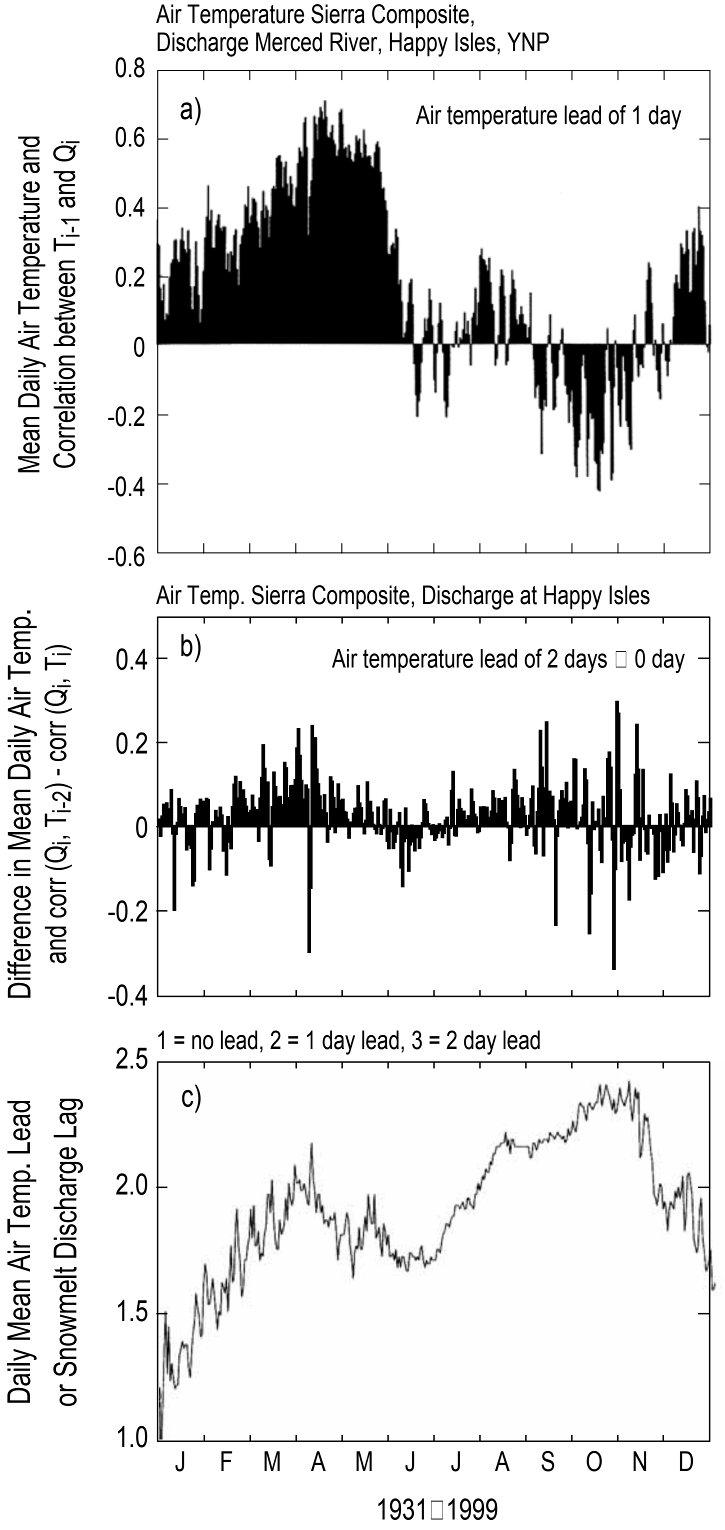

Figure 4 (a) Mean correlation between yesterday's daily air temperature and today's river discharge; (b) Mean correlation between discharge and temperatures at a two-day lead minus the correlation at a zero-day lead; (c) Mean of maximum weighted air temperature response for today, yesterday, or the day before yesterday.

The overall influences of air temperatures (at the full combination of lead times) on SMD clearly vary through the seasons (Figure 4a) in ways that reflect the seasonal temperature cycle that the day-to-day temperature variations deviate from. For example, atmospheric warming across much of western United States is causing a decrease in snow relative to rain at intermediate but not high elevations. At high elevations, the winter to early spring air temperature is too cold, even with the warming, to influence winter snowpack much (Dettinger and Cayan 1995). That is, high elevation air temperature in winter ranges from cold to less cold. Generally, though, when SMD starts, air temperatures are rising from cool to warm, whereas by the time that SMD peaks, air temperatures are already warm (ranging only from warm to very warm). At warm to very warm air temperatures, the variations in temperature should be less important to SMD, because widespread snowmelt occurs at both temperatures. When air temperatures range from cool to warm, larger snowmelt gradients are expected within the basin and thus larger SMD fluctuations result. Furthermore, because air temperature continues to rise well after SMD peaks, the timing of the SMD maximum may be more sensitive to initial snow water equivalent than air temperature history (c.f. Peterson and others 2000). Is the timing of the start of the spring SMD pulse more sensitive to air temperature while the timing of maximum SMD is more sensitive to initial snowpack depth?

Composites of the time-varying EKF response coefficients provide a way to study the likely differences in SMD response characteristics between wet and dry years, and cool and warm years. Eleven-year composites were computed for the response coefficients from the wettest, driest, coolest, and warmest years (based on the mean air temperature and river discharge over days 81 to 150) to characterize the seasonal cycles of temperature responses and daily ranges of timing of the spring pulse under these extreme conditions (Table 1). The greatest differences between the timing of largest coefficients in the composites were between the cool and warm composites, even though the wet composite peaked at higher coefficient values and the dry composite at lower values (Figure 5a). These greater differences in coefficient amplitudes favor a greater difference in SMD timing.

Table 1 Years contributing to the four climate composites based on mean air temperature and river discharge over days 81 to 150

Cool	*Warm*	*Wet*	*Dry*
1917	1926	1936	1924
1921	1931	1938	1931
1929	1934	1940	1936
1933	1939	1946	1934
1942	1947	1952	1953
1948	1966	1969	1961
1953	1976	1973	1964
1963	1978	1982	1976
1967	1990	1986	1977
1995	1992	1993	1990
1998	1997	1997	1991

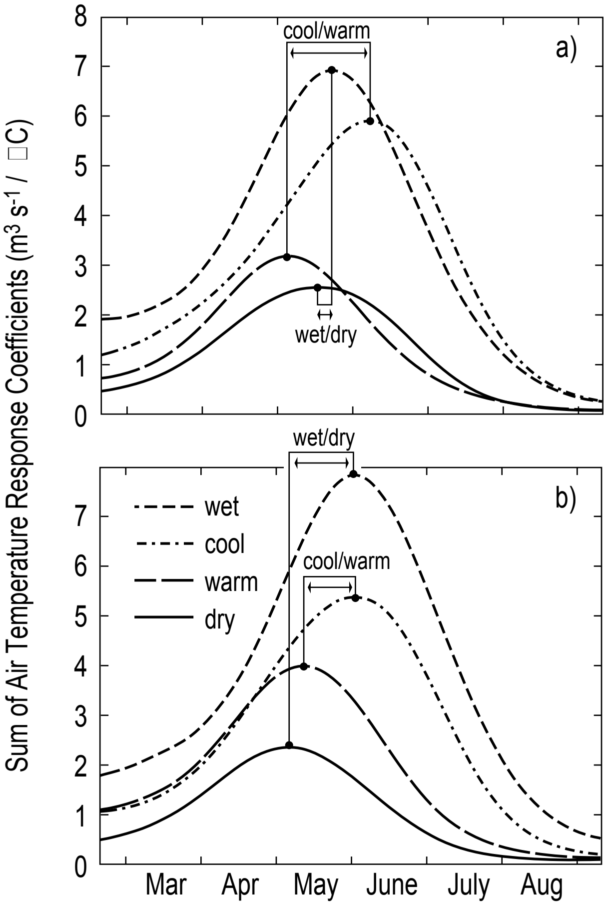

Figure 5 (a) Filtered composites of cool-, warm-, wet-, and dry-year snowmelt discharge response to air temperature. The spring composites were based on the air temperatures and discharge during days 81 to 150; (b) Same as above but for the discharge maximum composites, during days 111 to 181.

Repeating the experiment for the SMD maximum (composites based on mean temperature and discharge values over days 111 to 182), instead of the spring pulse show a relation opposite of the spring pulse (Figure 5, right panel) where the peak wet and dry response patterns extend over a greater length of time than the cool and warm response patterns. However, in this case the significance is less clear, because the wet pattern amplitude exceeds the cool pattern maximum in magnitude. Similarly, the dry pattern amplitude is less than the warm pattern, and the timing of the cool and wet peaks are the same.

To summarize, several lines of evidence indicate that, at the start of SMD, air temperature is the dominant control on the timing of the spring pulse (Cayan and others 2001). Similarly, but less clearly, as the peak SMD is approached, the importance of initial snow water content on SMD timing increases (Figure 6).

Table 2 Years contributing to the four climate composites based on mean air temperature and river discharge over days 111 to 181

Cool	*Warm*	*Wet*	*Dry*
1916	1926	1922	1923
1923	1940	1938	1931
1933	1966	1952	1934
1942	1972	1956	1939
1944	1976	1958	1961
1948	1981	1969	1976
1953	1985	1978	1977
1964	1986	1983	1987
1971	1987	1986	1988
1980	1992	1993	1990
1998	1997	1995	1994

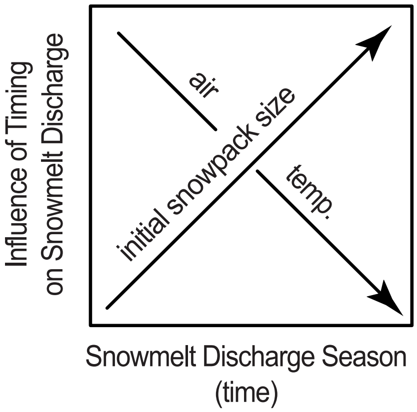

Figure 6 Simplified schematic of variation in timing response to air temperature and initial snowpack.

Summary and Conclusion

The linkage between air temperatures and SMD variations show subtle lead-lag relations such that the importance of "older" temperatures (e.g., yesterday's or the day before's) is, on average, greater near the timing of the spring pulse and less as snowmelt progresses. An explanation of these phenomena is that the system is more sluggish in response to air temperature—due to larger spatial gradients in the readiness of snowpacks at various elevations to contribute snowmelt—at the start of SMD than later in the annual cycle.

The difference in amplitude and timing of the SMD response to air temperature between cool and warm years was greater near the time of the spring pulse than later in the SMD season. This pattern of sensitivities reversed when wet and dry years were contrasted. The early vs. the later distinction is more clearly illustrated near the spring pulse; the difference in cool vs. warm was greater than wet vs. dry even though the difference in amplitudes were greater for the wet and dry composites (which would favor a greater difference in timing). This was not the case for later responses. The implication is that the spring pulse is more sensitive to air temperatures than is the timing of maximum SMD.

Acknowledgements

Many thanks for the helpful reviews provided by Noah Knowles and Jessica Lundquist.

References

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. Changes in the onset of spring in the western United States: Bulletin of the American Meteorological Society, 82, 399-415.

Cayan, D.R., D.H. Peterson, L. Riddle, M.D. Dettinger, and R. Smith. 1999. The Spring Runoff Pulse from the Sierra Nevada. 14th Conference on Hydrology American Meteorology Society, pp. 77-79.

Cayan, D.R., L.G. Riddle, and E. Aguado. 1993. The Influence of Precipitation and Temperature on Seasonal Stream flow in California. Water Resources Research 29(4): 1127-1140.

Dettinger, M.D. and D.R. Cayan. 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California, Journal of Climate, 8, 606-623.

Dettinger, M.D., D.R. Cayan, N. Knowles, A. Westerling, and M.K. Tyree. 2002. Recent projections of 21st century climate change and watershed responses in the Sierra Nevada, California, Sierra Nevada 2002: Science for Management and Conservation, 6 pp.

Ljung, L. 1988 System Identification Toolbox User's Guide for Use with Matlab. The Mathworks, Inc., 21 Eliot St., South Natick, Massachusetts, 59 pp.

Ljung, L. 1989 System Identification: Theory for the User. Prentice-Hall, Inc., Inglewood Cliffs, New Jersey, 515 pp.

Lundquist, J.D., and M.D. Dettinger. 2003, Linking diurnal cycles in river flow to interannual variations in climate: American Meteorological Society, 83rd Annual Meeting, 17th Conference on Hydrology, Long Beach, CA, J2.4-1 to J2.4-5.

Lundquist, J., and D. Cayan, 2002. Seasonal and spatial patterns in diurnal cycles in streamflow in the Western United States. J. Hydromet., 3, 591-603.

Peterson, D.H., D.R. Cayan, R.E. Smith, M.D. Dettinger, and L. Riddle. 2001, An experimental forecast of maximum daily snowmelt discharge for the year 2001: Scripps Institution of Oceanography (CAP) California Applications Program (on-line publication).

Peterson, D.H., R.E. Smith, M.D. Dettinger, D.R. Cayan, and L. Riddle. 2000. An organized signal in snowmelt runoff over the west: Journal of the American Water Resources Association, 36, 421-432

Slack, J.R., and J.M. Landwehr. 1992. Hydroclimatic Data Network (HCDN): A USGS Streamflow Data Set for the United States for the Study of Climate Variations, 1874-1988. USGS Open-File Report 92-129. 193 p.