

Spring Onset in the Sierra Nevada: When Is Snowmelt Independent of Elevation?

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ABSTRACT

Short-term climate and weather systems can have a strong influence on mountain snowmelt, sometimes overwhelming the effects of elevation and aspect. Although most years exhibit a spring onset that starts first at lowest and moves to highest elevations, in spring 2002, flow in a variety of streams within the Tuolumne and Merced River basins of the southern Sierra Nevada all rose synchronously on 29 March. Flow in streams draining small high-altitude glacial subcatchments rose at the same time as that draining much larger basins gauged at lower altitudes, and streams from north- and south-facing cirques rose and fell together. Historical analysis demonstrates that 2002 was one among only 8 yr with such synchronous flow onsets during the past 87 yr, recognized by having simultaneous onsets of snowmelt at over 70% of snow pillow sites, having discharge in over 70% of monitored streams increase simultaneously, and having temperatures increase over 12°C within a 5-day period. Synchronous springs tend to begin with a low pressure trough over California during late winter, followed by the onset of a strong ridge and unusually warm temperatures. Synchronous springs are characterized by warmer than average winters and cooler than average March temperatures in California. In the most elevation-dependent, nonsynchronous years, periods of little or no storm activity, with warmer than average March temperatures, precede the onset of spring snowmelt, allowing elevation and aspect to influence snowmelt as spring arrives gradually.

1. Introduction

Recent studies (Peterson et al. 2000; Cayan et al. 2001) have shown that the fluctuations of selected rivers draining the Sierra Nevada and Rocky Mountains are highly correlated each spring, indicating an organized, regional-scale signal of snowmelt initiation and runoff. These basins integrate the effects of broad ranges of aspect and elevation. All have area exceeding 100 km², and most exceed 400 km². As described here, recent data collected during the spring 2002 snowmelt season from subbasins of the Tuolumne and Merced Rivers in Yosemite National Park, California, and from California Department of Water Resources (CA DWR) snow pillows throughout the central Sierra Nevada suggest that, in certain years, this simultaneity extends to almost the entire range of elevations within these watersheds.

When considering snowfed basins, intuition and various historical data suggest that snow at lower elevations melts first. The standard atmospheric lapse rate describes a decrease in air temperature of 6.5°C per 1000-m elevation gain. Using snow pillow measurements from 1880- to 2800-m elevation in the Truckee River basin, Reece and Aguado (1992) found an approximate 4-day delay in the start of the snowmelt season for each 100 m increase in altitude. However, these results are based on average conditions, and recent observations from 2002 (discussed below) suggest that an individual year can differ drastically from the norm.

A realistic description of the elevational distribution and timing of snowmelt and runoff is crucial to successfully model basin-scale snowmelt and spring streamflow. To improve simulation accuracy, models often partition a basin into elevation zones (Singh and Singh 2001; Rango and Martinec 1981), and recent spatially distributed models (Daly et al. 2000; Marks et al. 1999; Williams and Tarboton 1999) use elevation as an important defining characteristic for each grid cell. However, measurements at high elevations are scarce,

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and parameter changes with elevation are often estimated, which can cause errors. For example, temperature lapse rates are usually prescribed as constants, but examination of observed surface temperatures indicates that they differ diurnally, synoptically, and seasonally and do not always increase linearly with elevation. Singh (1991) found that changes of $1^{\circ}\text{C km}^{-1}$ in the lapse rate for the Beas watershed (345 km², spanning 1900–5400-m elevation) produced variations of 28%–37% in the snowmelt runoff over a 2-month period. McGurk et al. (1993) and Aguado (1990) both found that elevational similarity is more important than horizontal displacement in identifying regions of similar snow conditions in the Sierra Nevada.

Understanding elevational effects becomes increasingly important with the prospect of global warming. Over the next 50 yr, it is estimated that, in response to projected climate warming of 3°C , late-spring snow accumulation in California would be diminished by one-third to one-half (Roos 1987). Models of the California snowpack (Knowles 2000) indicate that middle to lower elevations are most sensitive to warming temperatures and may lose much of their snow cover. With the resulting diminished water supply, coupled with increasing water demands from both humans and endangered species, prediction of daily flow fluctuations will become even more critical for reservoir operations (U.S. Bureau of Reclamation 2000). Hence, a more thorough examination of how snowmelt occurs across elevation zones is needed.

The present study was inspired by results from an intensive field study in Yosemite National Park in 2002. Surprisingly, the observations of 2002 indicate that the onset of spring snowmelt was virtually independent of elevation. In light of these field observations, historical datasets were assembled and examined to determine how the onset of spring varied at different snow pillows and river basins and how frequently synchronous springs, such as 2002, occur. Finally, the synoptic and climatic conditions in the California region that support synchronous, elevation-independent onsets of spring melt were compared with those in nonsynchronous, elevation-dependent years.

2. Data

a. Snow pillows

The CA DWR manages a network of automatic snow-monitoring stations throughout the Sierra Nevada. These snow pillows measure the weight of the snow accumulation and thereby indicate the snow water equivalent (SWE) height of the snow column. The CA DWR snow pillows report information at hourly intervals, but because pillows can experience several hours of delay in responding to changes in SWE (Beaumont 1965; Trabant and Clagett 1990), the daily averages are used here. Most changes in SWE represent snow accumulation or

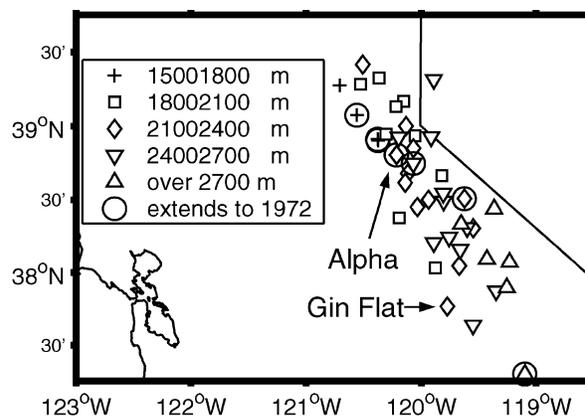


FIG. 1. Snow pillows used in this study. The circled sites are used to extend the record back to 1972. Reference sites are identified with an arrow.

melting. For the present study, 47 stations in the central Sierra, spanning elevations from 1500 m (5100 ft) to 3400 m (11 000 ft), are employed (map, Fig. 1), providing data from 1992 to 2002. A subset of six snow pillows at a range of elevations from 1500 to 2800 m (circled stations, Fig. 1) provide data for a longer period. These stations are chosen because they are representative of stations at similar elevations (all correlate with mean SWE at similar elevations at correlation coefficients greater than 92% during the 1992–2002 period) and have a reliable daily record dating back to 1972, the year the first snow pillows were used in California. Pascoes, at 2800 m, lies in the southern Sierra but is included because it is in the highest elevation band and has recorded SWE variations, which are highly correlated with those of other stations above 2700 m, since 1972. Gin Flat, at an elevation of 2149 m (7050 ft) in the Merced River watershed in Yosemite National Park, is employed as a reference station for the 1992–2002 dataset. Alpha, at 2320 m (7600 ft), in the American River drainage basin, is employed as a reference for the 1972–91 dataset (marked, Fig. 1). The reference stations are chosen for their data reliability and representativeness in defining a date of snowmelt initiation each spring.

Most snow pillows are located in flat meadows, with surrounding forested areas that shelter the pillow from wind scouring (Farnes 1967). Compared to nearby forested areas, these sites tend to accumulate more snow and are also more exposed to sunlight during the melt season. Very shallow snow on slopes and wind-scoured peaks is likely to melt earlier than snow at a nearby pillow, while deep snowdrifts at the base of a north-facing cirque are likely to melt later. While snow pillows do not record the full range of snow properties due to varying slope, aspect, and vegetative cover, they provide the most comprehensive set of high-elevation measurements available.

TABLE 1. Stream gauge records.*

Station name*	Start of record	Gauge elev (m)	Area (km ²)	Basin elev (m)
W. Walker	Oct 1938	2009	469	2660
W. Walker	Oct 1915	1682	647	2510
E. F. Carson	Oct 1960	1646	715	2440
W. F. Carson	Oct 1915	1754	169	2450
S. F. Kern	Oct 1915	884	1373	1890
S. F. Tuolumne	Oct 1923	853	225	1580
M. Tuolumne	Oct 1916	853	190	1700
N. F. American	Oct 1941	218	886	1190
Duncan Canyon	Oct 1960	1606	26	1830
Merced	Oct 1915	1224	470	2740
Bear Creek	Jan 1991	2245	135	2740
Emerald Lake	Jan 1990	2800	1.2	2900

* W. = West, E. F. = East Fork, W. F. = West Fork, S. F. = South Fork, M. = Middle Fork

b. Streamflow

1) HISTORIC STREAMFLOW

Mean daily discharge measurements are examined for 12 gauges on unimpaired (without dams or diversions) rivers from the central and southern Sierra Nevada. Eleven of these streams are from the U.S. Geological Survey (USGS) hydroclimatic dataset (Slack and Landwehr 1992), and the twelfth, of the drainage from Emerald Lake in Sequoia National Park, is from the University of California, Santa Barbara research program (Tonnessen 1991; Melack et al. 1998). Eight of the twelve rivers drain the western slope of the Sierra Nevada, and four drain the eastern slope. Each of these rivers contains different contributing areas and elevations (Table 1), properties used to interpret differences in the yearly timing of spring melt. Generally, streams in the Sierra Nevada have not been gauged at higher elevations, so the USGS dataset alone is not able to identify the timing of melt at the highest reaches of the Sierra. Special research studies, such as that at Emerald Lake and that in Yosemite National Park (detailed below) provide information at higher altitudes.

Several studies (Peterson et al. 2000; Cayan et al. 2001) have shown that variations in the flow of the Merced River at Happy Isles are representative of those of basins throughout the western United States and that the spring rise in Merced streamflow is a useful indicator of the onset of spring across the region. The Merced River gauge has a long daily record (1916–present) of natural flows and is used as a reference station in this study.

2) 2002 STREAMFLOW

In summer 2001, 20 stream pressure sensors (Solinst Leveloggers; <http://www.solinst.com>) recording hourly water level and temperature were installed in the upper reaches of the Merced and Tuolumne Rivers (Fig. 2). This system of streams drains the high country of Yo-

semita National Park, which lies along the western slope of the southern Sierra Nevada. The watersheds contain a range of snowmelt-contributing elevations from 1200 to 3700 m. Sensor locations were selected to cover a variety of topographic characteristics to provide information about how and when different subbasins contribute to the river's flow. The monitored streams included drainages that are primarily north-facing slopes and some that are primarily south-facing slopes. Subbasin areas along the Tuolumne River ranged from 6 to 775 km²; gauge elevations ranged from 1200 m (3800 ft) at Hetch Hetchy to 2900 m (9600 ft) at Gaylor Creek. Subbasin areas along the Merced River ranged from 13 to 887 km²; gauge elevations ranged from 1040 m (3400 ft) at Pohono Bridge to 2500 m (8300 ft) on the Merced Peak Fork. Estimated 1 April solar radiation [using TOPORAD (Dozier and Frew 1990), which incorporates terrain shading in computing the spatial distribution of solar radiation over a grid of elevations], averaged over daytime hours, varied from 552 W m⁻² in Budd Creek basin to 635 W m⁻² in Gaylor Creek basin. In summer 2002, discharge measurements [using standard current meter techniques (Rantz 1982)] were made at each station to establish rating curves in order to calculate discharge rates from water levels. Because discharge measurements were limited (three to six for each site, at different levels of flow), reported discharge magnitudes are only estimates. However, the timing of the spring snowmelt pulse is the primary interest here and is unmistakable in both the raw water-level data and the approximated discharge curves.

c. Air temperature

Long-term measurements (1916–2000) of daily maximum and minimum air temperatures at the National Park Headquarters in Yosemite Valley, at an elevation of 1200 m, were obtained from the Western Regional Climate Center (<http://www.wrcc.dri.edu/>). Daily maximum and minimum air temperatures at nearby Hetch Hetchy Reservoir, also at an elevation of about 1200 m, were used to fill in observations on dates when data are missing from Yosemite Valley. Because temperature variations are due to large-scale synoptic patterns and are highly correlated across California (Cayan et al. 1993; Cayan 1996), Yosemite Valley temperature changes are a good indication of temperature changes across the Sierra Nevada.

For 2002, hourly air temperature measurements from the 47 snow pillows described above were used to examine elevational differences in temperature throughout the melt season. Daily mean temperature, T_{mean} , is the average of the 24 hourly observations. Anomalous temperature fluctuations at these 47 stations were all highly correlated ($R > 90\%$) with temperature changes in Yosemite Valley, supporting the use of Yosemite Valley temperatures as a long-term index.

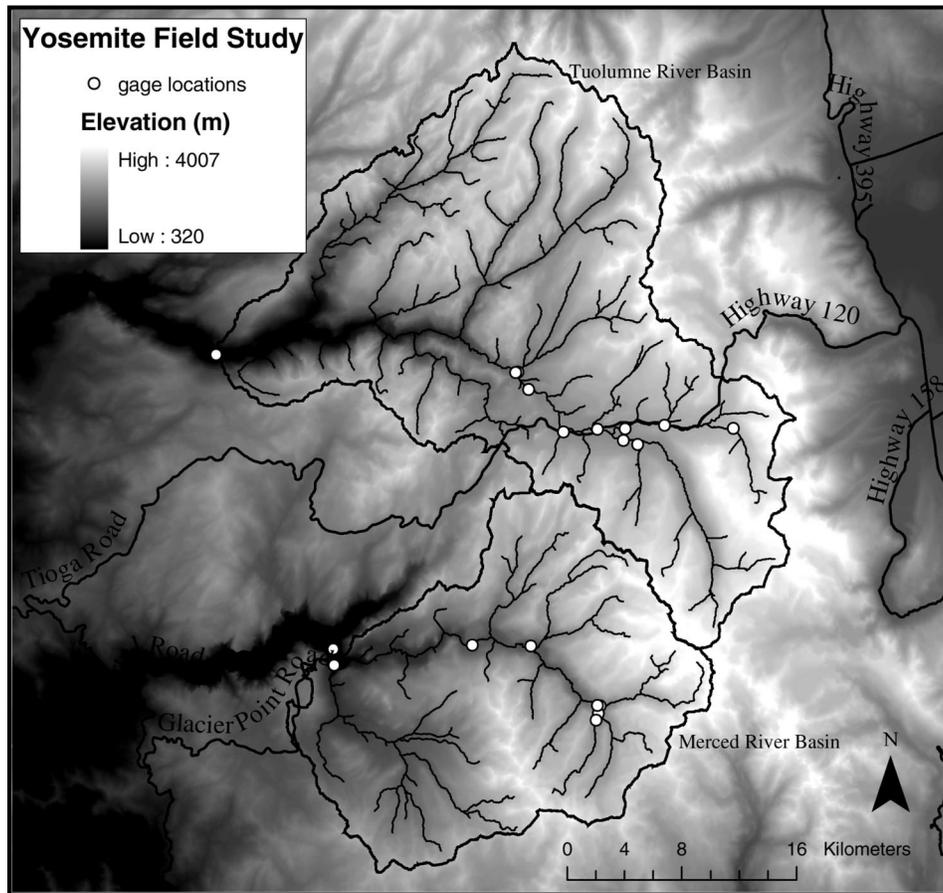


FIG. 2. Water pressure sensor locations in Yosemite National Park during spring 2002.

d. Precipitation

Daily precipitation (1916–2000) was provided by measurements at Yosemite Valley and Hetch Hetchy Reservoir (described in section 2c).

e. Upper-air measurements

Gridded upper-air analyses (temperature and height) for the Northern Hemisphere were obtained from National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) re-analysis data (Kalnay et al. 1996). Data employed were from 1948 to 2002. Older data are not available.

3. Methods: Measuring spring onset and synchronicity

Spring onset is determined using three separate measures: snowmelt at the snow pillows, streamflow from a network of Sierra Nevada rivers, and temperature change in Yosemite Valley. All three of these measures must meet the established criteria (detailed below) for a year to be classified as synchronous.

a. Snow pillows

For snow pillows, the onset of spring is identified as the day of maximum SWE because more melt than accumulation occurs thereafter. In years having multiple days of maximum SWE, the onset of spring is taken to be the latest day of maximum SWE that year. The first measure of synchronicity is based upon snowmelt at the set of 47 selected snow pillows. If more than 70% (33) of the snow pillows report maximum SWE occurring within ± 5 days of that of the reference station (Gin Flat, for 1992–2000, and Alpha, for 1972–91), the year meets the first criteria for synchronicity. In years failing to meet this criteria, less than 50% of the snow pillows begin spring melt within the same 10-day period.

b. Streamflow

Two methods are used to determine when discharge in snow-fed streams starts rising each spring. The first (Cayan et al. 2001), called the cumulative-departure method, identifies the day when the cumulative departure from that year's mean flow is most negative, which is equivalent to finding the day of the year when the

magnitude of flows shifts from less than average to greater than average. This algorithm is effective in avoiding early minor spring pulses and in identifying the rise of the bulk of the discharge, but the day that it identifies is often several days later than the initial temperature and river rise, which are apparent from inspection. This method does not perform well for rivers receiving significant contributions of runoff from winter rains in addition to spring snowmelt.

The second technique, called the inflection-point rise method, was developed for this study to more precisely determine the day when melt begins, that is, the inflection point on the discharge graph rather than the rise of the largest bulk spring flow. When spring snowmelt begins, discharge typically changes from a nearly flat or descending hydrograph to a rapid, continuous rise. The inflection point at this transition is identified by the following procedure: 1) normalize discharge by basin area to measure flow in mm h^{-1} and calculate slope ($\text{mm h}^{-1} \text{ day}^{-1}$); 2) require that the slope of the hydrograph passes from $<0.001 \text{ mm h}^{-1} \text{ day}^{-1}$ to $>0.001 \text{ mm h}^{-1} \text{ day}^{-1}$, thus ensuring a definite flow increase and not just a slight inflection, which can often be found in winter; 3) require that the 5 days following the onset have a positive slope, to ensure that the river continues rising and to eliminate the possibility of selecting spikes in discharge; and 4) require that the onset day falls between 1 March and 30 May, to be in a reasonable range for spring. In years with multiple inflection points meeting the above criteria, the discharge level at the time of the inflection is used to determine whether this is a transition between winter and spring or just a midseason fluctuation. If the flow drops below half of the mean flow (measured between 1 March and 19 July) following the first inflection point, winter has returned, and the second inflection point counts as the “real” spring onset. In cases with several spring storms, which often add substantially to the snowpack, this process can be repeated to select the third inflection point. If the discharge remains above half of the mean flow, winter has not returned. Later inflection points are considered to be spring fluctuations, and the first inflection point is selected. The onset date identified by this method corresponds very well with dramatic spring temperature rises and the day that snow pillows start melting. It performs well for rivers with mixed runoff regimes arising from both winter rains and spring snowmelt. However, it is not as effective in years with many small rises and flows associated with spring storms. Figure 3 compares the onset of spring measured by the two different methods.

To take advantage of the strengths of both methods, a hybrid approach is adopted. The cumulative-departure and inflection methods are combined so that the inflection point most immediately preceding the cumulative-departure date is chosen as the onset of spring. In cases where the cumulative-departure date is earlier than the inflection date (because of the strong influence of winter

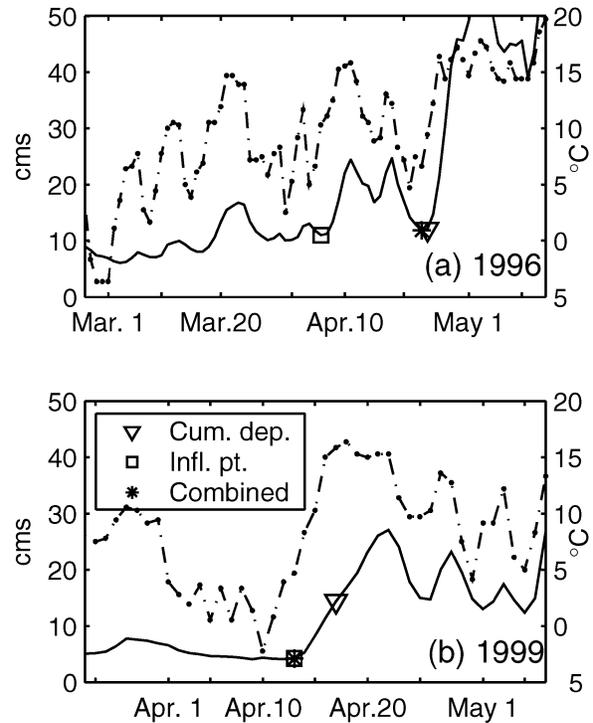


FIG. 3. In some years, such as (a) 1996, multiple small stream rises make the onset date difficult to determine. In other years, such as (b) 1999, the onset of spring is clear by any method, with an accuracy of a few days. The solid line, left axis, is Merced River discharge at Happy Isles. The dashed line, right axis, is mean daily temperature in Yosemite Valley.

rains), the inflection-point rise method is used alone. The date identified by this hybrid method consistently agrees with that chosen by inspection of each individual hydrograph, usually to within ± 2 days. Greater accuracy is achieved in years with a steep and abrupt rise in discharge.

One aspect of the degree of synchronicity is determined by considering the relative time of onset of spring discharge in the Sierra streams (Table 1), with the Merced River at Happy Isles used as a reference station. When more than 70% of the streams rise within ± 5 days of the Merced River onset day, the year meets the second criteria for synchronicity. There is more certainty in the identification of synchronous springs in recent years (1942–2002) because more discharge measurements are available (Table 1).

c. Temperature

Examination of temperature and SWE changes at snow pillows throughout the Sierra shows that the transition from snow accumulation to snowmelt occurs when the daily mean temperature (T_{mean}) rises above 1°C (N. Knowles 2003, personal communication). This threshold is consistent with the U.S. Army Corps of Engineers' (1956) temperature index method for deter-

mining snowmelt, which predicts melt at forested sites once T_{mean} is greater than 0°C . It is also consistent with Singh and Singh's (2002) prescription of the temperatures at which precipitation is a mixture of rain and snow ($0^{\circ} \leq T_{\text{mean}} \leq 2^{\circ}\text{C}$). The present study uses the 1°C temperature threshold as an indication of the timing of spring melt. When T_{mean} is greater than 1°C for several consecutive days, spring melt is considered to have begun.

Daily temperatures at Yosemite Valley and Hetch Hetchy are used to measure the temperature range spanned in the 10 days surrounding the spring pulse day as identified by the snow pillow reference station. In years prior to snow pillow measurements, the streamflow reference station is used. As a third criterion of synchronicity, a synchronous year is defined as one in which temperatures rise from so cool that there is no melt at elevations as low as 1500 m (5000 ft), the lowest elevation of snow pillows, to so warm that melt occurs at elevations as high as 3400 m (11 000 ft), the highest elevation of snow pillows, in less than 10 days' time. The reference station employed here is Yosemite Valley, whose 1200-m elevation lies 300 m below the lower and 2200 m below the upper boundaries of the range considered here. Assuming a $6.5^{\circ}\text{C km}^{-1}$ standard atmospheric lapse rate, these criteria require the temperature at Yosemite Valley to warm from $<3^{\circ}$ to $>15^{\circ}\text{C}$ in order to produce a warming from implied temperatures $<1^{\circ}\text{C}$ at the lowest snow pillows to subsequent temperatures $>1^{\circ}\text{C}$ at the highest snow pillows. Relaxing the criteria to limit melt to elevations below 3000 m (10 000 ft) requires a smaller warming of Yosemite Valley temperatures, as little as 10°C (raising temperatures from 3° to 13°C). If the temperature lapse rate is more gradual than $6^{\circ}\text{C km}^{-1}$, a smaller temperature change at Yosemite Valley is required to raise temperatures above the 1°C melting threshold at higher elevations. When a temperature change exceeding 12°C occurs within ± 5 days of the reference spring pulse day, the year meets the third, and final, criteria for synchronicity.

d. Combined snowmelt, streamflow onset, and temperature determine synchronicity

Hence, a synchronous spring is identified by three criteria. Over 70% of snow pillows must record maximum SWE and melt within the same 10-day period. Within this period, over 70% of the gauged streams must begin rising, and the Yosemite Valley temperature must increase over 12°C . In years when all three of these situations occur, snowmelt initiation is considered to be independent of elevation.

4. Spring 2002 results: A synchronous spring

Measurements from spring 2002 provide insights into how snowmelt and spring runoff began at different altitudes in the Sierra. In contrast with most years, the

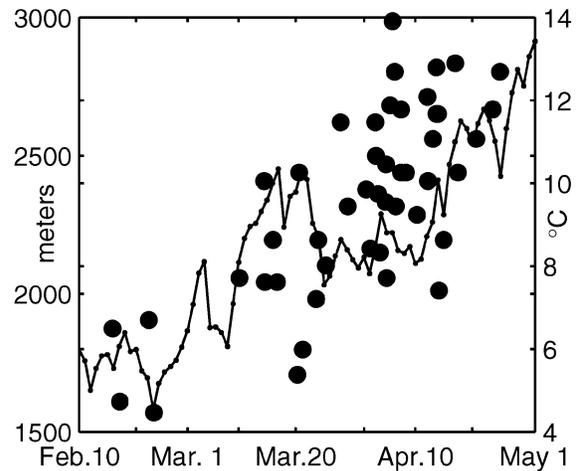


FIG. 4. Mean daily temperatures at Yosemite Valley and Hetch Hetchy (line, right axis) from 1916 to 2000 show that, on average, temperatures increase through the spring. Average day of maximum snow accumulation at snow pillows covering a range of elevations (circles, left axis) from 1992 to 2002 shows that higher elevations begin melting later in the season, on average.

2002 spring onset was quite abrupt and encompassed the entire range of elevations where observations were available. Averaged over 85 yr (1916–2000), Yosemite Valley temperatures (Fig. 4, right axis) increase through the spring. Because temperatures decrease with increasing elevation, the average day of maximum snow accumulation and snowmelt initiation, calculated from the 1992–2002 dataset (Fig. 4, dots, left axis), is later in the season for higher-elevation snow pillow stations. However, the snowmelt distribution in a given year, as exemplified by spring 2002, can differ widely from average conditions.

a. Tuolumne meadows subbasins

In spring 2002, water pressure sensors (map, Fig. 2) measured the onset of spring runoff in 10 different subbasins of the Tuolumne River in Yosemite National Park. Until late March, each of the monitored streams was in its winter dormant state of low or no streamflow. Despite differences in elevation, aspect, and potential solar radiation (detailed in section 2b), all gauges exhibited their initial streamflow rise between 26 and 30 March (Fig. 5a).

b. Upper Merced subbasins

Water pressure sensors (map, Fig. 2) measured the onset of spring 2002 runoff in several different subbasins of the Merced River. As in the Tuolumne River subbasins, the streamflow at each of the Merced subbasins rose between 26 and 30 March. Discharge calibration data, available for six of the Merced sites, illustrate the uniform nature of spring 2002 runoff (Fig. 5b). The date of rise at each stream was calculated using

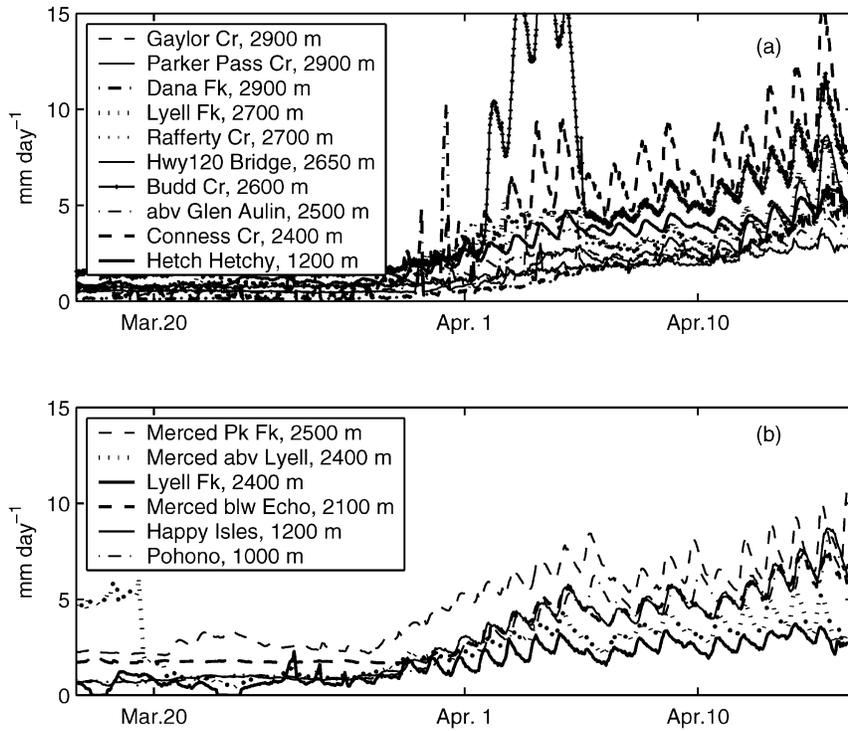


FIG. 5. (a) Approximate discharge, normalized by basin area, for 10 instrumented subbasins of the Tuolumne River in Yosemite National Park in spring 2002. (b) Approximate discharge, normalized by basin area, for six subbasins of the Merced River in Yosemite National Park. In spite of differences in aspect and elevation, spring discharge began in all basins between 26 and 30 Mar 2002.

the hybrid algorithm (described in section 3b). The inflection point occurred at most of the gauges on 26 March, with the latest gauges, Gaylor Creek and Parker Pass Creek, each at 2900 m, lagging only 4 days behind (Fig. 6). Given the uncertainty of ± 2 days in the algorithm, the 4-day spread in rise dates is small, meeting

the streamflow criterion for a synchronous onset of spring. All 16 (100%) of the monitored streams in the Tuolumne and Merced subbasins, as well as all of the historic rivers (Table 1), rose within ± 5 days of the Merced River at Happy Isles.

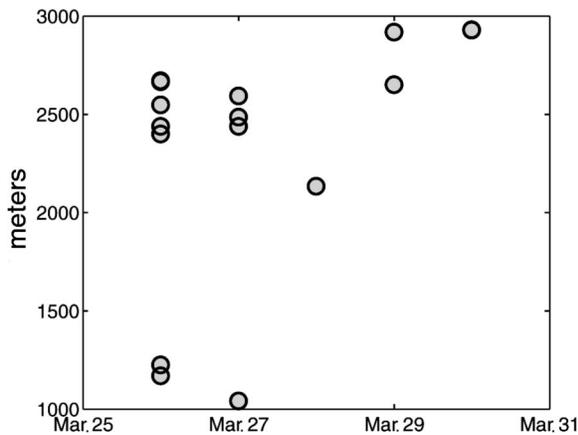


FIG. 6. The onset day (circles) when streamflow began rising was 26 or 27 Mar at most gauges in the Merced and Tuolumne River basins. The highest gauges, monitoring Gaylor Creek and Parker Pass Creek at 2900 m, began rising on 30 Mar, only 4 days later.

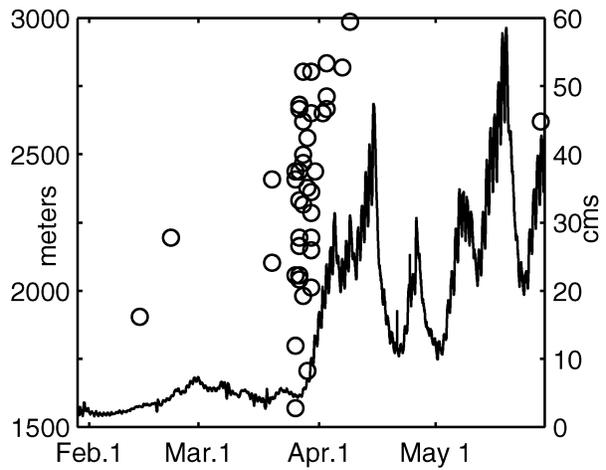


FIG. 7. Nearly all of 47 snow pillows throughout the central Sierra (circles, elevation on left axis) recorded snowmelt initiation in spring 2002 starting during the same 5-day period the streams rose, shown by the Merced River at Happy Isles (solid line, right axis).

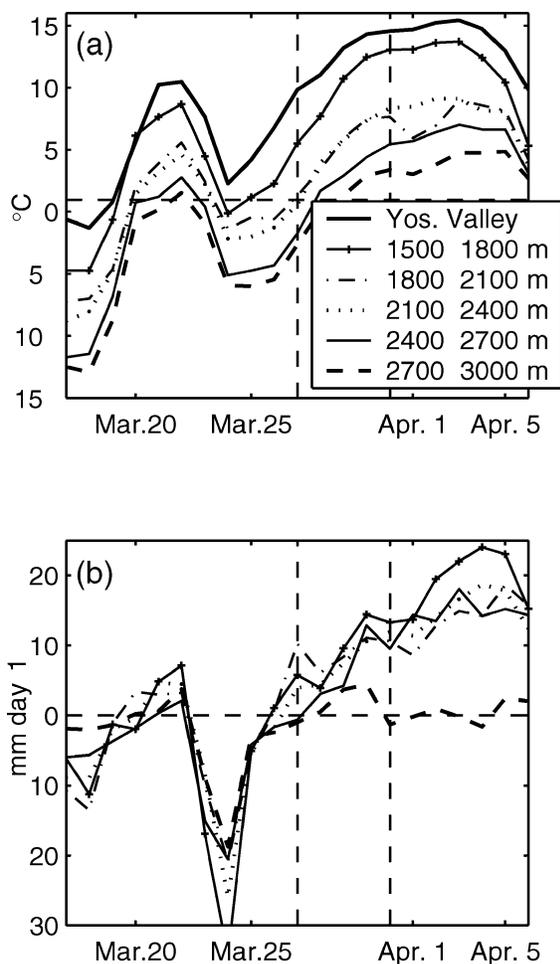


FIG. 8. (a) Average temperatures and (b) snowmelt rates by elevation for snow pillows in the central Sierra in spring 2002. Negative melt indicates a snow gain.

c. Snow pillows

In spring 2002, the date of maximum snow accumulation and initiation of spring melt at most of 47 central Sierra snow pillows (discussed in sections 2a and 3a) occurred between 26 and 30 March (Fig. 7), coinciding with the 5-day period when the Tuolumne and Merced Rivers began to rise. Eighty-eight percent of the snow pillows recorded melt initiation within ± 5 days of the date of maximum SWE at Gin Flat, satisfying the snowmelt requirement for a synchronous spring.

d. Temperature

Using temperature measurements at the 47 snow pillow stations during the spring 2002 period, mean temperature and melt rates were calculated in five elevation bands. Two large increases in temperature preceded spring snowmelt (Fig. 8a). The first was immediately followed by a drop in temperature and an increase in

SWE. After the first temperature rise, a small amount of melting occurred at all elevations (Fig. 8b), but this was quickly offset by the snow accumulation after 21 March. (Storms adding snow to the pack are indicated by negative melt in Fig. 8b). The second temperature rise increased mean daily temperatures from 0° to 14°C in the lowest (1500–1800 m) elevation band and from -6° to 5°C in the highest (2700–3000 m) elevation band in a period of 10 days. The period when streamflow increased rapidly in the Merced and Tuolumne Rivers, 26 to 30 March, is marked by vertical dashed lines. During this time, mean temperatures exceeded 1°C (horizontal dashed line, Fig. 9a) at all elevations, and mean snowmelt rose above 10 mm day^{-1} at most elevations. The highest elevation band did not show much melt during this time period. However, the highest band contains only three snow pillows, and because streams gauged at 2900 m rose significantly on 30 March, it seems likely that these snow pillows underrepresented the actual melt occurring above 2700 m at this time. Yosemite Valley temperatures rose from 2° to just over 15°C (Fig. 9a), while mean temperatures rose above 1°C in all elevation bands. This meets the temperature criteria for a synchronous spring (as described in section 3c). Together, the temperature rises, snowmelt rates, and streamflow rises all occurred between 26 and 30 March, exhibiting a marked degree of simultaneity and indicating that the spring 2002 onset was synchronous.

5. Historical context: How common are synchronous springs?

The rapid and simultaneous initiation of snowmelt and runoff at all elevations in 2002 demonstrates that the elevational makeup of the onset of spring can differ greatly from average conditions. How common are elevation-independent synchronous springs compared to gradual ones, which depend on elevation? Because the in-depth Tuolumne and Merced subbasin network was not operational until summer of 2001, other measurements must be used to place spring 2002 in context.

a. 1992–2002: Snow pillows across California define synchronicity

With 47 independent site measurements of snowmelt, snow pillows provide the most comprehensive measure of spring onset over a broad range of elevations, and hence, the most sensitive measure of the degree of synchronicity. Comparing the streamflow and air temperature responses with the snow pillow response during the 11 yr from 1992 to 2002 provides a reference for spring onset behavior in prior years, when fewer measurements are available.

Using the requirement that at least 70% of snow pillows must begin melting within ± 5 days of the Gin Flat reference station, 4 of the 11 yr (36%) qualify as synchronous. In the other 7 yr, lower elevation stations

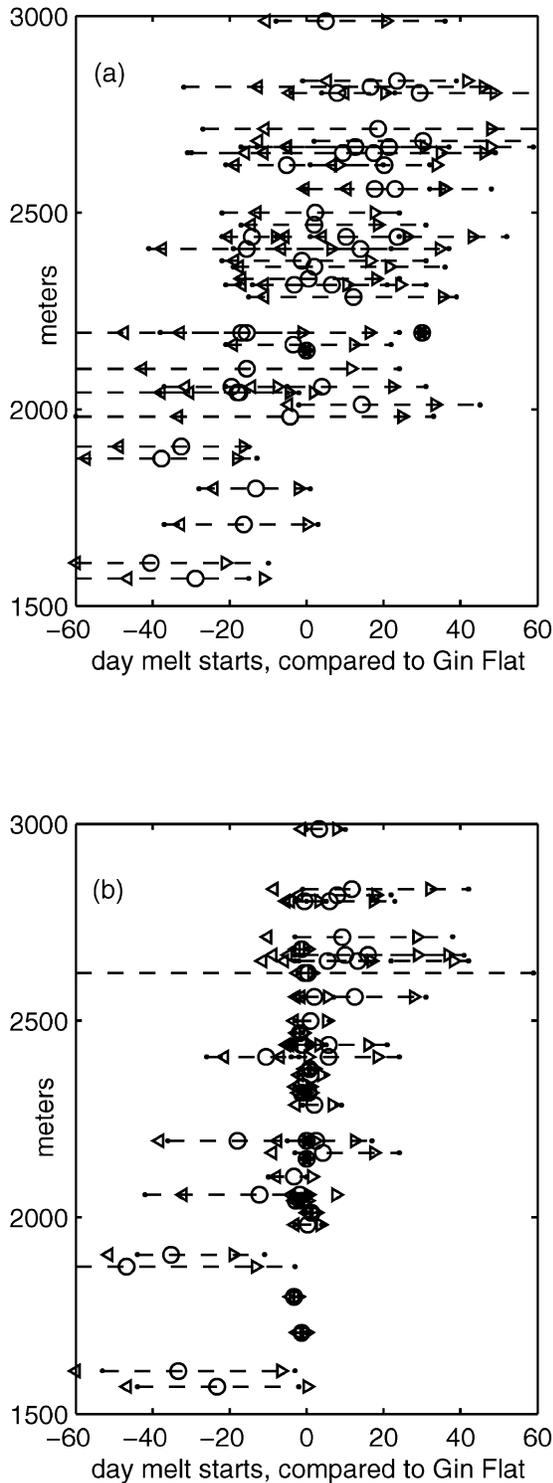


FIG. 9. (a) In nonsynchronous years, the average (circle) day of year melt starts relative to Gin Flat is earlier for lower and later for higher elevations. (b) In synchronous years, the average (circle) day of year melt starts relative to Gin Flat is independent of elevation at most stations. Triangles show 1 std dev, and dots show extremes for each station.

begin melting first (Fig. 9a), but there is a large range of scatter. In contrast, melt initiation in synchronous years (Fig. 9b) is uniform at all but a few stations. Averaging Yosemite Valley temperatures centered on the Gin Flat reference melt day reveals that the average temperature jump in snow-pillow-defined synchronous years (Fig. 10b) is larger than in nonsynchronous (Fig. 10a) years. The average jump in synchronous years is 10°C , compared with 6°C for nonsynchronous years. In addition, rivers at various elevations rise more uniformly in synchronous years (Figs. 10c and 10d).

b. Combined temperature and streamflow: Extending back to 1916

Yosemite Valley temperature and discharge of the Merced River and other Sierra streams have been measured since 1916, and many snow pillows have been operational since 1972. Without a network of snow pillows to provide a definitive estimate of the spring onset and the extent of synchronous melt, streamflow and temperature records are used together to indicate a synchronous year. Hence, the streamflow and temperature cutoffs are used together. For a year to be classified as synchronous, over 70% of the rivers must rise within ± 5 days of the Merced River's rise, and the temperature increase within that 10-day span of time must be at least 12°C . These criteria are stricter than those for snow pillows alone, which showed a typical temperature increase of only 10°C for a synchronous year, because the available data are less comprehensive. Figure 11 illustrates the years selected by these criteria, as well as the values for surrounding years. The fraction of snow pillows melting within ± 5 days of the reference is also marked for the years when data are available. Of the 4 yr identified as synchronous by the 47 snow pillows, only 2, 1999 and 2002, qualify as synchronous by the combined criteria. Several years have either a large temperature rise or several rivers rising together, but only a few years have both, revealing how rarely the conditions that characterized 2002 have occurred during the past century.

For any one measure (snow pillows, streamflow, or temperature), about 40% of the years within the 1916–2002 period satisfy the criteria for a synchronous onset (dashed lines, Fig. 11). However, only 8 yr (9%), qualify as synchronous using the combined criteria. If the combined criteria are relaxed (requiring only 60% of snow pillows to melt, 60% of streams to rise, and a 10°C temperature jump), 17 yr (22%) would qualify.

6. Climatic and synoptic forcing

The analyses above demonstrate that a large temperature rise from a relatively cool period results in widespread, synchronous melt across a range of elevations. However, it is of interest to determine, from a broader-scale perspective, which atmospheric or oceanic patterns

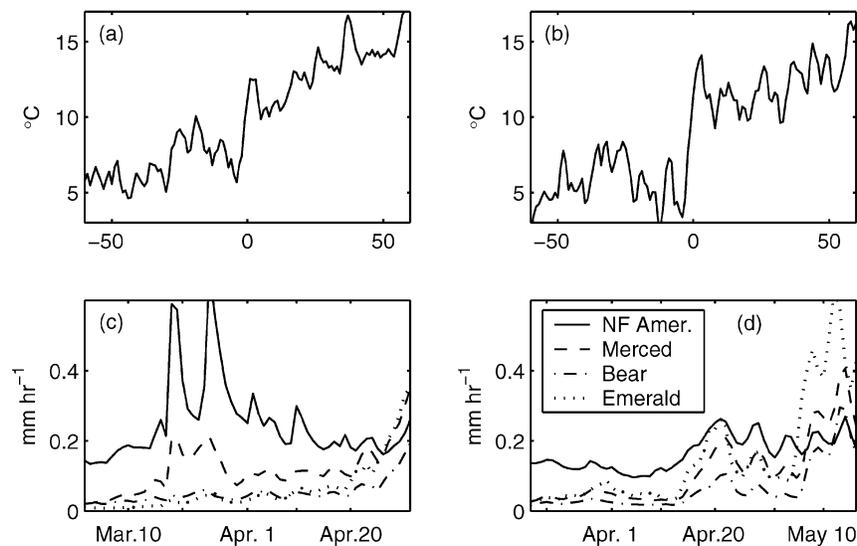


FIG. 10. Using the snow pillow records from 1992 to 2002 to determine synchronicity, the average temperature jump for (a) nonsynchronous years (1992–97, 2001) is 6°C. For (b) synchronous years (1998–2000, 2002), the average temperature jump is 10°C. In (c) 1993, a nonsynchronous year, lower-elevation rivers (American and Merced) start rising a month before higher-elevation streams (Bear and Emerald), while in (d) 1999, a synchronous year, rivers at all elevations start rising together.

cause a synchronous year. Scrutiny of the synchronous years identified in Fig. 11 indicates that there is not a consistent pattern for them to be anomalously wet or dry years, nor do these spring onset times occur consistently early or late. Correlation analysis indicates that the degree of synchronicity is not linked reliably to El Niño, the Pacific Decadal oscillation, or other well-known atmospheric indices. However, there appear to be distinct temperature anomalies that occur during the months leading up to synchronous springs. There is also a clear synoptic pattern that triggers the melt on the days before and during melt onset. These patterns are consistent between synchronous years and may be helpful for improving streamflow forecasts and snowmelt models.

a. Anomalous monthly temperatures

To examine potential climatic influences, a synchronicity index is established by taking the mean value of all available yearly measurements of synchronicity (illustrated in Fig. 11), including temperature jump as a fraction of 17°C, the fraction of rivers that rise together, and the fraction of snow pillows that record melt together. The fraction of 17°C is used for the temperature rise because this weights the 12°C rise criteria as 70%, the same as the river and snow pillow criteria, giving them each equal weight when averaged. The index has a mean value of 60%, indicating that, on average, over half of monitored Sierra elevations start melting at once. Synchronous years (circled in Fig. 11) have an index value at least 20% greater than the mean, indicating that, in these springs, over 80% of the Sierra melts together.

At the opposite extreme, 6 yr (1937, 1946, 1972, 1979, 1993, and 1995) have an index value at least 20% less than the mean, suggesting less than 40% of the Sierra melts together. In these years lower elevations melt much sooner than higher elevations. The index has a weak correlation ($R = -0.21$, at the 95% confidence interval) with the date of spring onset, such that earlier springs are somewhat more likely to be synchronous. This is likely due to the fact that April and May storms generally bring rain and not snow to elevations below 1900 m.

Although many factors introduce variability in a given year, a climatic pattern emerges for synchronous years. During synchronous years, March mean 850-hPa temperatures along the north coast of California are about 1°C cooler than average (at a 95% confidence interval or above; Fig. 12a), reflecting a fairly broad occurrence of the spring storms discussed above. In contrast, December, January, and February have warmer than average 850-hPa temperatures across California (Fig. 12b). Performing the same analysis on the most nonsynchronous, elevation-dependent years reveals the opposite patterns. March is about 1.5°C warmer than average (at the 99% confidence level) throughout California (Fig. 13a), and winter (December–January–February) over California is about 1°C cooler than average (Fig. 13b). April temperatures (not shown) do not differ significantly between synchronous and nonsynchronous years.

b. Daily weather patterns

The weather patterns surrounding the day of spring onset in synchronous years are remarkably repeatable.

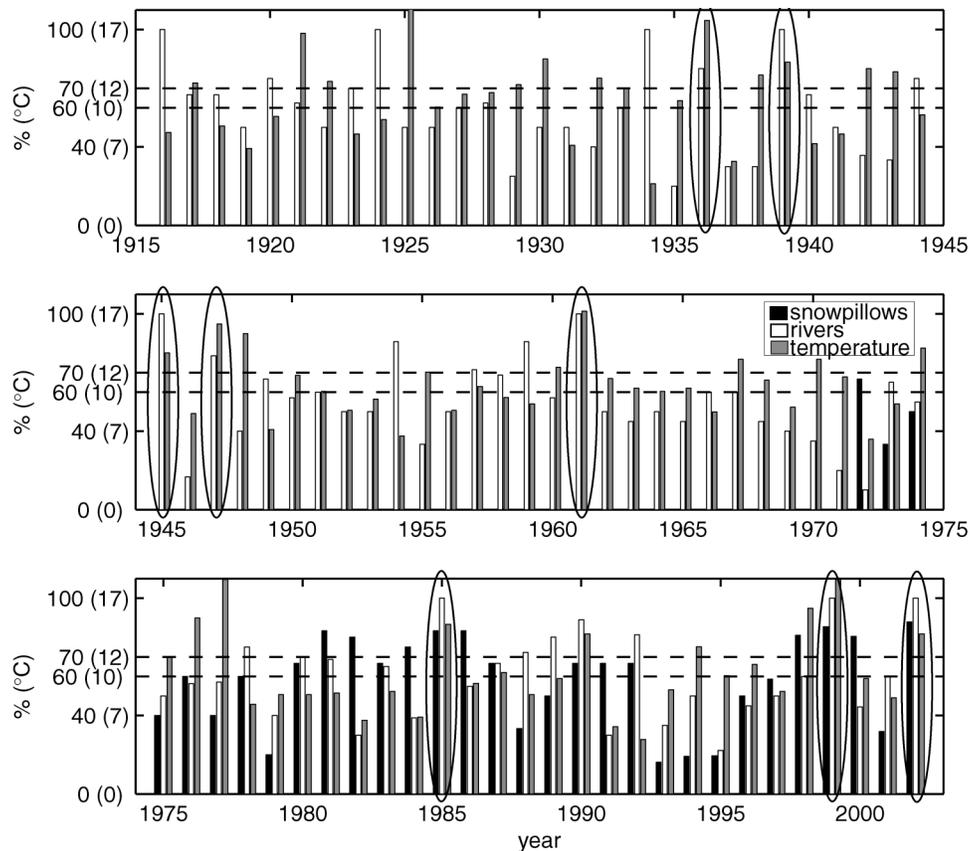


FIG. 11. For each year from 1916 to 2002, the degree of synchronicity is measured by three methods: 1) percent of snow pillows reaching maximum SWE within ± 5 days of the reference station, 2) percent of California rivers rising within ± 5 days of the reference, and 3) the temperature jump ($^{\circ}\text{C}$) that occurs within ± 5 days of the reference. Synchronous years (circles) are identified when all available measures exceed 70% (or 12°C), marked by the upper horizontal dashed line. The lower dashed line indicates a 60% cutoff.

Prior to the melt day, a 700-hPa trough is stationed over the West Coast (Fig. 14a), bringing cool northern air to California (Fig. 14b). On the day melt begins, a ridge develops to the north, and in combination with the trough to the south, forms a high amplitude “backward-S shape” in the upper-level winds (Fig. 14c), which drives northeasterly winds over the Sierras. The wind currents descend and warm the western slopes (Fig. 14d). Following the melt onset day, the ridge replaces the trough (Fig. 14e), and warm air moves in from the southwest (Fig. 14f).

In most (all but 1945) of the identified synchronous years, the spring melt pulse was preceded by both precipitation and minimum temperatures less than 2°C in Yosemite Valley, which is cold enough to bring snow to elevations at 1500 m (5000 ft) or lower. Snow from this late-winter storm then melts simultaneously at both low and high elevations when temperatures warm dramatically. Comparing snow pillow records in both synchronous and nonsynchronous years illustrates the importance of late-winter storms in the accumulation and subsequent melting patterns of the spring snowpack. During synchronous years, the SWE records all have a

clearly defined peak (Fig. 15a), where SWE increases up until the day when melt begins. Thus, at Gin Flat and at snow pillows at higher and lower elevations (not shown), there is a clear division between snow accumulation and melt. In contrast, the Gin Flat SWE records during nonsynchronous years exhibit a broad, flat top (Fig. 15b), revealing a period of several weeks to a month when little SWE is either gained or lost. This waiting period of gradual temperature change allows the snowpack to begin melting more incrementally than in synchronous years. In the absence of strong synoptic forcing, the lapse rate becomes important in causing lower elevations to melt first.

7. Discussion

A new array of streamflow measurements in the high-altitude basins of the Sierra Nevada during spring 2002 has demonstrated that snowmelt and streamflow patterns can differ considerably from expected conditions. While in most years melting begins at different times at different elevations in the Sierra Nevada, spring 2002 was one among only eight springs with remarkably syn-

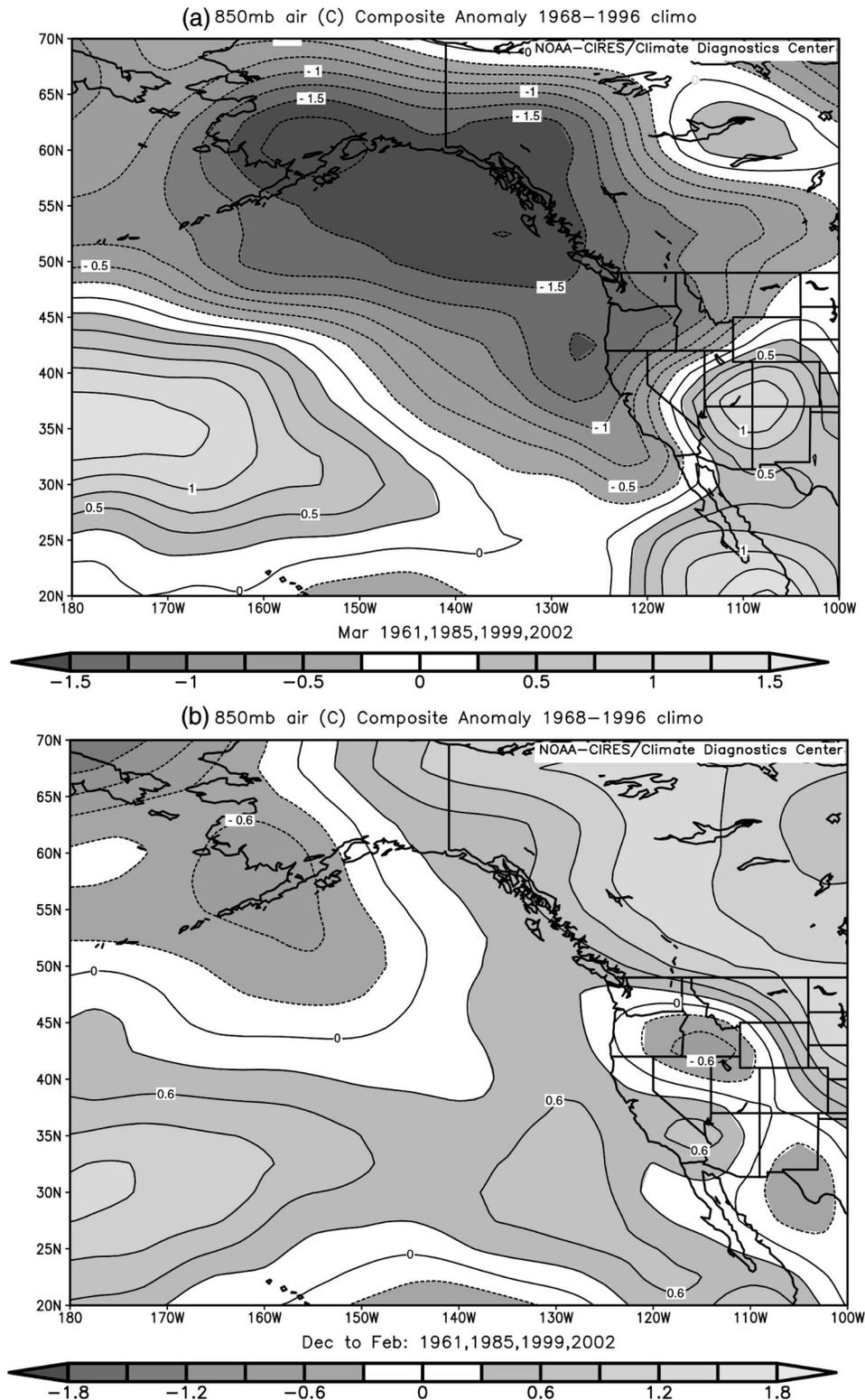


FIG. 12. (a) The 850-hPa air temperatures just offshore of California are about 1°C cooler than average during Mar of synchronous years (years marked by a circle Fig. 11). (b) Dec through Feb 850-hPa air temperatures in California are warmer than usual during synchronous years. (Anomalies greater than 0.8 in magnitude are significant at the 95% confidence level or greater using a two-tailed t test.) Calculations and images from software from the NOAA-CIRES Climate Diagnostics Center, Boulder, CO (<http://www.cdc.noaa.gov/>).

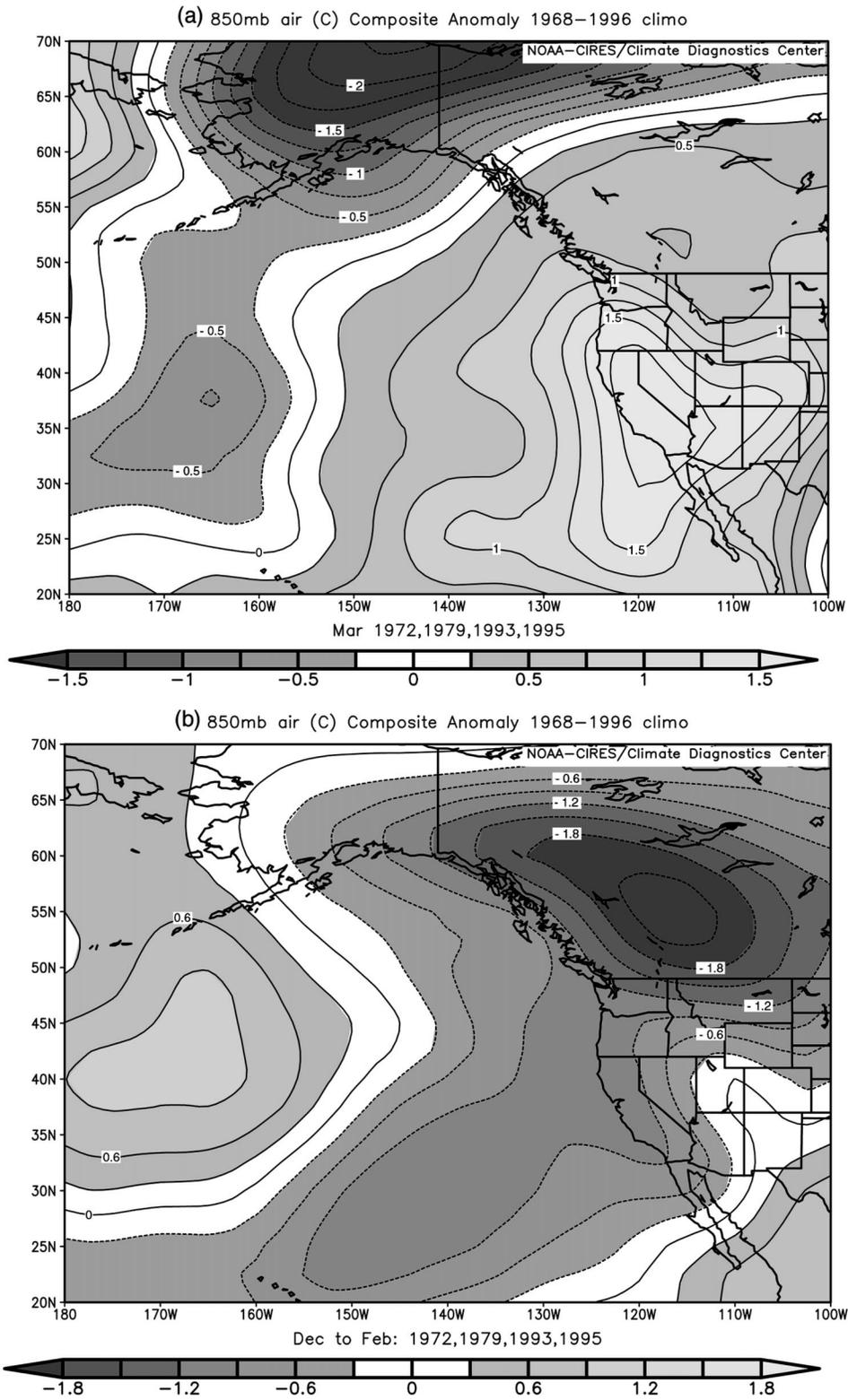


FIG. 13. (a) For extremely nonsynchronous years, Mar is an anomalously warm month in California. (b) In contrast, Dec through Feb are anomalously cold over California. Values over California are significant at the 99% confidence level using a two-tailed t test. Images provided by the NOAA–CIRES Climate Diagnostics Center.

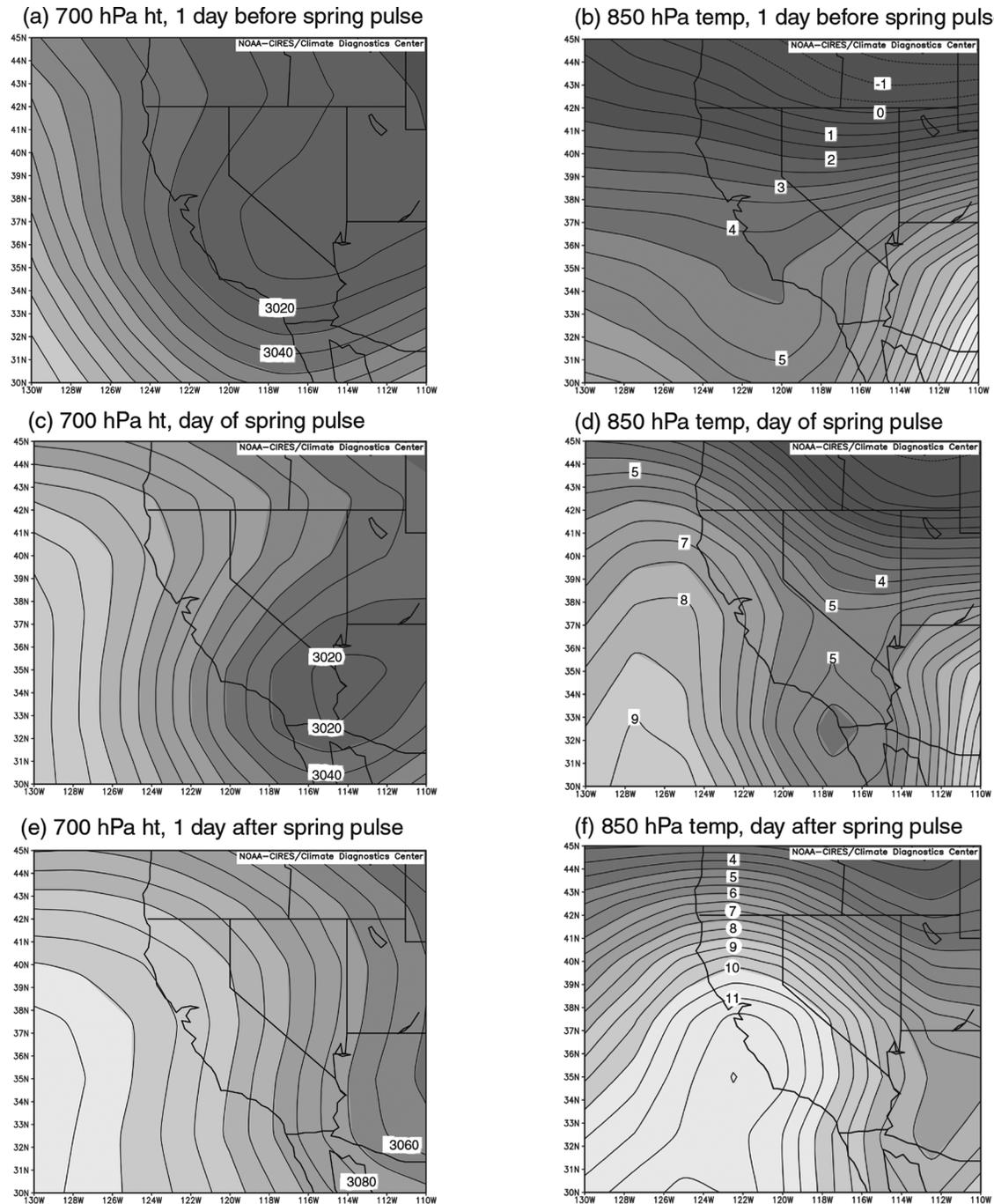


FIG. 14. Composite 700-hPa geopotential height maps (m) and composite 850-hPa temperature maps ($^{\circ}\text{C}$) for (a), (b) the day before, (c), (d) during, and (e), (f) the day after the onset of spring during synchronous years. Images provided by the NOAA-CIRES Climate Diagnostics Center.

chronous snowmelt onsets during the past 87 years. As defined here, for a synchronous year to occur, snow below 1800 m (6000 ft) must last long enough in spring to melt at the same time as higher elevations. For this to happen, March must be anomalously cool, often with late-winter storms adding snow to all elevations. Furthermore, synchronous snowmelt onset cases are trig-

gered by a clear sequence of synoptic events. First, several days in advance of spring onset, a trough sets up over the West Coast, bringing cool air and often storms. Then, on the day of snowmelt onset, the low pressure trough is supplanted by a ridge over the Pacific Northwest, bringing dry, downslope flows and rapidly warming temperatures to the Sierra Nevada.

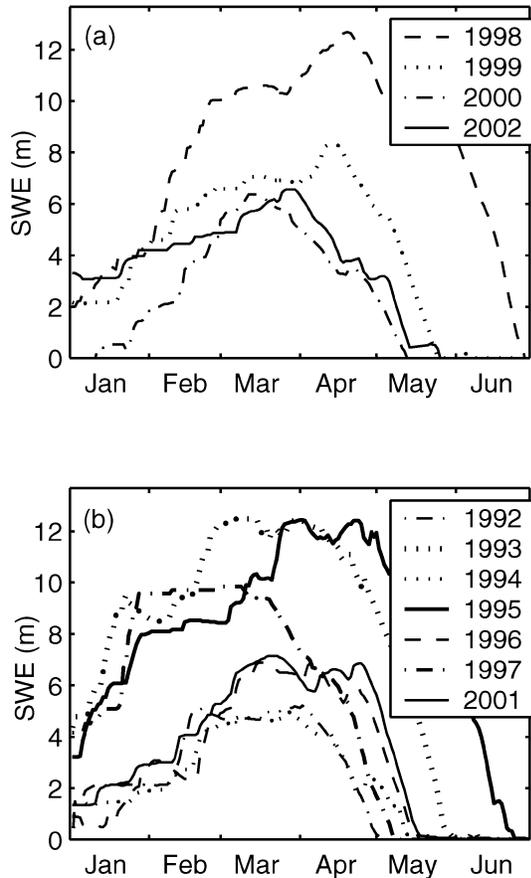


FIG. 15. (a) The SWE curve for synchronous years has a clearly defined peak, marking the transition between winter and spring. (b) In nonsynchronous years, the SWE curve has a flat top, indicating a long transition period between winter snow accumulation and spring snowmelt.

Smith (1974) found that Sierra snowpacks are warm and are often isothermal at 0°C for weeks to months before spring melt, so minimal time is necessary to raise the snowpack temperature prior to melt. Hence, sudden changes in temperature are accompanied by almost immediate snowmelt and rises in streamflow. In the colder Rocky Mountains, snowpack temperatures are often below 0°C and require differing amounts of time to warm before melting begins. An examination of snowpack telemetry (SNOTEL) stations in the Rocky Mountains reveals that snowmelt timing at stations in the Rocky Mountains is much less synchronous than in the Sierra Nevada. However, synchronous melting does occur occasionally, as in 1983, when over 20 SNOTEL stations in Colorado and Wyoming, at elevations ranging from 2100 to 3500 m, began spring melt on the days surrounding 22 May. This anomalously late synchronous onset resulted in unusually heavy runoff, which forecasts underestimated by 30% to 100% (Shafer et al. 1984).

Recent synchronous springs in the Sierra Nevada (1999 and 2002) were not particularly wet years, and

their periods of warm temperatures and rapid melt were cut short by late storms. However, an anomalously wet, late synchronous spring, such as that observed in Colorado in 1983, could cause flooding in the Sierra Nevada. A typical observed melt rate in May in the Sierra Nevada is 4 cm day^{-1} . Should this melt rate occur simultaneously over the entire area of the Merced River basin above Happy Isles (from 1224 to 3600 m), 3 mm h^{-1} of water would rush past the Happy Isles gauge. This would be 50% greater than the 2 mm h^{-1} flows that marked the disastrous flood of 1997. Usually snow at lower elevations has disappeared long before this high melt rate is achieved, so only the highest elevations contribute at this time. However, a synchronous onset in May, with dramatic warming and simultaneous melt at all elevations, could be disastrous.

The observations presented here provide motivation for making more measurements at high altitudes and for using physically based, spatially distributed models, such as that developed by Daly et al. (2000), for operational forecasting. As the climate warms, this motivation will increase. Warmer temperatures will result in closer-to-isothermal Rocky Mountain snowpacks, increasing the likelihood of synchronous spring snowmelt there. Research in the European Alps (Beniston et al. 1994; Beniston and Rebetez 1996) has suggested that higher elevations are warming more dramatically than lower elevations, which will result in a more gradual lapse rate and an increased probability of synchronous snowmelt across elevation zones. Burgeoning populations in California and the West are making water resources all the more precious, and improved snowmelt and streamflow forecast models have an important role to play in managing these water resources most effectively. As the observations presented here demonstrate, enhanced high-altitude monitoring and a better understanding of spatial and temporal patterns of snowmelt are needed to meet these objectives.

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