Seasonal and Spatial Patterns in Diurnal Cycles in Streamflow in the Western United States

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ABSTRACT

The diurnal cycle in streamflow constitutes a significant part of the variability in many rivers in the western United States and can be used to understand some of the dominant processes affecting the water balance of a given river basin. Rivers in which water is added diurnally, as in snowmelt, and rivers in which water is removed diurnally, as in evapotranspiration and infiltration, exhibit substantial differences in the timing, relative magnitude, and shape of their diurnal flow variations. Snowmelt-dominated rivers achieve their highest sustained flow and largest diurnal fluctuations during the spring melt season. These fluctuations are characterized by sharp rises and gradual declines in discharge each day. In large snowmelt-dominated basins, at the end of the melt season, the hour of maximum discharge shifts to later in the day as the snow line retreats to higher elevations. Many evapotranspiration/infiltration-dominated rivers in the western states achieve their highest sustained flows during the winter rainy season but exhibit their strongest diurnal cycles during summer months, when discharge is low, and the diurnal fluctuations compose a large percentage of the total flow. In contrast to snowmelt-dominated rivers, the maximum discharge in evapotranspiration/infiltration-dominated rivers occurs consistently in the morning throughout the summer. In these rivers, diurnal changes are characterized by a gradual rise and sharp decline each day.

1. Introduction

Many government agencies, such as the United States Geological Survey (USGS) and the Swiss National Hydrological and Geological Survey, routinely make hourly measurements of river stage at thousands of stream gauge stations. Regular patterns of diurnal variation are common features of these rivers, many of which are primary water sources for cities, industries, and agriculture. A coarse but informative view of diurnal cycle activity in stream discharge across the continental United States is provided by an analysis of 748 USGS unimpaired, telemetered stream stage records[1] (Slack and Landwehr 1992) during the early summer of water year 2000. Remarkable from this survey (June 2000 diurnal cycles shown in Fig. 1) is the strong presence of distinct diurnal cycles in streams throughout the western United States, which feature both snowmelt and evapotranspiration/infiltration driving mechanisms, as will be developed in the narrative and illustrations of the present study.

Often the diurnal amplitude, measured as half the difference between the daily maximum and minimum

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[1] This datastream, as intercepted by an automated workstation, is noisy, usually having only four unevenly spaced samples per day, but yields a coherent picture of streams with decided diurnal cycles. To detect a diurnal cycle, the data was broken into 10-day segments, and each was fit to a 24-h harmonic. After experimentation, a stream-stage record was identified as having a diurnal cycle when the correlation coefficient between the fitted harmonic and the original data exceeded 0.2. Note that in subsequent treatment of a subset of this data with more complete sampling, a different methodology is used to identify the diurnal cycle.

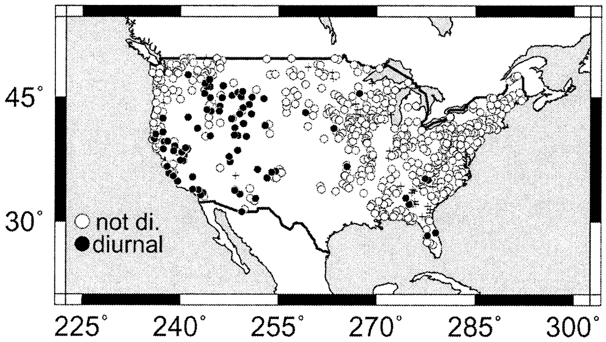


FIG. 1. June 2000 stations with clear diurnal cycles.

discharge, exceeds 10% of the daily mean flow (Fig. 2, Merced River discharge). Because of its widespread occurrence, the diurnal cycle may provide a diagnostic tool in analyzing how climate change affects watersheds. Information from the diurnal cycle will complement point measurements of climate change, such as temperature and precipitation, which are sparse at high altitudes and not always indicative of the watershed as a whole.

In most cases, diurnal cycles in streamflow are ultimately caused by diurnal variations of solar radiation and temperature, which regulate diurnal water additions or losses. Processes identified as producing diurnal streamflow cycles include daily variations in rates of precipitation, evapotranspiration, infiltration, and snowmelt. Although diurnal cycles can also result from water management and are common downstream of hydroelectric dams during the summer, this study focuses on unimpaired rivers. Thus, natural diurnal fluctuations may be used to understand processes contributing to river discharge and to indicate how much water is added or removed each day. Such information might foreshadow flow increases or decreases over longer timescales and could be used in water management decisions.

Although the presence of diurnal cycles in streamflow is well known to practicing hydrologists, previous studies have focused on the diurnal cycle in individual rivers for limited time periods, often only several weeks to several months. Diurnal cycles driven by snowmelt and those caused by evapotranspiration/infiltration have been studied separately, so the two processes have not been compared. This study examines the diurnal cycle in a more comprehensive manner by analyzing a collection of western United States watersheds in terms of their temporal characteristics and seasonal patterns. Several questions not covered in the previous literature are addressed: 1) How prevalent is the diurnal cycle in streamflow? 2) Are there characteristics of the diurnal cycle that can be used to distinguish between snowmelt- and evapotranspiration/infiltration-dominated processes in a river's water balance? 3) Do diurnal characteristics, such as the hour of maximum discharge, shift systematically and predictably over the season?

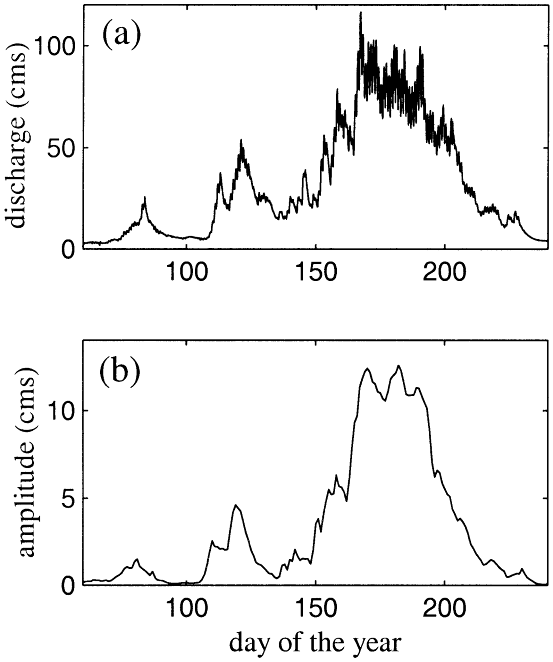


FIG. 2. (a) Hydrograph of Merced River at Happy Isles, Yosemite National Park, CA, in 1998. (b) Amplitude is about 10% of the mean discharge throughout the spring and summer melt season.

2. Mechanisms of diurnal flow cycles

a. Evapotranspiration

Many studies have linked daily fluctuations in river discharge to evapotranspiration, which consists of the sum of evaporation from water bodies, bare soil, and snow cover, and of transpiration from vegetation (Troxell 1936; Wicht 1941; Erup 1982; Seyhan et al. 1983). Illustrations from the studies cited here reveal an asymmetric diurnal cycle in the summer months, with a sharp decay and a gradual rise in the daily streamflow (Bren 1997; Seyhan et al. 1983; Kobayashi et al. 1990), as illustrated by the April and May 1996 hydrograph of the heavily vegetated Temecula Creek in southern California (Fig. 3). This asymmetry has not been discussed explicitly in previous studies and is described further here as a distinctive signature of the mechanism dominating the evolution of the diurnal cycle of a stream whose diurnal cycle is dominated by evapotranspiration.

b. Infiltration in losing reaches

Because water viscosity and hydraulic conductivity are temperature dependent, the rate of loss from a stream through seepage down through the streambed depends on stream temperature (Freeze and Cherry 1979; Kundu 1990; Constantz 1998; Ronan et al. 1998). In losing

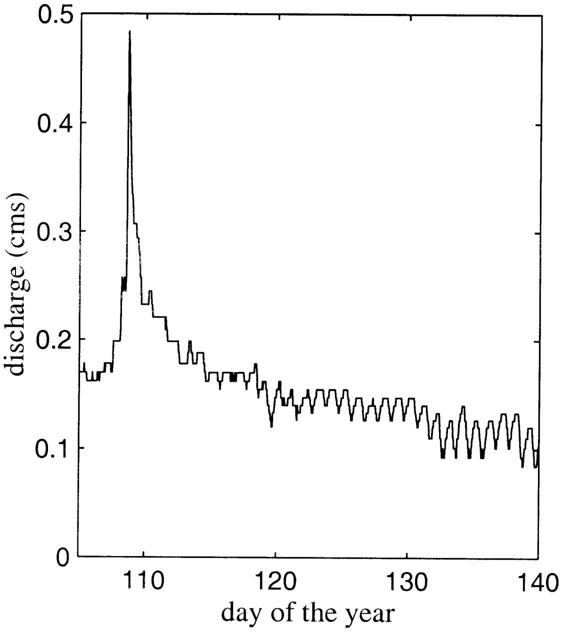


FIG. 3. Diurnal fluctuations ($m^3 s^{-1}$, or cms) at Temecula Creek near Temecula, CA, become more pronounced as temperatures warm from Apr through May 1996. [Note: The stair-step pattern appears because fluctuations in stream height are on the order of 0.01 ft (3.05 mm), which is the smallest increment recorded by the float-activated stilling well. However, USGS personnel rate this stream as having good quality data, not affected by impairments or diversions.]

reaches, where water drains from the streambed to a groundwater reservoir, the most water is lost when the water temperature is warmest. Diurnal variations in stream temperature are largest when 1) the stream has a low discharge and/or a large surface-area-to-discharge ratio and 2) the stream is exposed to high rates of heat exchange with the atmosphere because of significant diurnal variations in air temperature and radiative fluxes (Vugts 1974; Risley 1997; Taylor 1998). Diurnal hydrographs of rivers having large infiltration losses exhibit asymmetries similar to those associated with evapotranspiration, with a rapid decline and a slow rise each day.

c. Diurnal cycles in precipitation

The present study is limited to the continental western United States, where precipitation occurs primarily in winter and is associated with large synoptic systems, for which diurnal variability in precipitation is weak or nonexistent. In this region, because precipitation-induced variations do not retain a constant or steadily evolving phase, they produce nearly equal amounts of variance at a range of frequencies adjacent to the diurnal frequency. Hence, the criteria for determining whether a station has a distinct diurnal cycle, discussed in section 4, disqualifies rivers with only precipitation-induced power at the diurnal frequency. For these reasons, precipitation-induced diurnal cycles are not examined further in the present analysis.

d. Snowmelt

Many watersheds in the western United States drain mountainous topography and contain a substantial amount of runoff from snowmelt, which typically begins in early April and may last through July or August. Studies of snowmelt from local snowpacks or from small basins exhibit diurnal cycles in snowmelt and river discharge that are asymmetric, with sharp daily upward ramps and then gradual recessions (Braun and Slaymaker 1981; Kobayashi and Motoyama 1985; Davar 1970; Jordan 1983a; Young and Lewkowicz 1988; Singh et al. 2000; Caine 1992). The observed asymmetry may be explained by the vertical percolation of snowmelt water through a snowpack, which has been modeled with Darcy's law of propagation through a porous medium (Colbeck 1972; Dunne et al. 1976; Jordan 1983b). Because the speed of propagation is proportional to the size of the melt flux, larger pulses of melt overtake smaller ones, resulting in the discharge of a shock-front-shaped hydrograph at the base of the snowpack, with a steep increase and gradual decline.

Textbooks (Davar 1970; Singh and Singh 2001), numerical models of the percolation of snowmelt water through a snowpack (Colbeck 1972; Dunne et al. 1976; Jordan 1983b), and localized, small-basin observations (Jordan 1983a; Bengtsson 1982; Singh et al. 2000; Caine 1992) all report that the hour of day of maximum flow becomes earlier as the snowpack thins and matures, reflecting shorter travel times for surface melt to reach the base of the snowpack. Singh et al. (2000), Caine (1992), and Jordan (1983a,b) propose using the shape and timing of the hourly hydrograph to predict snow depth and hydraulic conductivity for small alpine basins. However, most USGS gauges monitor watersheds larger than those that have been previously examined in these process studies, and most gauges are located downstream, at elevations below the snowfield. Grover and Harrington (1966) explain that below the snowfield, the peaks and troughs of the diurnal cycle will occur later than at the edge of a snowfield, with a delay that depends on the distance from the snowfield and the stream's velocity. Grover and Harrington (1966) predict that as the snow melts and retreats, this delay will increase, progressively shifting the flow peak to later in the day.

Given the range of stream gauge locations, upstream channel network geometry, and the relative strengths of stream inflows (e.g., where the snow is melting), when and where can the documented shift in peak flows to earlier in the day be observed? In constrast, how often does the peak flow remain constant or shift to later in the day? Can the diurnal streamflow timing be used to determine snowpack characteristics on this scale? The present analysis seeks to shed light on these questions.

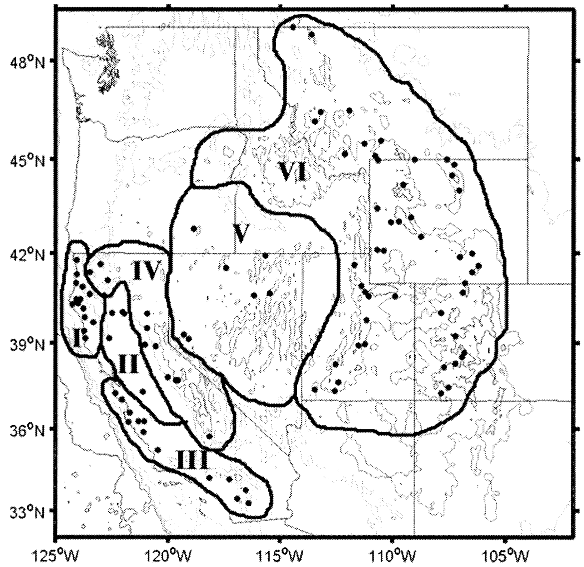


FIG. 4. Locations of gauges (black dots) and ecological/climatic regions (I: northern California coast; II: California central valley; III: southern California coast and semidesert; IV: Sierra Nevada; V: Nevada–Utah Mountains and semidesert; VI: Rocky Mountains).

3. Region of study

This study focuses on USGS gauges providing hourly records in the western conterminous United States, from 100°W to the Pacific Coast (Fig. 4). As a means of classifying the large collection of stream characteristics, six regions are identified based on their elevation, climate, and ecoregion (Bailey et al. 1994). Region I includes the northern California coast, where most precipitation falls in winter (Mead 1950), and vegetation consists of California coastal steppe, mixed forest, and redwood forest. The California central valley comprises region II and is ecologically classified as California dry steppe (Bailey et al. 1994). Most precipitation falls as winter rain, but many rivers in this region drain the Sierra Nevada, so river characteristics may reflect winter rains and spring and summer snowmelt. Region III has California coastal chaparral, open woodland, shrubs, conifer forests, meadows, and semidesert. This region receives the least amount of precipitation (Mead 1950) and does not drain any areas with persistent snow. Region IV is the Sierra Nevada and southern Cascade Mountains, where most precipitation falls as winter snow, most runoff occurs during the spring (Langbein and Wells 1955), and vegetation consists of Sierran steppe, mixed forest, and alpine meadows (Bailey et al. 1994). Region V, the Nevada–Utah Mountains semidesert region, contains conifer forests and alpine meadows but receives less than half the annual precipitation (most of which falls as winter snow) of the Sierra Nevada and Rocky Mountain regions (IV and VI) (Mead 1950). Region VI, the Rocky Mountains, contains Rocky Mountain steppe vegetation, conifer forests, and alpine meadows (Bailey et al. 1994), and most precipitation occurs as winter snow (Langbein and Wells 1955). Based on these climatic and physiographic characteristics, the mountains of the western United States (regions IV and VI) are expected to have snowmelt-dominated diurnal cycles. The deserts and coast of southern California (region III) are expected to have diurnal cycles due to evapotranspiration and/or infiltration to groundwater.

4. When do diurnal cycles occur?

For this analysis, hourly discharge rates for the five years from 1996 to 2000 for 100 unimpaired rivers in the western United States were obtained from gauges identified in the USGS Hydro-Climatic Data Network (HCDN) (Slack and Landwehr 1992). Hourly discharge records are not readily available from all USGS regions, and the data analyzed is by necessity of a subset of stream gauges in the western United States. The hourly discharge rates were analyzed with a sliding Fourier window 10 days wide, advanced 1 day at a time, as described below. This allows determination of the period of the year during which the diurnal cycle is a distinct component of the streamflow variability.

There is generally a seasonal structure in the diurnal cycle. The time of year with a distinct diurnal cycle varies greatly between rivers responding to different diurnal forcings. This seasonality can be used to help identify whether water is added to or removed from a given basin. For example, four California basins, representative of different climate types, exhibit distinct patterns in their Fourier power spectra over the course of the year (Figs. 5 and 6). Moist, rain-dominated rivers in coastal northern California (region I), such as the Smith River (Fig. 6a), exhibit a red spectrum, with no diurnal peak. Here the greatest variation occurs at the lowest frequencies, with an exponential decrease in variation as frequencies increase. This spectral shape is present all year, but the most power at all frequencies is in the winter rainy season. Arid rivers (region III), which are dominated by either infiltration or evapotranspiration removing water from the river each day, are exemplified by Temecula Creek (Fig. 6b). Temecula Creek exhibits a red spectrum, with the largest power during the winter rainy season, and a clear diurnal peak from late May to October. Snowmelt-dominated rivers (regions IV, V, and VI), such as the Merced River (Fig. 6c), have the most power in the spring and early summer, when a clear diurnal cycle and its higher harmonics emerge. These harmonics include frequencies of 2 and 3 cycles per day (cpd) and account for the asymmetry in the daily variation. Mixed rivers (region II), such as the American River (Fig. 6d), have drainage basins of intermediate elevations and contain characteristics of each of the three types. For example, the American River has a rain-dominated power spectrum without a distinct diurnal cycle from January to early April, a snow-

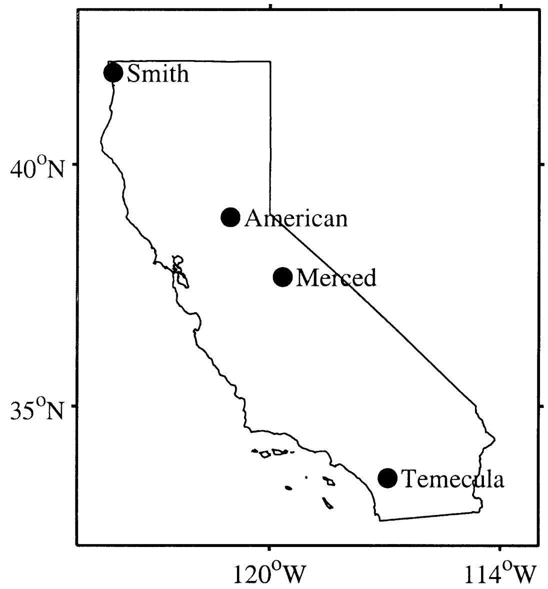


FIG. 5. Locations of rain-dominated Smith River, snowmelt-dominated Merced River, evapotranspiration/infiltration-dominated Temecula Creek, and American River, used to illustrate spectral characteristics of different diurnal cycle types in Fig. 6.

melt-dominated diurnal peak from April to July, and an arid-type diurnal peak from August to October.

These spectra illustrate that streamflow variations tend to be broadband (having power spread over many different, adjacent frequencies), red noise spectra. All of the rivers have some power at the diurnal frequency, but the diurnal cycle must stand out if useful physical insight is to be derived from its characteristics. Thus, only those periods during which the diurnal frequency has at least 30% more power than frequencies immediately above or below it are deemed to have discernable ‘‘diurnal cycles.’’ To determine whether the diurnal component emerges from the broadband spectrum, hourly streamflow series at each station are broken into a succession of 10-day segments, overlapping so that a new segment starts each day. Then, Fourier transforms of all the segments with the central day of the segment located in a given month are averaged together, so that, for example, the spectrum for June for a specific year is the average of 30 Fourier series from that year and for all five years is the average of 150 Fourier series. For each average power spectrum, the difference in magnitude between the power in the diurnal component and the average of the power at the two adjacent frequencies is computed. Because this difference (which varies by several orders of magnitude between rivers) depends on the initial size of the components for a given river, this value is then scaled by the size of the diurnal component. This allows a determination of streams where the power of the diurnal frequency exceeds that of adjacent broadband frequencies by at least 30% of the size of the diurnal component. When the diurnal peak does not rise above this threshold, the diurnal power is assumed to be broadband variance or masked by noise, and that station is disqualified from further consideration for that month. Scaling by the relative size of the diurnal peak is preferable to scaling by the fraction of variance associated with the diurnal timescale because the latter method favors low-flow, arid-region rivers that have little low-frequency variance and rejects rivers with diurnal cycles superimposed on large, low-frequency, seasonal cycles.

Using the above criterion, many snow-fed rivers yield diurnal cycles during the winter months (Fig. 7a), when intermittent periods of warming and melting occur. The snow-fed rivers of the Sierra Nevada and Rocky Mountains show the largest number of stations with discernable diurnal cycles during the melt season of April through July (Fig. 7b) and have little or no distinct diurnal signal in August and September, when the snowpack is mostly gone (Fig. 7d). In contrast, arid-region rivers exhibiting percentages greater than 30% are absent in winter (Fig. 7a), begin to emerge in spring (Fig. 7b), and are most prevalent in the middle of the summer (Fig. 7c). Many rivers along the California coast also yield distinct diurnal cycles during late spring to early fall, with the highest number of stations in July and August, the hottest months (Fig. 7c). [Note that the Smith River (Fig. 6a), on the northern coast of California (Fig. 4), is not one of these.]

5. Amplitude of the diurnal cycle

As illustrated in Fig. 2, the amplitude of the diurnal cycle changes with the magnitude of total discharge over the course of a year. The amplitude is calculated as half the difference between the maximum and minimum daily discharge and is averaged over the period being examined. The ratio of the amplitude of the diurnal cycle to the average total daily discharge is a measure of the percentage of the discharge being added and/or removed each day. The average amplitude of the diurnal cycle for high-elevation rivers, assumed to be snowmelt-dominated, ranges between 5% and 25% of the average total flow during the spring and summer melt season (Figs. 8a,b). This percentage is largest when direct snowmelt contributes most to the river. Even for rivers that are supported solely through melting snow, much of the snowmelt infiltrates into the groundwater and reemerges days later as part of a long recession curve. On the other hand, the relative size of diurnal cycles in California coastal and arid rivers increases during the summer months, when the total flow decreases (Figs. 8b–d). Thus, in February (Fig. 8a), the largest part of flows in the Rocky Mountains is the diurnal component. These are still present but smaller in relative terms in May (Fig. 8b), when all of the snowmelt rivers have discernable diurnal cycles. In July (Fig. 8c), as summer progresses, the diurnal cycles from snowmelt-driven rivers in the Sierra Nevada and Rocky Mountains diminish, while those of coastal and southern California streams

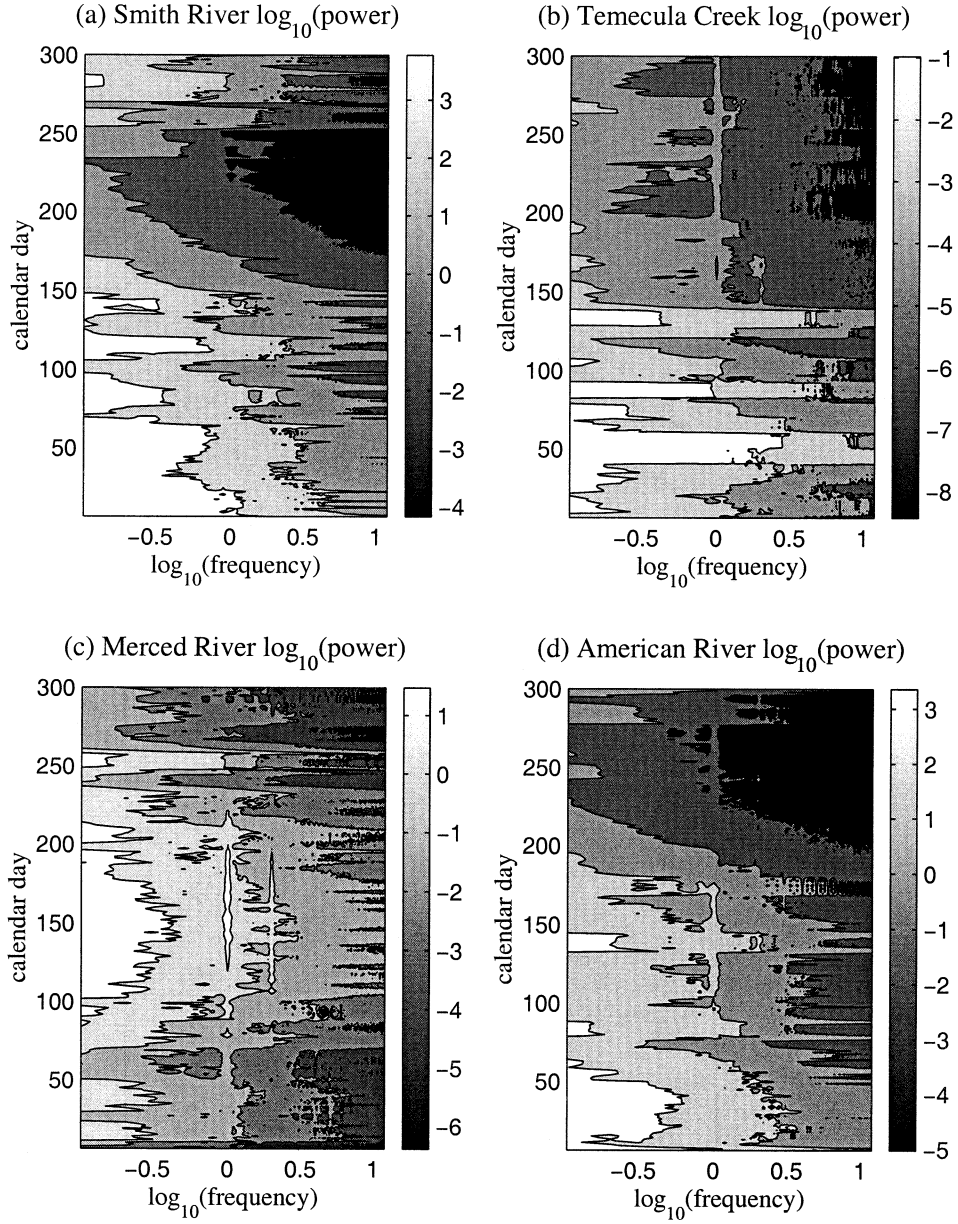


FIG. 6. Spectrograms of log-transformed streamflow power (cms^2 cpd^{-1}) for (a) Smith River, (b) Temecula Creek, (c) Merced River, and (d) American River (for locations see Fig. 5). The *y* axis shows the central calendar day for each 10-day period. The *x* axis shows the number of cycles per day on a log scale, so that 0 represents $10^0 = 1$, the diurnal cycle. Black to white shading signifies low to high spectral power.

remain high. In September (Fig. 8d), diurnal amplitudes are everywhere less than 10%, except for California coastal and arid streams, where amplitudes remain about 20%. The month-long and year-to-year averaging used in these plots mutes the large amplitudes commonly seen in individual rivers at specific times. For example, the diurnal amplitude of the Merced River often exceeds 10% of the daily mean flow but decreases markedly during cold spells, so the average amplitude in spring and summer is slightly less than 10%.

There is a weak relationship between basin area and relative amplitude (Fig. 9), such that the relative amplitude tends to be larger for smaller basins. While some small basins do have small relative amplitudes, none of the largest basins achieve large relative amplitudes, likely due to a larger groundwater reservoir and to the averaging of a larger number of factors contributing to streamflow. Aside from this trend, compared across basins, the relative amplitude of the diurnal cycle does not correlate strongly with tabulated basin characteristics, such as mean monthly temperature, mean monthly discharge, or mean basin elevation. Each basin appears to

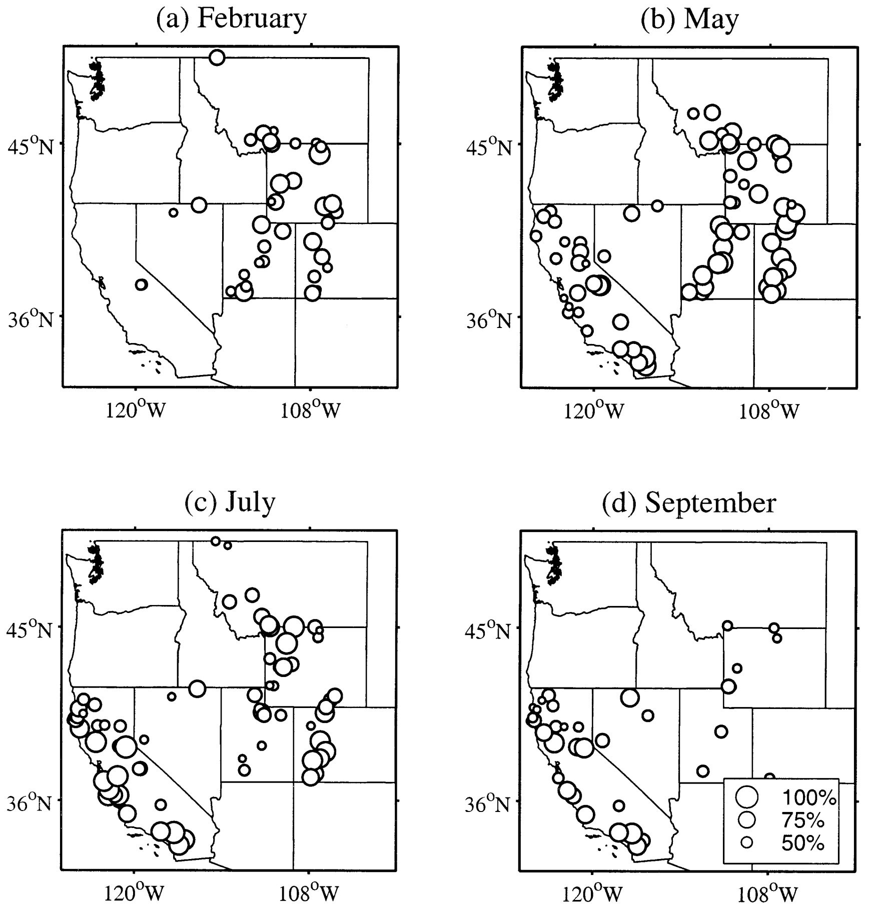


FIG. 7. Presence of a distinct diurnal cycle for (a) Feb, (b) May, (c) Jul, and (d) Sep, as determined by percent difference between diurnal component of power spectrum and adjacent frequencies.

have a unique identity due to local physiographic and hydrologic characteristics. While the diurnal characteristics of a single basin correlate with climatic variations on interannual timescales, we do not find the presence of universal correlations that link mean climatological characteristics, physiographic, and hydrologic characteristics to simple measures of the diurnal cycle.

6. Timing of daily flow maxima

In addition to their differing seasonal characteristics, the hourly timing of diurnal flow peaks differs between snowmelt-dominated and evapotranspiration/infiltration-dominated streams. Figure 10 illustrates the typical hour of maximum discharge for rivers having distinct diurnal cycles in the western United States. Streamflows in arid-region rivers consistently reach their daily maxima at about 1000 local standard time (midmorning) throughout the summer months (black circles in Fig. 10). This timing reflects the loss of water from the system by streambed infiltration, transpiring vegetation, or evaporation during daylight hours, causing a decrease in flow after midmorning.

For snow-fed rivers, the times of daily flow maxima during peak melt are often near midnight or in the early hours of the morning (open circles and squares in Fig. 10), reflecting delays in travel time to the river gauge from the location of maximum melt the previous afternoon. For example, the Merced River (Fig. 2) consistently peaks in the early morning during peak melt season. Variations between rivers occur due to different gauge locations and different basin characteristics.

The seasonal evolution of the timing of daily flow maxima may indicate whether daily processes add or remove water from a given basin. In snow-fed streams, flow paths and travel times change considerably over the melt season, as the snow line shifts location in the basin and the rate of flow through the snowpack changes as the snow thins and matures. As these processes take place, the hour of maximum flow recorded at a snowmelt-dominated river gauge shifts during the course of a season. Evapotranspiration and infiltration produce a distinct diurnal cycle in flow when they occur in riparian vegetation (Bren 1997) or in the streambed (Constantz 1998) near the gauge. The travel distance between the location of the diurnal forcing and the river gauge is

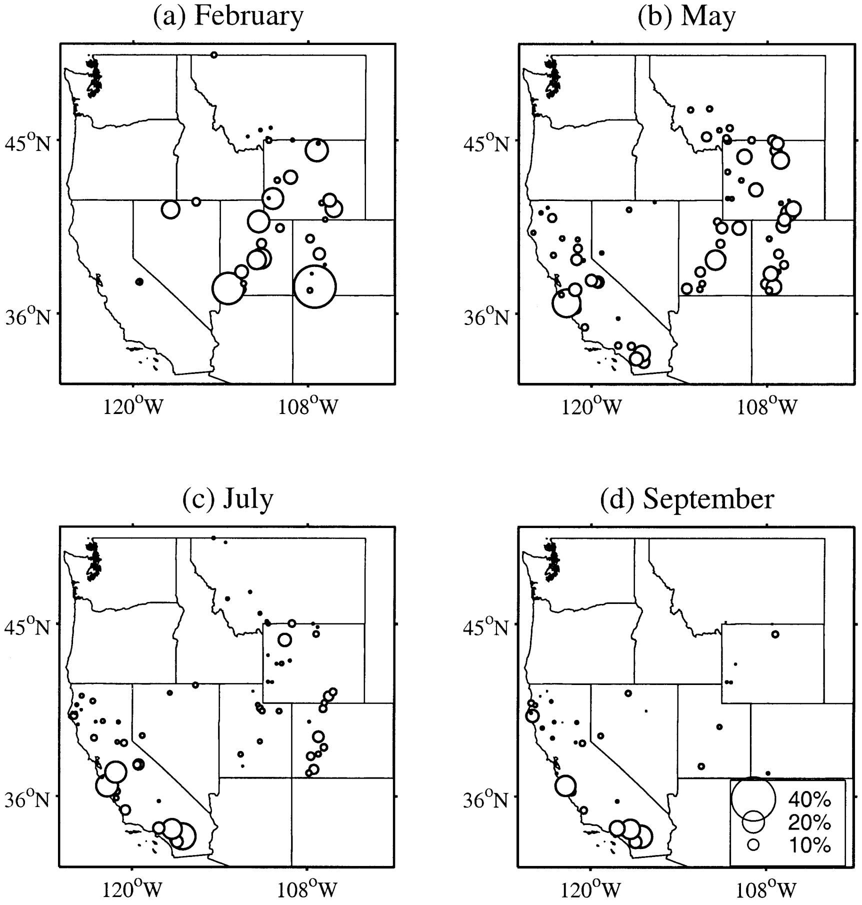


FIG. 8. Amplitude of the diurnal cycle (%) for (a) Feb, (b) May, (c) Jul, and (d) Sep, calculated as half the distance between the maximum and minimum flow each day, expressed as a fraction of mean daily flow.

constant, and, because this distance is short, variations in travel time due to changes in streamflow velocity are small. Hence, the hour of maximum flow tends to be consistent, with little shift in time as the season progresses.

For a perspective from several rivers across the western United States, Fig. 11 shows the average change in the time of maximum flow during late spring (May) and midsummer (July). For this calculation, hourly discharge observations for the month are broken into 6-day segments, advancing by 1-day increments so that segments overlap. Each segment is Fourier transformed, and the hour of maximum flow is calculated from the phase of the diurnal and semidiurnal components. The hours of maximum flow are unwrapped to remove the circular aspect of the data; for example, a peak at 0100 following a peak at 2400 will be unwrapped to 2500. Then a line is fit to the hours of maximum flow over the whole month using least squares analysis, and the slope of the best fit line is considered the average shift. (Note: For this analysis, only rivers with the percent difference of the diurnal frequency from neighboring frequencies greater than 30% are included.) Figure 11 shows that arid-region rivers exhibit little or no change in timing in either May or July.

In contrast, the time delay between snowmelt and water reaching a stream gauge exerts much control over the hour of maximum discharge recorded in snow-fed streams. In May (Fig. 11a), most rivers show little or no shift, suggesting that processes acting to shift the timing earlier and later balance each other. Small shifts of peak flows to earlier times of day occur in some rivers and may be due to faster propagation of meltwater through the snowpack as the snow height decreases (Jordan 1983a,b) or to increasing velocities in both the snowpack and river channel, associated with larger discharge (Grover and Harrington 1966). However, the most consistent change of peak timing in snow-fed watersheds is the shift of maximum flows to later in the day during the latter portion of the melt season (Fig. 11b). This shift almost always occurs during the period of declining flows and reflects increasing travel times as the snowline retreats to the highest reaches of the basin (Grover and Harrington 1966). This timing shift suggests that on a large scale, near the end of the season,

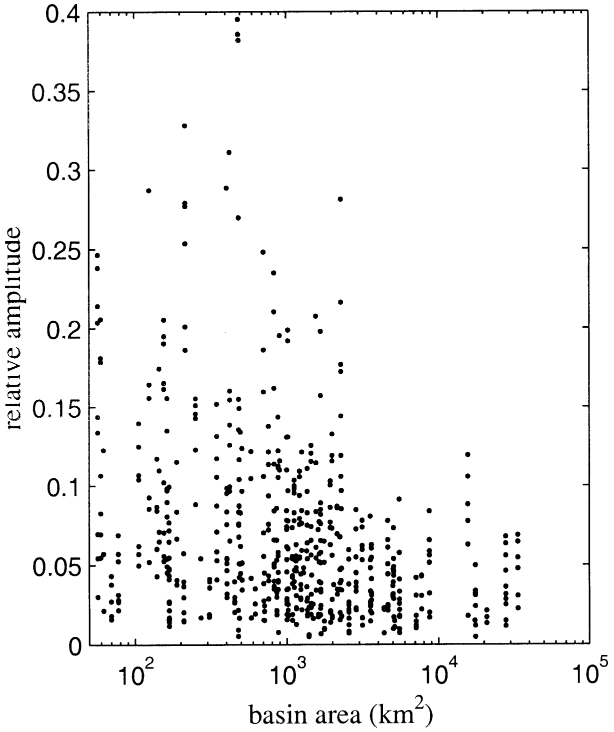


FIG. 9. Relative amplitude of the diurnal cycle as fraction of mean flow for all streams for each month having a distinct diurnal cycle.

the spatial snow distribution is important in affecting diurnal timing.

7. The shape of the diurnal cycle

The shape of the diurnal cycle also reflects processes that control the daily river flow. Where water added to the river is the dominant diurnal influence, such as in a snow-fed river, the diurnal cycle is characterized by a sharp rise (about 10 h) and gradual decline (about 14 h) (Fig. 12a, Merced River). In rivers from which water is being removed through infiltration and evapotranspiration, such as in arid regions, the diurnal cycle is characterized by a gradual rise (about 14 h) and sharp decline (about 10 h) (Fig. 12b, Temecula Creek). Figure 13 shows differences in the period of time each day when flow is rising and falling during May and July in rivers across the western United States. At snow-fed rivers, during peak snowmelt season (Fig. 13a), the rise time is shorter

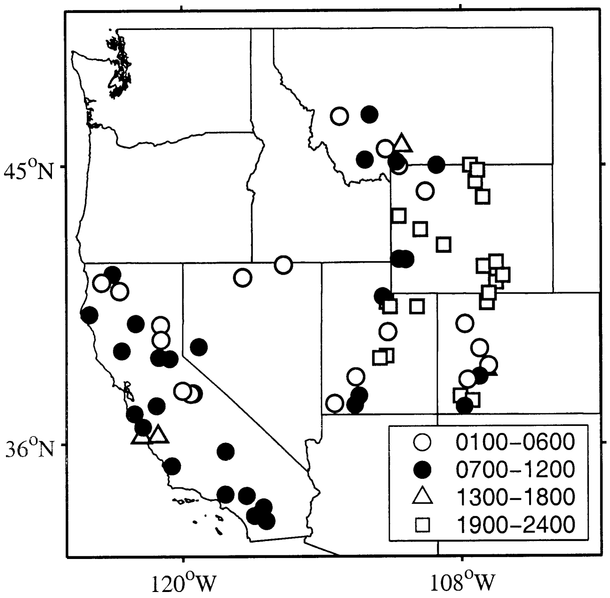


FIG. 10. Average hour of maximum discharge during May, using 1996–2000 records.

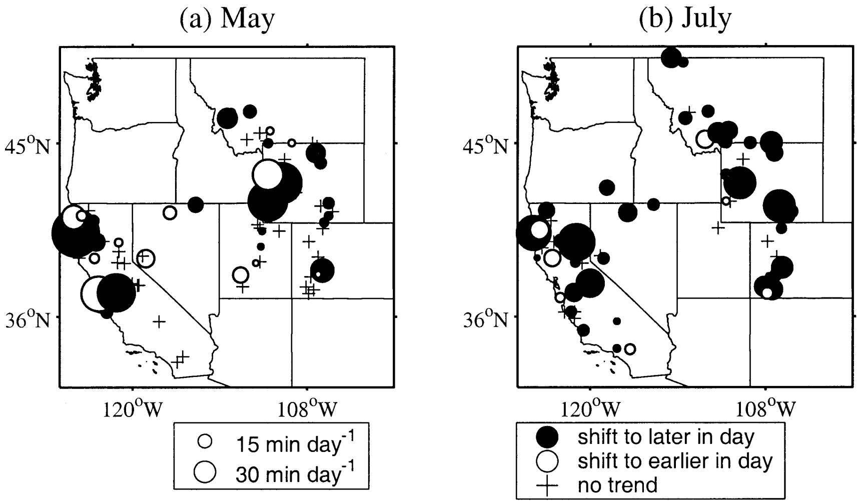
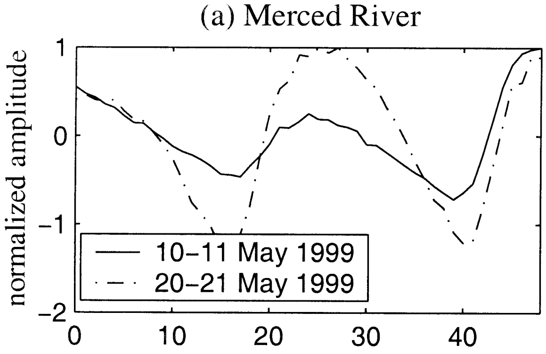


FIG. 11. Average rate of change in the hour of maximum discharge from the beginning to end of the month for (a) May and (b) Jul, years 1996–2000. Black = shift to later in the day; white = shift to earlier in the day; and + indicates a station where the diurnal cycle is distinct, as defined in section 4, but where there is no discernable shift in the hour of peak discharge.

than the decay time, while at arid-region and coastal rivers the decay time is shorter than the rise time. Because there is little precipitation at this time of year in the western United States, most rivers without snowmelt input are presumably losing water each day through evapotranspiration or channel infiltration. As summer progresses (Fig. 13b), more rivers shift to having a shorter decay and longer rise daily, as more water is lost from the channel rather than added. Inspection of several individual streams indicates that large drainage basins often exhibit a more symmetric diurnal cycle than small basins, perhaps because large basins integrate both additions and removals of water most of the time.

Knowledge of the shape of diurnal cycles may also be useful as an indicator for rivers that exhibit diurnal cycles dominated by early-year snowmelt and late-year evapotranspiration/infiltration. In these rivers, high-elevation stretches of the watershed can be snowmelt-dominated while, at the same time, lower-elevation stretches are evapotranspiration/infiltration-dominated. One such river is the Moshiri headwater basin in the boreal forest of northern Japan, which has been extensively studied by Kobayashi (1985, 1986; Kobayashi et al. 1990). Although the basin is thickly covered with snow, no diurnal variation occurs during the winter months (Kobayashi et al. 1990). During spring melt in April and early May, diurnal variations are very evident (Kobayashi 1985, 1986), with a characteristically steep rising limb and gradual falling limb. However, in the summer after the snowmelt season has passed, evapotranspiration exceeds precipitation and creates a pronounced diurnal cycle. In June and July, the diurnal cycle clearly has a sharp decline and more gradual rise (Kobayashi et al. 1990). The late May diurnal cycle is



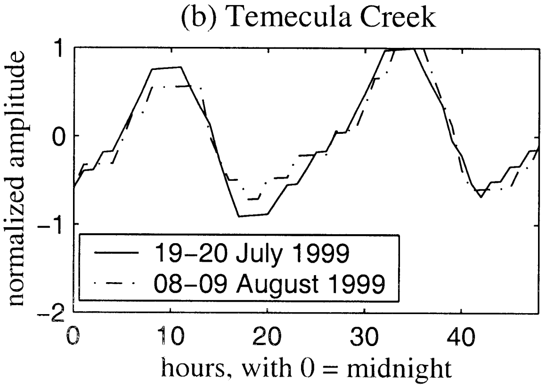


FIG. 12. (a) Normalized flows for Merced River for several days in 1999. Normalization is achieved by fitting a straight line to the data, subtracting the line to remove any low-frequency trends, and then dividing by the maximum amplitude to yield an amplitude of 1. (b) Normalized flows for two days in Temecula Creek.

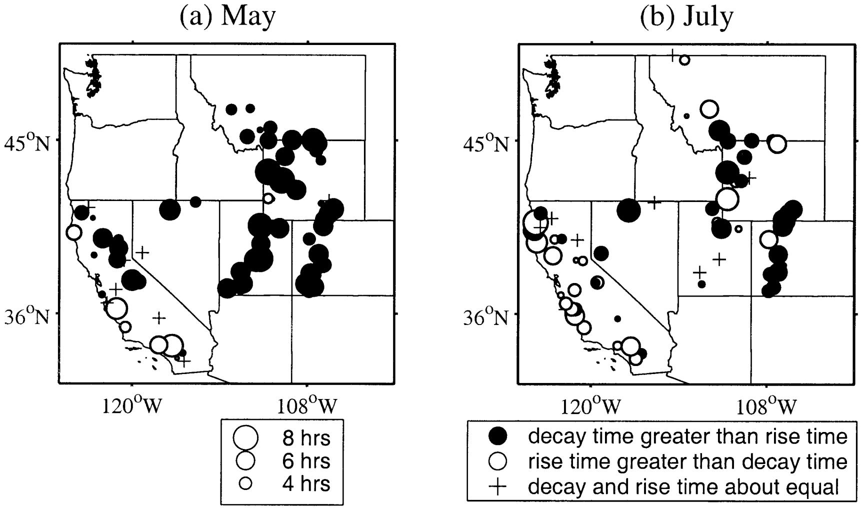


FIG. 13. Diurnal cycle asymmetry, calculated as the difference between the average diurnal hydrograph rise time (from minimum to maximum discharge) and the decay time (from maximum to minimum discharge) for the months of (a) May and (b) Jul. A + indicates a station where the diurnal cycle is distinct, as defined in section 4, but where there is no difference between the decay and rise times.

highly symmetric (Kobayashi et al. 1990, their Fig. 6). In light of the present study, this symmetry suggests that snowmelt is becoming balanced by evapotranspiration/infiltration. Constantz (1998) shows that summer variations in streamflow in St. Kevin Gulch near Leadville, Colorado, and in the Truckee River, the Little Truckee River, and Donner Creek near Truckee, California, are dominated by varying infiltration rates. His graphs show steep falling limbs and gradual rising limbs. In the spring, these same streams are dominated by melting snow, as inferred by nearby gauges (Fig. 13a), and presumably exhibit a steep rise and gradual fall each day. These asymmetries are not discussed explicitly by the authors but are apparent from the figures presented in the cited papers.

Within the present dataset, the Little Bighorn River at Stateline near Wyola, Montana, presents a clear example of how the shape of the diurnal fluctuations within a single river can change between seasons (Fig. 14). In Fig. 13, the Little Bighorn River (represented by the dot on the border between Montana and Wyoming) shifts from a longer decay time than rise time in May (black dot in Fig. 13a) to a longer rise time than decay in July (white dot in Fig. 13b). Figure 14 shows how characteristics of the diurnal cycle differ between these two months. In May the fluctuations are snowmelt-dominated, with steep rises and more gradual declines each day, and the maximum discharge occurs near midnight (Fig. 14b). In July (Fig. 14c), diurnal variations have steep declines and more gradual rises and are nearly 180° out of phase with the May cycles. The hour of maximum discharge has shifted to about 12 h later in July than in May, peaking near noon, but the hour of minimum discharge is only about 6 h later in July, reflecting the different shape of the diurnal cycle between the two time periods. The July period is likely dominated by evapotranspiration because the Little Bighorn River, with a 500-km^2 basin and a mean basin elevation of 2386 m, is 87% covered by forests, including stands of Douglas fir, ponderosa pine, and cottonwoods, with brushy foliage that often shades the river. The diurnal patterns illustrated in Fig. 14 occur in all five years (1996–2000) examined for this river, but the transition between them occurs at different times of the year, probably depending on snow accumulation and weather patterns.

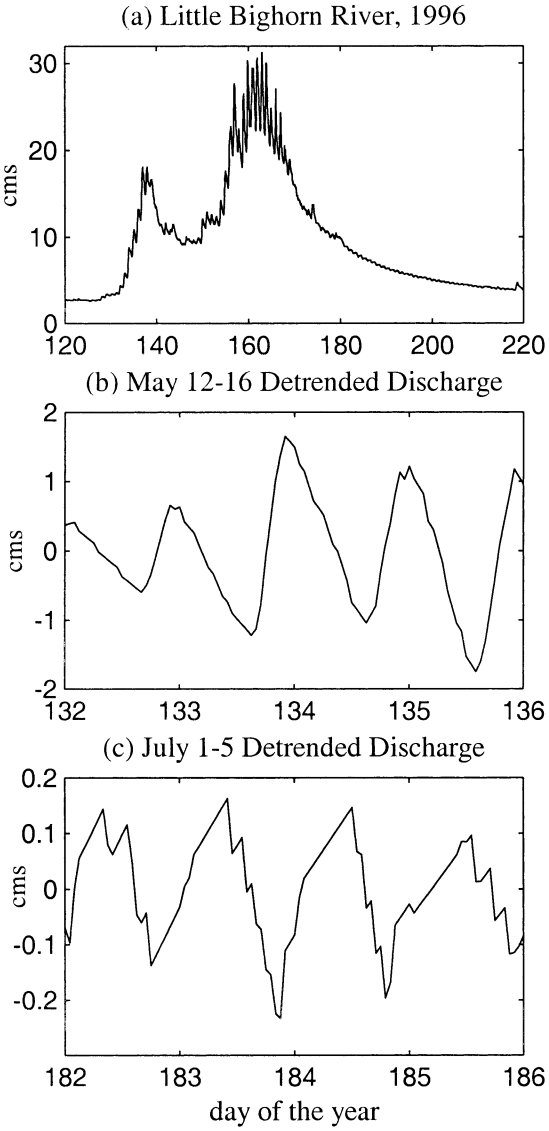


FIG. 14. (a) A 1996 hydrograph for the Little Bighorn River, illustrating how diurnal cycle changes as snowmelt forcing gives way to evapotranspiration/infiltration forcing. Periods illustrated in (b) and (c) were fit to a line, which was then subtracted out to accentuate the diurnal fluctuations.

8. Summary and discussion

The diurnal cycle is an identifiable component of streamflow variation in a majority of the routinely monitored, unimpaired rivers in the western United States, with an amplitude that often comprises over 10% of the mean daily discharge. Characteristics of the diurnal cycle can be used to understand whether dominant physical processes add to or remove from a river's water balance. Spectral characteristics readily allow discrimination between rivers dominated by rain, snowmelt, and evapotranspiration/infiltration. Snowmelt-dominated rivers, like the Merced River (Fig. 2), have highest flows and largest diurnal fluctuations during the spring and early summer melt season. These snowmelt-driven fluctuations are characterized by sharp daily rises followed by gradual daily declines. Toward the end of the melt season, in large basins, the hour of maximum discharge shifts to later in the day as the snow line retreats to high alpine zones farther from the gauge. Evapotranspiration/infiltration-dominated rivers, like Temecula Creek (Fig. 3), have seasonal maximum flows during the winter rainy season, but the diurnal cycle comprises the largest percentage of total flows during the summer, when discharge is lowest. The hour of maximum discharge usually occurs in the morning, and diurnal changes are characterized by a gradual rise in streamflow and a sharp decline.

The widespread occurrence of the diurnal cycle may provide a diagnostic tool in analyzing how climate change affects watersheds. The correlation between regional temperature change and shifts in snowmelt behavior to produce earlier runoff has generated much interest in the climate community (Dettinger and Cayan 1995). Mid-elevation Sierra Nevada watersheds have shifted 10% of their runoff from April–July runoff to other periods of the year, and spring and summer snowmelt has declined markedly (Dettinger and Cayan 1995). For lower-elevation gauges, such as the American River, which have runoff supplied from both precipitation and snow, the diurnal signature can be used to determine periods when runoff is caused primarily by snowmelt. In Fig. 6d, the diurnal frequency emerges in mid-April and disappears in mid-July. A census of dates at which this frequency emerges and disappears for successive years could indicate how a given river responds to interannual climate variability and presumably to climate change. For example, as climate warms, it is quite likely that both dates should advance to earlier in the year, and the period of snowmelt-driven diurnal cycles should decrease. Changes in the characteristics of the diurnal cycle could serve to monitor the magnitude of these changes.

The shift from snowmelt-dominated to evapotranspiration/infiltration-dominated diurnal variations, can also be distinguished using hourly data. This may provide another useful climatic tool, indicating when the snowpack disappears and the basin dries out each year.

The present study illustrates patterns in the diurnal flow cycle of many rivers of varying types across the western United States and complements previous studies, which have tended to address smaller and fewer basins and focus on one hydrological process at a time. As diurnal fluctuations become better understood, hourly measurements of discharge may become useful tools in hydroclimatic diagnostics and prediction.

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