# SNOW, TOPOGRAPHY, AND THE DIURNAL CYCLE IN STREAMFLOW

Jessica D. Lundquist (1), Noah Knowles (1), Michael Dettinger (2), and Daniel Cayan (1,2)

## ABSTRACT

Because snowmelt processes are spatially complex, point measurements, particularly in mountainous regions, are often inadequate to resolve basin-scale characteristics. Satellite measurements provide good spatial sampling but are often infrequent in time, particularly during cloudy weather. Fortunately, hourly measurements of river discharge provide another widely available, but as yet underutilized, source of information, providing direct information on basin output at a fine temporal scale. The hour of maximum discharge recorded each day reflects the travel time between peak melt and the time most water reaches the gauge. Traditional theories, based on numerical models of melt-water percolation through a snowpack and localized, small-basin observations, report that the hour of daily maximum flow becomes earlier as the snowpack thins and matures, reflecting shorter travel times for surface melt to reach the base of the snowpack. However, an examination of hourly discharge from 100 basins in the Western United States, ranging in size from 1.3 $km^2$ to 10,813 $km^2$, reveals a more complex situation. The sequences of seasonal evolution of the hour of maximum discharge are unique to each basin, but within a given basin are remarkably consistent between years, regardless of the size of the snowpack. This seems to imply that basin topography strongly influences the timing of peak flow. In most of the basins examined, at the end of the melt season, the hour of maximum discharge shifts to later in the day, reflecting increased travel times as the snowline retreats to higher elevations.

## INTRODUCTION

Textbooks (Davar 1970; Singh and Singh 2001), theoretical models (Colbeck 1972; Dunne et al. 1976; Jordan 1983b), and studies of small mountain basins (Jordan 1983a; Bengtsson 1982; Caine 1992) all report a shift in the hour of peak flow to earlier in the day as the snowmelt season progresses and the snowpack thins. Melt-

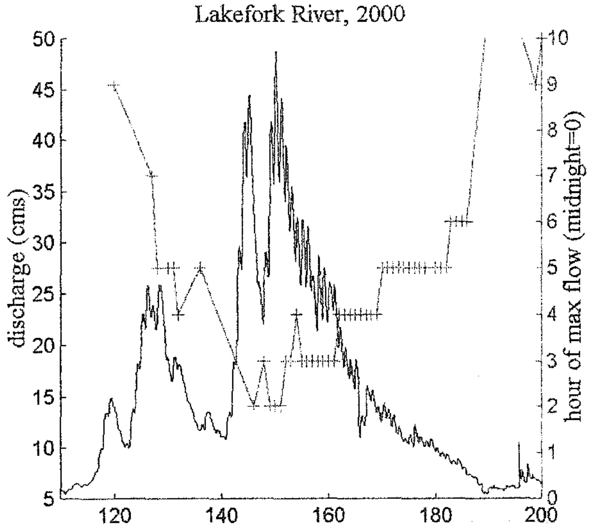

**Figure 1** *Lakefork River has an hour of peak flow (hatched line, right axis) that varies inversely with discharge (solid line, left axis), shifting to earlier in the day during the first half of the melt season.*

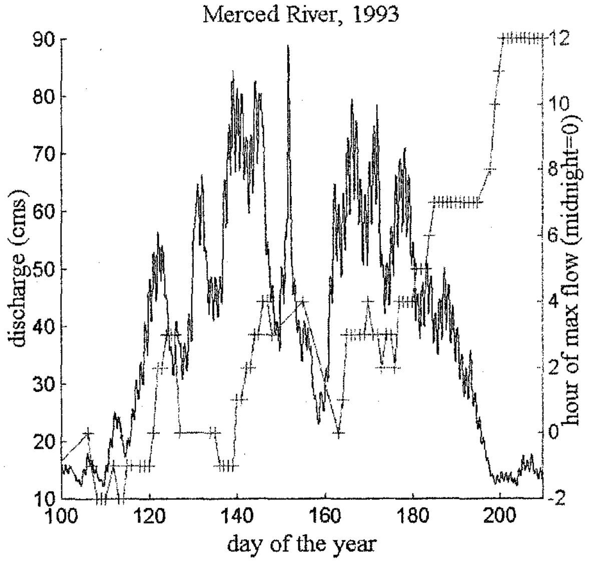

**Figure 2** *The hour of peak flow (hatched line) in the Merced River varies with discharge (solid line) for the first half of the melt season and then shifts to peak flows later in the day.*

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[1]Scripps Institution of Oceanography
University of California, San Diego, MC-0213
9500 Gilman Drive
La Jolla, CA 92093-0213
(858) 534-1504
jlundquist@ucsd.edu

[2] United States Geological Survey

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water travels from the top to the bottom of the snowpack more rapidly for smaller snow depths, resulting in an earlier peak in river discharge. However, for large basins, such as Lakefork (865 $km^2$) and Merced (469 $km^2$), travel times within the river channel are at least as important as travel times within the snowpack. Faster travel velocities occur during times of higher flow, resulting in earlier daily peaks. As a result, timing varies inversely with total discharge (Figure 1). Another contributing factor is that greater travel distances result in later daily peaks. Assuming that lower temperatures correlate with smaller flows and a lower, closer, elevation of melt, earlier peak flows should correlate with lower discharge (Figure 2). However, the clearest signature of increased travel distances occurs near the end of the season when the snowline retreats to higher elevations (Figures 1 and 2).

## TEMPORAL AND SPATIAL VARIATIONS

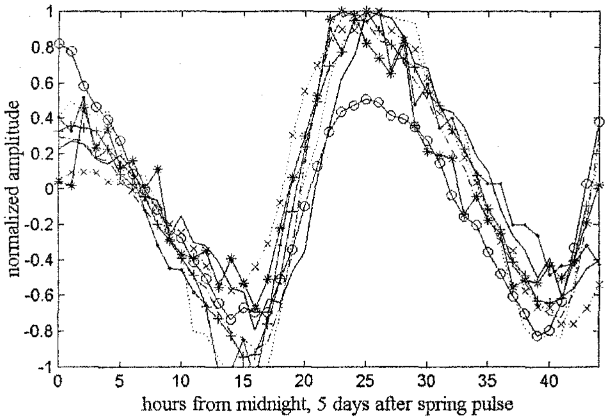


**Figure 3** *The diurnal cycle in streamflow for the Merced River, measured 5 days after the onset of snowmelt, the spring pulse, peaks near midnight every year from 1992 to 2000, regardless of varying snowpack size. (Each line represents a different year and has been shifted in time to bring the spring pulses together.)*

For most basins, local topography seems to influence the timing of the diurnal cycle in streamflow more than the depth of the snowpack. The hour of peak flow during the initial spring pulse for a given basin is the same every year, regardless of the size of the snowpack (Figure 3). In contrast, the hour of peak flow varies widely between basins, even for the same day on the same year.

## LARGE-SCALE PATTERNS

Few of the routinely-monitored USGS gauges in the Western United States show the diurnal peak occurring earlier in the day as the snowpack thins. During peak snowmelt, in May (Figure 4a), most rivers show no significant change in hourly timing. A few do shift to either earlier or later peaks, but no clear pattern emerges. Near the end of the snowmelt season, in July (Figure 4b), most rivers show a clear shift toward peak discharges later in the day.

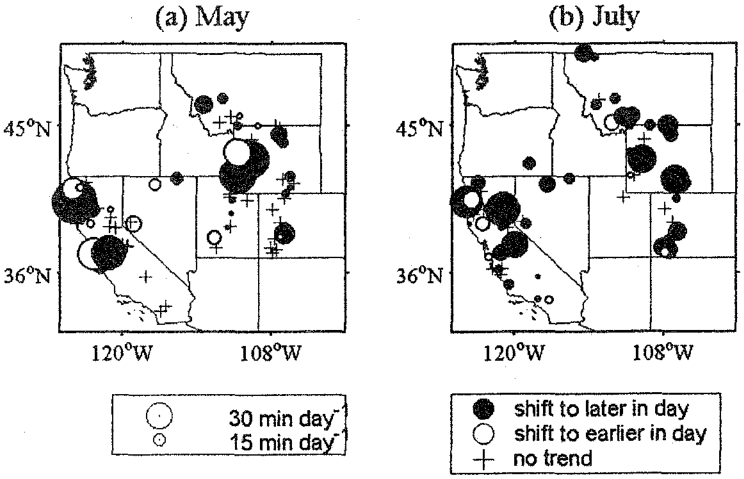
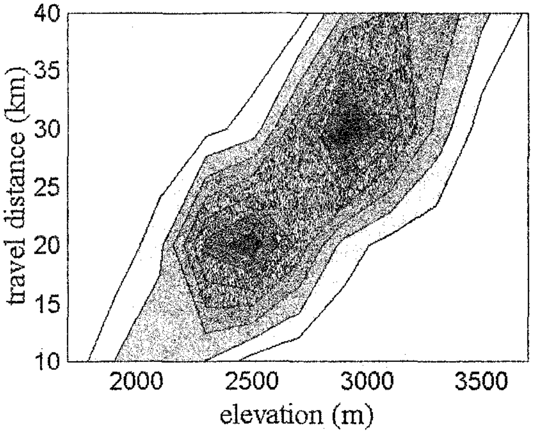


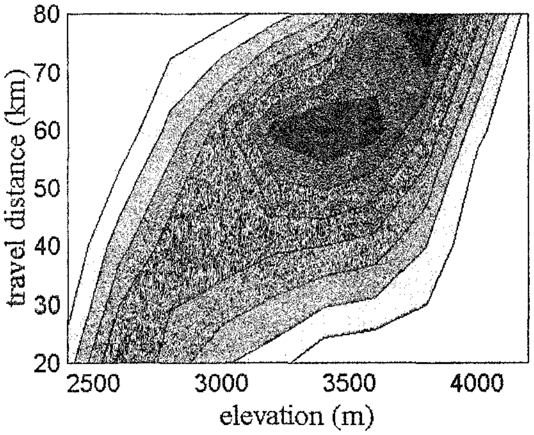
**Figure 4** *The average shift in the hour of maximim streamflow (right) is calculated over the months of (a) May and (b) July for the years of 1996 to 2000 for rivers exhibiting diurnal cycles. Most mountain rivers shift to later daily peaks in July, suggesting that on a large scale, snow distribution is more important than snow depth in affecting diurnal timing.*

## HOURLY STREAMFLOW TIMING AND SNOWMELT ELEVATION

In most mountain rivers, and particularly the Merced River (Figure 5), travel distance is highly correlated with elevation, so that flows originating from high altitudes have farther to go and hence arrive at the gauge later in the day. In the Merced River, the hour of maximum flow correlates well with the mean altitude of melt (Figure 6), as determined by the Bay-Delta Watershed Model (BDWM) (Knowles, 2000). This pattern is consistent between years and may be used to correlate the elevation of snowmelt with diurnal timing. Because the elevation and extent of snow cover are important parameters in most snowmelt-dominated runoff models, learning the mean snowmelt altitude from the time of the daily peak flow could be a useful predictive tool.



(a) Merced River corr. coeff. = 0.82



(b) Lakefork River corr. coeff. = 0.68

**Figure 5** *Contour plots of area distributed with stream travel distance and elevation for the Merced (a) and Lakefork (b) rivers. Distance and elevation are better correlated in the Merced basin, which might explain why peak flow timing varies more strongly with elevation.*

The effects of topography on diurnal cycle timing are tested with a streamflow model. Following Arora and Boer (1999), the model uses Manning's equation to determine time-dependent flow velocities at every routing model time-step so that velocities vary with the amount of runoff entering a grid cell. The channel is modeled with a triangular cross-section, with segment lengths, slopes, and widths determined from a 30-m digital elevation model for the basin. Each altitude zone feels the diurnal effects of the sun and supplies meltwater to the river in a daily cycle: $A_i(t)\sin\omega t$, where $\omega=2\pi/24$ hrs. As the season progresses, the diurnal amplitudes ($A_i$) change to simulate snow melting in different portions of the basin.

The BDWM is used to determine the amount of melt input originating from each elevation, which is used to force the changing amplitudes in the streamflow model. This generates a hydrograph with diurnal variations that qualitatively mirror observations (Figure 7). The amplitude of the diurnal cycle is larger than is regularly observed because the model contains only surface-runoff and no ground-water reservoir. The shifts in hour of peak discharge are only 25% the magnitude of the observed shifts, suggesting that factors other than the topographic variation of melt input also influence the streamflow timing.

## CONCLUSIONS

The topography of a basin is an important factor in determining the timing of the diurnal cycle in streamflow, as evidenced by patterns that are repeated each year in a given basin (Figure 3), but are different between neighboring basins in a given year. The altitudinal distribution of snow in a basin is also an important parameter, particularly in basins such as the Merced, where elevation is strongly correlated with travel distance (Figure 5). However, simple models (Figure 7) only partially reproduce these results, suggesting that the processes controlling the diurnal cycle shape and timing can be quite complex.

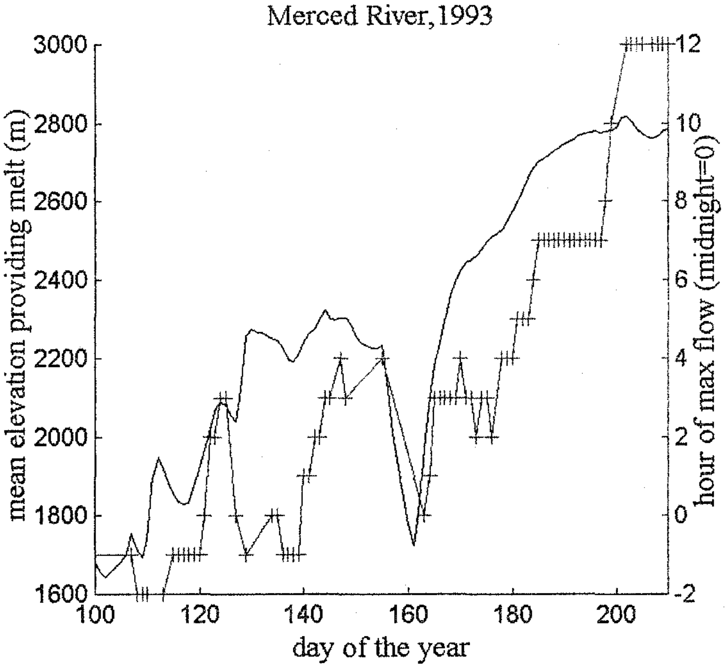


**Figure 6** *The BDWM-simulated mean altitude of snowmelt (solid line, left axis) correlates well with the hour of peak flow (hatched-line, right axis) for the Merced River for 1993.*

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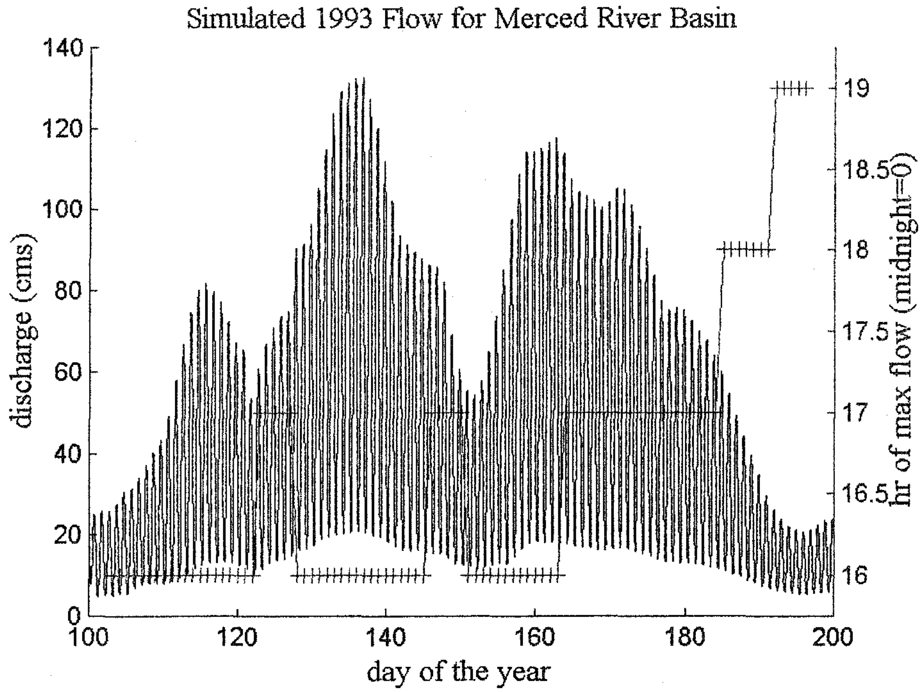

**Figure 7** *Model-generated streamflow (solid line, left axis) and timing of peak flow (hatched line, right axis) are qualitatively similar to observations (Figure 2). However, the amplitude of the diurnal cycle is too large, and the changes in timing of peak flow are too small.*

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