

## J2.4 LINKING DIURNAL CYCLES OF RIVER FLOW TO INTERANNUAL VARIATIONS IN CLIMATE

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### ABSTRACT

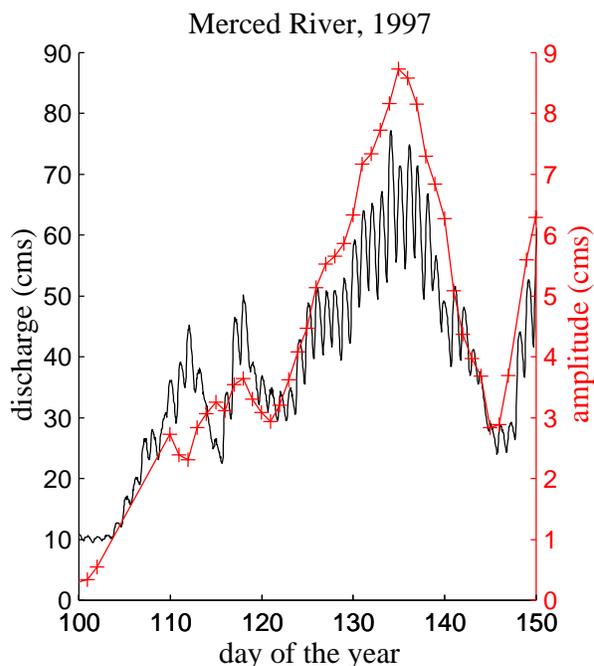
Many rivers in the Western United States have diurnal variations exceeding 10% of their mean flow in the spring and summer months. The shape and timing of the diurnal cycle is influenced by an interplay of the snow, topography, vegetation, and meteorology in a basin, and the measured result differs between wet and dry years. The largest interannual differences occur during the latter half of the melt season, as the snowline retreats to the highest elevations and most shaded slopes in a basin. In most basins, during this period, the hour of peak discharge shifts to later in the day, and the relative amplitude of the diurnal cycle decreases. The magnitude and rate of these changes in the diurnal cycle vary between years and may provide clues about how long-term hydroclimatic variations affect short-term basin dynamics.

### 1. INTRODUCTION

In the Western United States, over half of the water supply is derived from mountain snowmelt, where the snow provides a natural reservoir that delays runoff and provides water in the spring and summer when it is needed most. However, while the population continues to grow, an alarming change has been noted in recent decades in late season runoff. April-July runoff from mid-elevation Sierra Nevada watersheds has decreased by 10% in favor of other periods of the year, and spring and summer snowmelt has declined markedly (Dettinger and Cayan 1995). Whether this is long-term natural variability or the forerunner of anthropogenic climate change is unknown, but the trends and short-term variations are well-correlated with regional temperature change and have generated much interest in the climate community (Cayan et al. 2001). In the long run, it is estimated that, in response to projected global warming of 3°C, the spring-summer snowmelt would be diminished by about one-third (Roos 1987), and winter floods would likely increase. Thus, understanding snowmelt processes, from modeling surface energy balances to determining the timing and magnitude of snowmelt runoff to better understanding climatic change, is crucially important.

Snowmelt processes are spatially complex and thus difficult to forecast and incorporate in large-scale hydrologic and atmospheric models. Much of the

difficulty arises because snow occurs in patches of nonuniform depth and density, particularly in mountainous regions. In situ measurements of the snowpack are both difficult to make and not necessarily representative of region-wide characteristics. Satellite images and geographical information systems offer broader spatial coverage, but this data, which is often infrequent in time, is still difficult to relate to the actual snowmelt and river discharge originating from a basin. Fortunately, hourly measurements of river discharge provide another widely available, but as yet unutilized, source of information, providing direct information on basin output at a fine temporal scale. Each hour, the United States Geological Survey (USGS) monitors thousands of rivers that drain mountainous regions with marked spring snowmelt periods (Slack and Landwehr, 1992). Many of these, including the Merced River at Happy Isles (Figure 1), exhibit diurnal cycles comprising over 10% of the daily flow each spring (Lundquist and Cayan, 2002). The shape and timing of these diurnal cycles relate directly to the rate and location of snowmelt and to the pathways travelled by meltwater. Thus, changes in the diurnal cycle from such basins can provide information about snowmelt and runoff generation during the course of a snowmelt season and from year to year.



**Figure 1:** The amplitude of the diurnal cycle (hatched red line, right axis) is about 10% of the total streamflow (solid line, left axis).

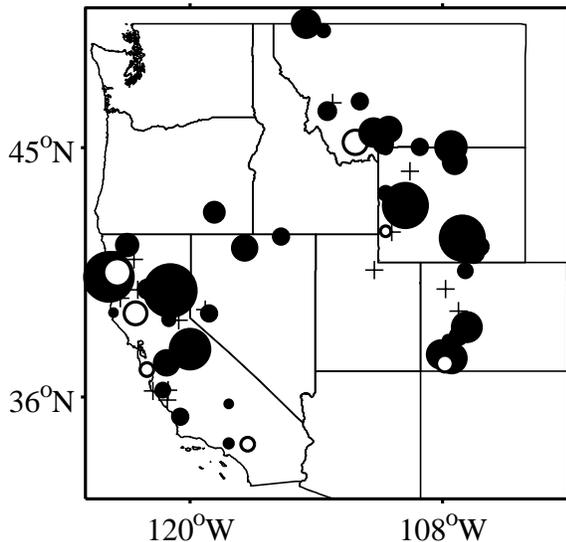
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## 2. PATTERNS AND VARIATIONS IN DIURNAL CYCLE CHARACTERISTICS

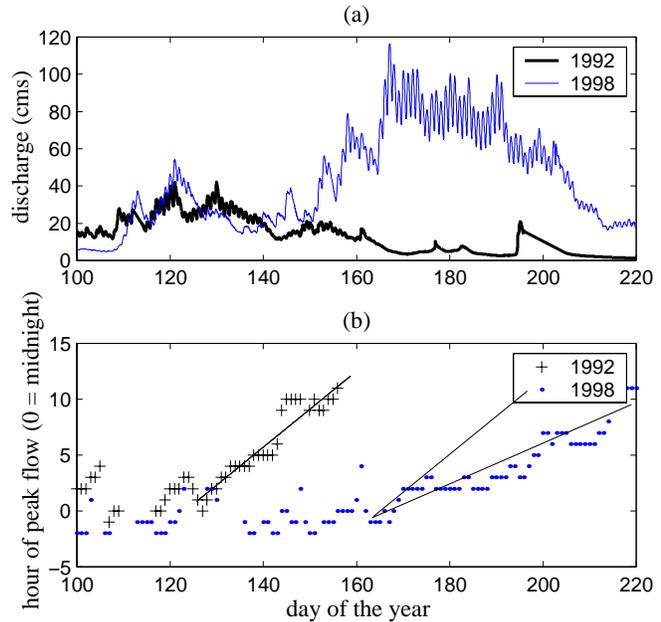
Diurnal cycle characteristics and patterns during 1996 to 2000 were analyzed at 50 snowmelt-dominated river gages. Some characteristics, like diurnal-cycle timing, amplitude, and shape, appear to be dominated by basin characteristics (fixed between years but varying between basins) and others appear dominated by meteorological and snow characteristics (varying more between years than between neighboring basins). Early in the season, when most basins are covered in snow, the size and topography of the basins appear to be more important than the depth of the snowpack. During the height of the melt season, the diurnal characteristics are consistent from year to year in most basins. Later in the season, as the snowpack retreats and the basin dries out, the difference between wet and dry years becomes much more apparent.

### 2.1 Timing of diurnal flow maxima

Textbooks (Davar 1970; Singh and Singh 2001), numerical models of the percolation of snowmelt water through a snowpack (Colbeck 1972; Dunne et al. 1976), and localized, small-basin observations (Jordan 1983; Bengtsson 1982; Caine 1992) all report that the hour of day of maximum flow becomes earlier as the snowpack thins and matures, reflecting shorter times for meltwater to travel from the snow surface to the base of the snowpack. However, most



**Figure 2** Average shift in hour of maximum flow from beginning to end of July, 1996-2000. Black circles show shifts to later in the day, white to earlier in the day. Crosses show stations with no significant change. Circle sizes show rate of change, ranging from 0.1 to 0.75 hours per day.



**Figure 3:** Merced River discharge measurements (a) contrast a very dry year (1992) with a very wet year (1998). During both years, the hour of peak flow (b) shifts to later in the day as flows decline. This shift is much more rapid for 1992. A line with the 1992 slope is drawn next to the 1998 slope for comparison.

USGS gages monitor watersheds larger than those that have been examined in these local process studies, and most gages are located downstream, at elevations well below the snowfield. Grover and Harrington (1966) state that the peaks and troughs of the diurnal cycle occur later below a snowfield than at its edge, with a delay that depends on the distance from the snowfield and the stream's flow velocity. Lundquist and Cayan (2002) show that, during the peak melt season, most rivers show only small or inconsistent changes in the hour of peak flow. Rather, the most consistent change of peak timing in snowed watersheds is the shift of maximum flows to later in the day near the end of the melt season (Figure 2). This shift almost always occurs during the period of declining flows, and reflects increasing travel times as the snowline retreats to the highest, farthest reaches of the basin (Grover and Harrington 1966). This timing shift suggests that, at the medium- to large-basin scales, near the end of the season, snowmelt distribution is more important than snow depth in affecting diurnal timing. The hour of peak flow shifts to later in the day more rapidly in dry years (Figure 3), and the slope of this shift correlates inversely with the duration of the melt season, as measured by the number of days with a discernible diurnal cycle caused by snowmelt.

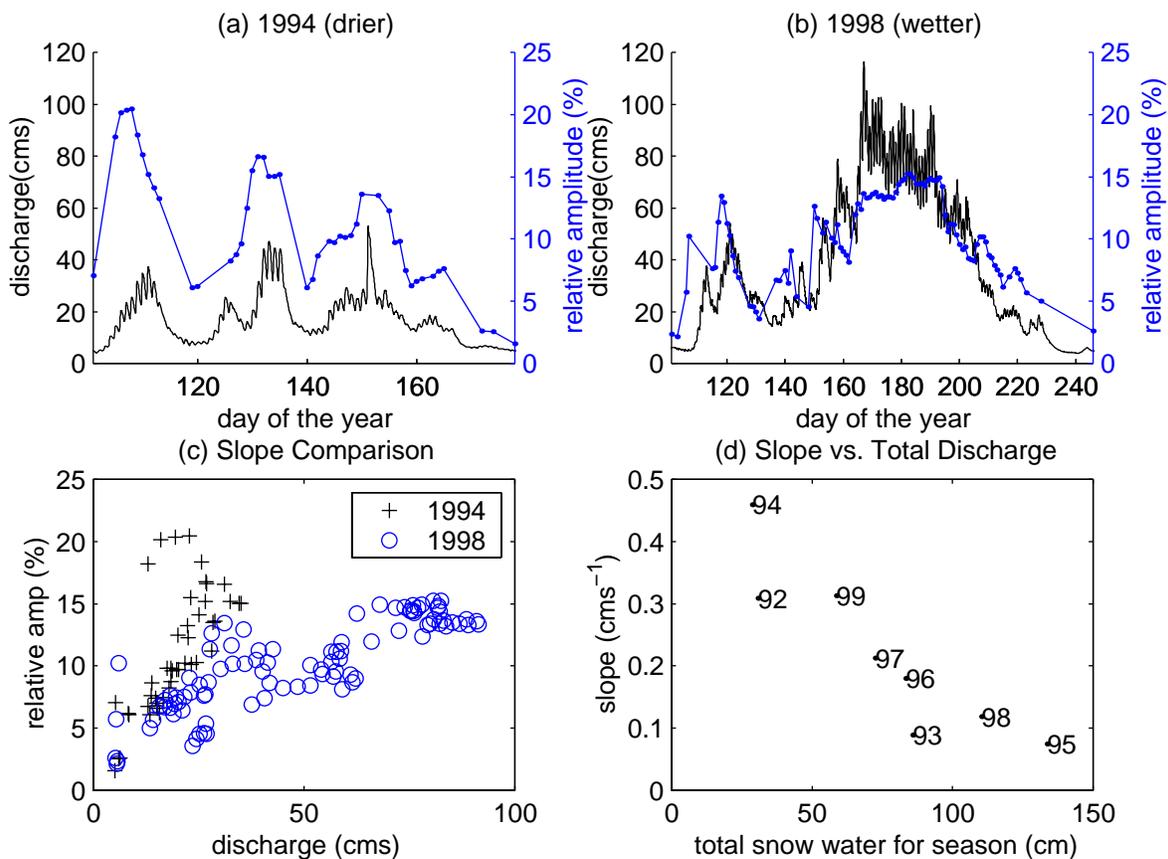
### 2.2 Diurnal amplitude/relative amplitude

Daily variations of the amplitude of the diurnal flow cycle are highly correlated with daily temperatures and

with total discharge in most basins (such as the Merced, Figure 1), reflecting both the rates of melt and the area over which melt is occurring. Relative amplitude — measured as the diurnal amplitude divided by the average daily discharge — is largest when most meltwater reaches the gage within one day of melting and is smallest when most meltwater arrives as part of the recession curve several days after melting (Collins and Young 1981). In most rivers, the relative amplitude correlates directly with total discharge (such as the Merced River, Figures 4a-d), suggesting that a greater fraction of meltwater travels via fast pathways to the gage during times of higher streamflow. However, if the relative amplitude is written as a linear function of discharge ( $A/Q = kQ$ , where  $A$  = amplitude of the diurnal cycle,  $Q$  = mean daily discharge, and  $k$  = the best-fit slope), the slope ( $k$ ) varies by a factor of five between wet and dry years in the Merced River (Figure 4d).

Figures 4a, 4b, and 4c illustrate how the drier year, 1994, has a larger relative amplitude than the wetter year, 1998. The larger relative amplitude reflects a larger portion of discharge travelling along fast pathways during the dry year. This suggests that, in the Merced Basin, subsurface flows are a greater percentage of the total runoff during wet years than dry years.

The Merced River occupies a glaciated basin, dominated by shallow soils and impermeable granite. Out of 34 river basins examined in the Sierra Nevada and Rocky Mountains, 20 exhibit increases in the slopes of relative amplitude vs. discharge relations in drier years. The basins that do not show such increases generally do not have a significant correlation between discharge and the relative amplitude. These basins have different types of rock and soils and probably have larger groundwater flow components.



**Figure 4:** Relationship between discharge and relative amplitude for the Merced River at Happy Isles, in California. (a) In a dry year, 1994, the relative amplitude correlates with the discharge. (b) In a wet year, 1998, the relative amplitude also correlates with the discharge, but while the discharge is much larger in 1998 than 1994, the relative amplitude is the same size or smaller. (c) Plotting relative amplitude as a function of discharge for the two years illustrates that, at every daily flow rate, the relative amplitude is greater during the dry year. (d) For all eight years analyzed here, the slope of the relative amplitude vs. discharge relation decreases as the total snow water for the season increases. The total snow water is calculated as the sum of the discharge during the season with a discernible diurnal cycle (dates pictured in 4a and 4b). This sum is normalized by basin area to provide an estimate of the average depth of the year's snowpack.

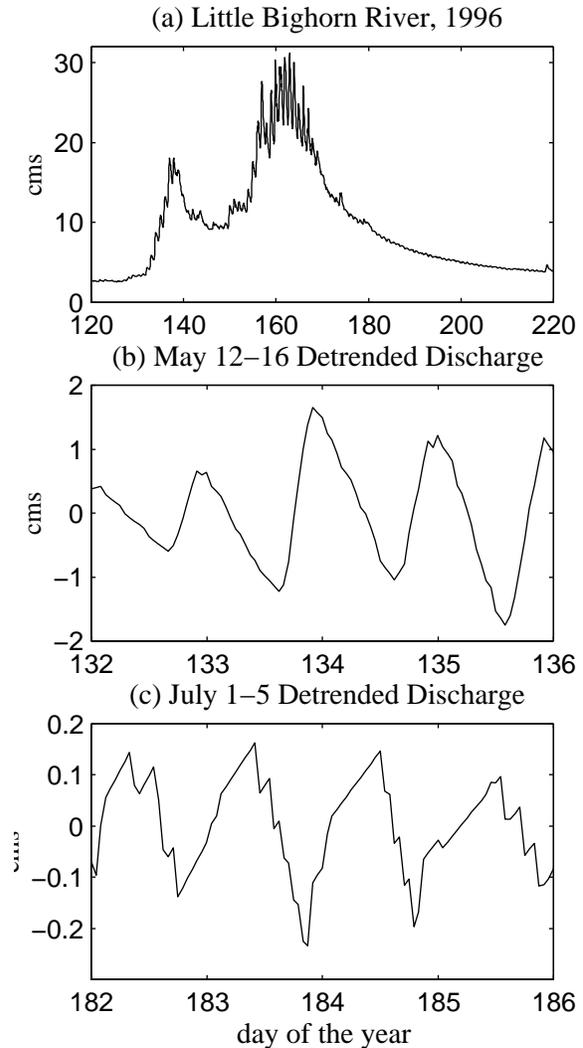
### 2.3 Diurnal cycle shape

Diurnal cycles in some streams switch from snowmelt-dominated characteristics in the spring to evapotranspiration/infiltration-dominated characteristics in the late summer (Lundquist and Cayan, 2002). This shift is most obvious in the shape of the diurnal cycle, as shown for the Little Bighorn River at Stateline near Wyola, Montana (Figure 5). Lundquist and Cayan (2002) found that where water is added diurnally, as in snowmelt, the diurnal cycle is characterized by a sharp rise and gradual decline (Figure 5b). Where water is removed diurnally, as by evapotranspiration or infiltration, the diurnal cycle is characterized by a gradual rise and sharp decline (Figure 5c). The change between these two shapes signifies a shift from wet (gaining water) to dry (losing water) conditions. The difference between the number of hours the hydrograph falls and the number of hours the hydrograph rises each day provides a simple numerical measure of the diurnal cycle's shape. Positive numbers indicate longer decays than rises and reflect snowmelt-domination. Negative numbers indicate longer rises and reflect evapotranspiration or infiltration. The date this index changes sign varies from year to year (Figure 6a), depending on the year's snowpack volume and thus the year's soil-moisture reserves. Figure 6b shows the date of this shift in the Little Bighorn River as a function of total annual runoff from 1996 to 2000. (1997 is excluded because frequent rainstorms in July obscured the diurnal cycle so that its characteristics could not be determined.) Overall, the Little Bighorn shifts between the two regimes later in the summer during wetter years.

### 3. DISCUSSION, CONCLUSIONS, AND FUTURE WORK

How will watersheds respond as temperatures warm and snowpacks diminish in size? Which areas of a basin will be driest, and how will ecosystems respond? Will snowmelt become more gradual (all winter long), and thus will streamflow derive more from groundwater and subsurface flows? Alternatively, will soils be depleted of moisture, resulting in smaller recharge rates and smaller subsurface components of flow? Will the snowmelt-dominated period each year become longer (but earlier) or just shorter?

The diurnal cycles of streamflow can help answer these questions. Conceptual modelling is needed to work out the details, but the observations provide clear indications that seasonal evolution of these diurnal cycles is a sensitive indicator of year-to-year differences in western snowmelt conditions. Contrasts between diurnal cycles in wet and dry years show that long-term changes and trends in western snowmelt would likely be evident in a carefully crafted set of indices based on the diurnal cycle characteristics. During drier years, the travel time between the melt source and the stream gage changes rapidly, perhaps indicating a more rapid retreat of the snowline away from the gage than in wet years. The



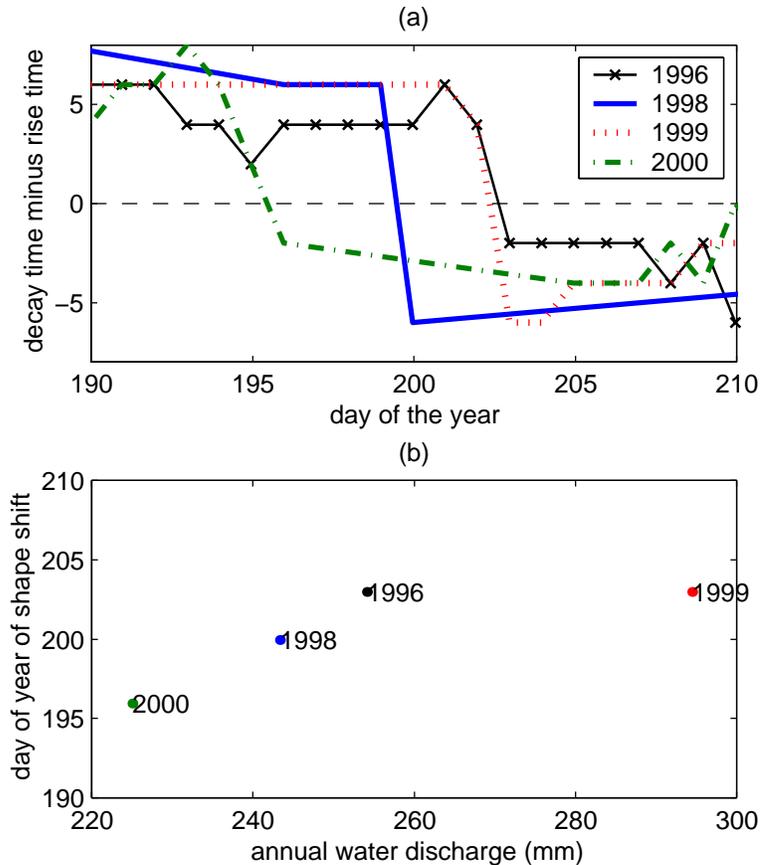
**Figure 5:** (a) The 1996 hydrograph for the Little Bighorn River, illustrating how the diurnal cycle changes as snowmelt forcing gives way to evapotranspiration/infiltration forcing. Periods illustrated in (b) and (c) were fit to a line, which was then subtracted out to accentuate the diurnal fluctuations.

relative amplitude of diurnal oscillations is smaller for a given discharge during dry years, suggesting that inflows from slower pathways, such as subsurface reservoirs, are depleted. Drier conditions also lead to earlier shifts from a snowmelt-dominated diurnal cycle (with a rapid rise and slow decay) to an evapotranspiration/infiltration-dominated diurnal cycle (with a slower rise and rapid decay).

Further work is needed to model how wetter and drier basin conditions will yield these diurnal cycle changes. Longer time-series and comparisons between basins with different soils, rocks, and vegetation will also help provide a clearer picture of the range of diurnal cycle responses to interannual variations in climate.

#### 4. REFERENCES

- Bengtsson, L. 1982: Groundwater and meltwater in the snowmelt induced runoff. *Hydrol. Sci. J.*, **27**, 147-158.
- Caine, N. 1992: Modulation of the diurnal streamflow response by the seasonal snowcover of an alpine basin. *J. Hydrology*, **137**, 245-260.
- Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson, 2001: Changes in the onset of spring in the Western United States. *Bull. Am. Met. Soc.*, **82**, 399-415.
- Colbeck, S. C., 1972: A theory of water percolation in snow. *J. Glaciol.*, **11**, 369-385.
- Collins, D. N., and G. J. Young, 1981: Meltwater hydrology and hydrochemistry in snow- and ice-covered mountain catchments. *Nordic Hydrol.*, **12**, 319-334.
- Davar, K. S. 1970: Section IX: Peak Flow – Snowmelt Events. *Handbook on the Principles of Hydrology*. D. M. Gray, Ed., Water Information Center, Inc., 9.1-9.25.
- Dettinger, M. D. and D. R. Cayan, 1995: Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *J. Climate*, **8**, 606-623.
- Dunne, T., A. G. Price, and S. C. Colbeck, 1976: The generation of runoff from subarctic snowpacks. *Water Resour. Res.*, **12**, 677-685.
- Grover, N. C., and A. W. Harrington, 1966: *Stream flow: measurements, records and their uses*. Dover Publications, Inc. 363 pp.
- Jordan, P. 1983: Meltwater movement in a deep snowpack 1. Field observations. *Water Resour. Res.*, **19**, 971-978.
- Lundquist, J. D. and D. Cayan, 2002: Seasonal and spatial patterns in diurnal cycles in streamflow in the Western United States. *J. Hydrometeorology*, **3**, 591-603.
- Roos, M., 1987: Possible changes in California snowmelt runoff patterns. *Proceedings of the 4<sup>th</sup> Annual PACLIM Workshop*, Pacific Grove, CA., 22-31.
- Singh, P. and V. P. Singh, 2001: *Snow and Glacier Hydrology*. Water Science and Technology Library, Kluwer Academic Publishers, 742 pp.
- Slack, J. R., and J. M. Landwehr, 1992: Hydro-climatic data network (HCDN): A U. S. Geological Survey streamflow data set for the united states for the study of climate variations, 1874-1988. *USGS Open-File Report 92-129*, 193 pp.



**Figure 6:** (a) Shifting of the flow in the Little Bighorn River from a longer diurnal decay time (snowmelt-dominated) to a longer rise time (evapotranspiration/infiltration-dominated), as the recent snowmelt season draws to a close. (b) The date of the shift as a function of the total discharge for each year. In general, drier years shift earlier in the summer.