A Recent Increase in Western U.S. Streamflow Variability and Persistence

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ABSTRACT

April–September streamflow volume data from 141 unregulated basins in the western United States were analyzed for trends in year-to-year variability and persistence. Decadal time-scale changes in streamflow variability and lag-1-yr autocorrelation (persistence) were observed. The significance of the variability trends was tested using a jackknife procedure involving the random resampling of seasonal flows from the historical record. The 1930s–50s was a period of low variability and high persistence, the 1950s–70s was a period of low variability and antipersistence, and the period after 1980 was highly variable and highly persistent. In particular, regions from California and Nevada to southern Idaho, Utah, and Colorado have recently experienced an unprecedented sequence of consecutive wet years along with multiyear extreme droughts.

1. Introduction

Water managers have been increasingly concerned about the expected impacts of climate variability and anthropogenically induced climate change on the hydrology of the western United States. As suggested by historical data analyses and model simulations, these variations and changes include shifts in the balance between snow and rainfall, resulting in earlier snowmelt and reduced late-summer streamflows (e.g., Hamlet and Lettenmaier 1999; Leung and Wigmosta 1999; McCabe and Wolock 1999; Mote 2003), and the possibility of an intensification of extreme hydrologic events (i.e., droughts and floods; Hamlet and Lettenmaier 1999; NAST 2000). Such climate-induced changes could add another layer of complexity to the management of natural resources in an already challenging environment of changing demographics and competing interests.

Several studies have focused on detecting trends in mean streamflow and in the magnitude of extreme events. Lettenmaier et al. (1994) found upward trends in monthly and annual streamflow volumes across most of the United States between 1948 and 1988. Mauget (2003) identified an increase in annual streamflow volumes after the 1970s, primarily in the Southeast, New England, and the Corn Belt. Several other studies (Lins and Slack 1999; Douglas et al. 2000) found that these

increases were due to increasing low and moderate flows, not high flows. McCabe and Wolock (2002) reinforced these studies, documenting a dramatic national increase in median and minimum flows after the mid-1970s. These studies together suggested that the hydrology of the United States was becoming more benign, with low flows becoming higher and high flows staying the same, despite the skyrocketing costs of flood damages (Pielke and Downton 1999). Groisman et al. (2001) asserted, contrary to other studies, that heavy precipitation events did increase, and the increases in high streamflows were detectable when one regionalized the data, as opposed to doing a site-by-site analysis. Specifically in the western United States, however, Groisman et al. (2001) asserted that there were no trends in streamflow volumes because less extensive snow cover was offsetting heavier precipitation. None of the above authors detected widespread significant trends in western U.S. streamflow; significant trends have mostly been observed in the eastern two-thirds of the United States.

No previous study, however, has investigated trends in streamflow variability and persistence. Long-term changes in the mean may have only subtle societal and environmental impacts, but changes in the magnitude and sequencing of extreme events could have direct impacts on ecosystems and natural resource managers (e.g., Voortman 1998). The hydrologic community has addressed streamflow variability and persistence but mostly in the context of developing statistical forecasting models and defining hydrologically homogeneous regions (Vogel et al. 1998). These studies assumed that streamflow persistence was caused by carryover storage

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of water in lakes and below the land surface and that precipitation, in general, is random, stationary, and lacks persistence.

This paper documents observed trends in western U.S. streamflow variability and persistence and discusses potential implications for water management and seasonal forecasting. It does not identify the forcing mechanisms for these changes, although it does suggest possible avenues for future research.

2. Data and methods

Slack and Landwehr (1992) identified a subset of Hydro-Climatic Data Network (HCDN) stream gauges as being free of significant human influences and therefore appropriate for climate studies. In the continental western United States, there are 475 such points west of 104.5°W longitude, excluding Alaska and Hawaii. This region is of particular interest to the Natural Resources Conservation Service (NRCS) because the agency has monitored snowpack and produced seasonal water supply outlooks in this region for almost 75 yr. Of these HCDN locations, a subset of 141 still-active gauges with 50 or more years of data was chosen. HCDN sites with "constant" yet significant irrigation withdrawals or regulation, as indicated by the HCDN metadata, were removed from this analysis.

Monthly streamflow data, obtained from the U.S. Geological Survey (USGS) online database (http://waterdata.usgs.gov/nwis/sw), were aggregated into April–September flow volumes. This period corresponds to the snowmelt and irrigation season across most of the interior western United States. For many locations this is also the target season of the NRCS water supply outlooks. Summer flows correlate very highly with annual flows in the interior western United States. For example, almost 90% of the annual flow on the East River at Almont, Colorado, occurs during April–September. However, this period does not correspond to the primary snowmelt period in Arizona and southern New Mexico (December–March) and instead reflects baseflow conditions and monsoon-driven variability. Similarly, the Cascade Mountains (Oregon and Washington) can experience rain on snow and midwinter melt before April. Analysis of annual flows in those regions may yield different results from those shown here.

At each stream gauge, the variance, lag-1-yr autocorrelation, coefficient of variation (CV; the standard deviation divided by the mean), mean, and skewness of the April–September flow volumes were computed for a 20-yr moving window over the period 1901–2002. Data had to be serially complete within the 20-yr moving window for these statistics to be computed; after 1940, at least 100 of the 141 available gauges had complete data during any given 20-yr period (Fig. 1). Note the sharp rise in data availability beginning in the 1930s. Although pre-1930 data were included in the computa-
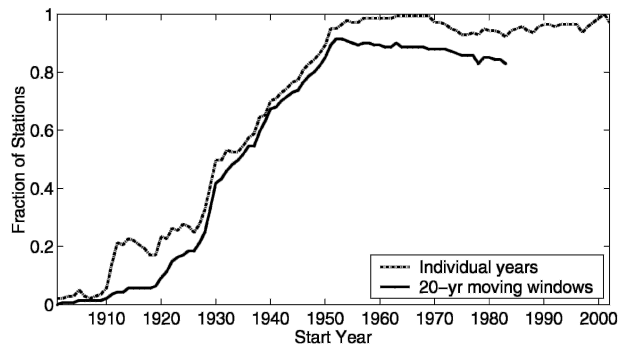

Fig. 1. Time series of fraction of stations reporting data for Apr–Sep in individual years (dashed line). The solid line indicates the fraction of stations reporting complete data in each 20-yr moving window, plotted at the start year of the window (e.g., 1970 = 1970–89).

tion of the various long-term moments (i.e., mean, variance, and skewness) mentioned below, the results during this early part of the record are highly sensitive to the clustering of sites in Idaho and Montana and do not reflect the behavior of the western United States as a whole. Therefore, this early period is not focused on in this study. Future researchers may fill the gaps in coverage and extend the period of record by investigating additional indicators that reflect hydrologic variability, such as tree rings.

The 20-yr time frame allowed a large enough sample size to develop reliable interperiod estimates of the variance and persistence (although a longer period would be more suitable for reliably estimating higher-order moments such as skewness). It also created enough moving-window periods to observe any decadal variability or trends. This paper analyzes annual values over 20-yr periods and therefore cannot provide any information about inter- or intraseasonal variability and persistence. Future results could be generalized across all time scales using wavelet analysis, which investigates the changes in the power spectrum of data versus time (Torrence and Compo 1998). For example, Cahill (2002) used wavelets to describe the long-term increase in short-term (<2 week) streamflow variability across the United States.

The variance for each 20-yr window was expressed as a ratio, relative to the variance of the period of record. If this ratio was greater than one, the period's streamflow was more variable than usual, and if the ratio was less than one, the period's streamflow was less variable than usual. The 20-yr-moving-window lag-1-yr autocorrelation was used to identify trends in persistence. Negative autocorrelation means that wet years tend to be followed by dry years and vice versa ("antipersistent") whereas positive autocorrelation indicates a tendency for consecutive dry and wet years ("persistent"). An increase in persistence implies a shift from high-frequency to low-frequency variability.

To support this analysis, the CV, mean, and skewness

for each 20-yr moving window were also computed. The CV is of interest in that it accounts for changes in variability associated with changes in the mean (i.e., drier periods tend to have lower variability). Each station's skewness was expressed as an anomaly relative to the period of record skewness. Most basins in the western United States have positive skewness, indicating a tendency for lower streamflow years to outnumber higher streamflow years and for a few unusually large events to have a major influence on the shape of the distribution.

One objective of this study was to determine if the variability during any given period was different from the variability of the period of record. The null hypothesis could be evaluated using an F test. This test, however, assumes that the data are independent and follow a Gaussian distribution, the second being a poor assumption for skewed flows in the semiarid western United States.

Instead, the significance of the change in variability was evaluated empirically. For each site, 20 yr (not necessarily consecutive) of available data from the period of record were selected at random without replacement. The ratio of the 20 random years' variance to the variance of the period of record was computed. This resampling was repeated 10 000 times (200 000 random selections of years per site) to obtain an empirical distribution of the variance ratio for each location. The observed variance ratio for each 20-yr period was compared to the variance ratios of the 10 000 synthetic periods to determine the probability of obtaining the observed ratio by chance. This same jackknife procedure was repeated for the CV, mean, and skewness.

This sampling technique, which drew randomly from the entire period of record, may have underestimated the statistical significance of the result compared to a technique that only drew from years outside the 20-yr window (e.g., an analysis of 1950–69 flows that randomly selected only years before 1950 and after 1969). This more appropriate technique, however, would have involved almost two orders of magnitude more analysis than the selected technique and thus was prohibitively expensive. The selected technique violates the assumption of independent samples in that it allows data to be compared to itself, although the effect on the results is likely to be small.

3. Results

Figure 2a shows a time series of the fraction of available stations reporting periods of significantly increased variability (solid) and decreased variability (dashed). Significance was determined by comparing each 20-yr-moving-window variance ratio to the empirically derived distribution and identifying those values that were greater than the 90th percentile (increased variability) or less than the 10th percentile (decreased variability).
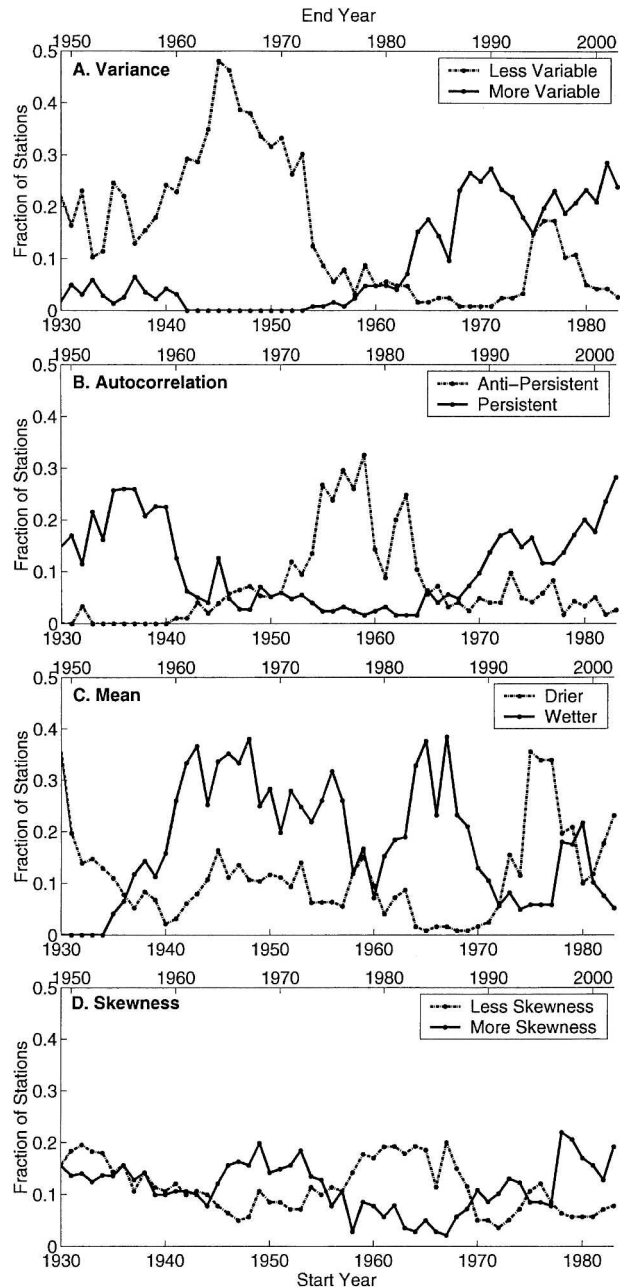

FIG. 2. (a) Time series of the fraction of western U.S. streamflow stations reporting significant increases (solid) or decreases (dashed) in 20-yr-moving-window variance compared to the period of record. Significance is defined as the 10th and 90th percentiles. (b) Fraction of stations reporting interannual lag-1-yr autocorrelation of greater than 0.3 (solid) or less than –0.3 (dashed). (c) As in (a), but for the mean. (d) As in (a), but for the skewness. The bottom x axis indicates the start year of the 20-yr moving window, and the top x axis indicates the end year.

The period 1945–64 was the most geographically widespread period of low variability in modern history, with 48% of sites reporting significantly below-average variability. During this period, none of the 104 reporting

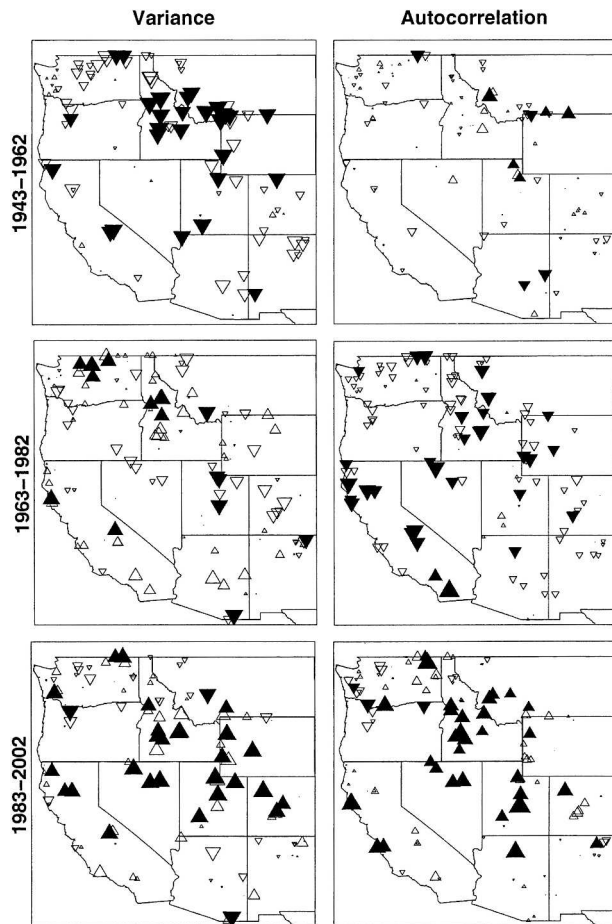**Variance**   **Autocorrelation**

FIG. 3. Maps of streamflow (left) variance ratio significance and (right) autocorrelation for three 20-yr epochs (top, middle, and bottom). Upward pointing triangles indicate positive autocorrelation or increased variance relative to the period of record. Downward pointing triangles indicate negative autocorrelation or decreased variance. Filled symbols indicate autocorrelation greater/less than ±0.3 or statistically significant variance departures. The size of the symbol is proportional to the magnitude of the departure.

sites in the western United States had significantly above-average variability. The variability decrease was most pronounced in Idaho and Montana, with decreases also in the Cascades, central California, the Great Basin, and the Southwest (see also Fig. 3, upper left). Increased variability marked the period after the mid-1960s, when 29% and 27% of sites reported significantly above-average variability in 1982–2001 and 1971–90, respectively. This variability increase was focused primarily in California, the Great Basin, and northwestern Colorado (Fig. 3, lower left). From 1976 to 1995, there was also a small rise in the number of sites that had less variability, primarily confined to the Cascade Mountains of Washington and Oregon.

Figure 2b shows a time series of the fraction of available stations whose lag-1 autocorrelation was greater than (solid) or less than (dashed) ±0.30 (approximately

10% significance for a one-tailed test) in a 20-yr moving window. This time series shows that in 1936–55, 26% of sites had high year-to-year persistence. By 1959–78, 33% of sites had highly negative autocorrelation, a tendency for wet years to be followed by dry years and vice versa. In the most recent 20 yr, 28% of the sites had high year-to-year persistence, the most widespread of any period of history (Fig. 3, lower right).

One might expect that the increase in variability in the recent period was associated with increases in mean flows (e.g., the 1950s drought was a period of low variance). Especially where flows are skewed, one or several exceptionally wet years can significantly raise both the 20-yr mean and variance. As mentioned in the introduction, few authors have been able to detect trends in mean flow in the western United States. Additionally, in the analysis performed here, statistically significant changes in the CV were very well correlated with changes in the variance, suggesting that the changes in the mean had a secondary influence on these results, if at all. Figure 2c shows a time series of the fraction of available stations reporting periods of significantly increased mean flows (solid) and decreased mean flows (dashed). Generally, periods of high flow (1940s–70s) and low flow (1930s–50s and 1980s–present) do not necessarily match periods of high or low variance. Additionally, the spatial patterns of mean and variance trends do not match (cf. Fig. 3 left and Fig. 4 left).

Finally, Figs. 2d and 4, right, show the behavior of streamflow skewness over time. The late 1940s to early 1970s was a period of relatively high streamflow skewness, followed by lower skewness from the 1960s–80s and a return to higher skewness in recent times, especially in northern states. The most recent 20-yr period had the highest percentage of stations reporting a positive skew anomaly (62%) of any period in history while the 1978–97 period had the most number of sites with statistically significant skewness increases (22%). Therefore, there has been an increasing tendency toward having many low-flow years, punctuated by a limited number of relatively high flow years. It is very difficult to develop reliable estimates of higher-order moments (e.g., skewness) with a limited set of data (e.g., 20 yr), so these findings should be interpreted with caution.

The results shown in Fig. 2 were somewhat influenced by the spatial distribution of sites used in this analysis, with a high density of sites in Idaho, Montana, and the Pacific Northwest and a sparse network of sites in Nevada and the Southwest. There was also a very strong cross correlation of flows across sites; although the spatial correlation varies regionally, in the interior west, sites 650 km apart at the same latitude generally have interannual flow correlations of 0.7. This correlation is less for sites in the same longitude band, consistent with Cayan's (1996) investigation of snowpack. Future research should investigate the field significance of
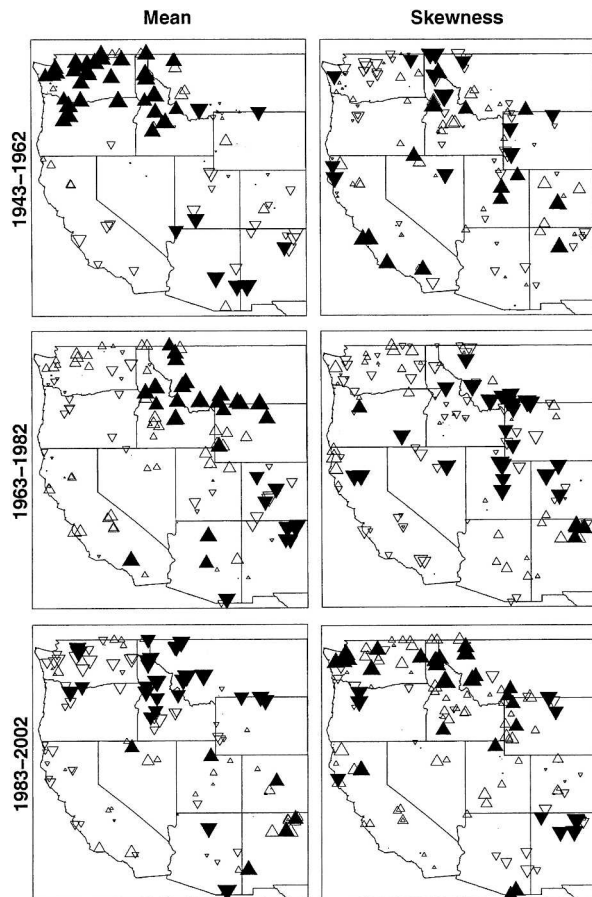
FIG. 4. As in Fig. 3, but for the (left) mean significance and (right) skewness significance. See Fig. 3 for symbol definitions.

these results, perhaps by using cluster or principal components analysis.

It is also possible that autocorrelation, variance, skewness, and the mean are interrelated and that some configurations (e.g., high autocorrelation and low variance) may be naturally easier to achieve than others (e.g., high autocorrelation and high variance). Each location's time series of 20-yr-moving-window autocorrelation, variance, skewness, and mean were correlated, and the interannual relationships between the four characteristics investigated. Although individual sites had large magnitude correlations among the different characteristics (e.g., autocorrelation and variance at a location may have tended to vary together), there was no obvious spatial pattern or regional coherence to these correlations. At best, there was a weak negative correlation between mean and skewness (57% of the sites had a correlation between mean and skewness less than −0.3) and a weak positive correlation between mean and variance (48% had a correlation greater than 0.3). The westwide median correlation between autocorrelation and variance was 0.055, far from being statistically significant. This site-based analysis suggests

that it is likely that streamflow variance and persistence change independently of one another. It is unknown whether a more sophisticated analysis involving regionalization of the data (e.g., Groisman et al. 2001) would reveal clusters of sites whose variance and persistence vary together as a region.

As a representative example of a shift from low variability and antipersistence to high persistence and high variability, Fig. 5 displays a time series of flows in northwestern Colorado. Although individual years may vary, the general pattern of flows is typical of what was experienced throughout Colorado, Utah, and Nevada. The period 1935–75 was relatively benign, with many years of consistently near-normal flows, especially from the mid-1960s to 1970s. The series of four consecutive very wet years (1983–86) was unprecedented, as was the extended deficit that followed (1987–94). Again, a wet period ensued in 1995–98 followed by near-record drought conditions in 2002. The period after 1980 displays very high variability and year-to-year persistence whereas prior decades were less variable and less persistent.

4. Discussion

Decadal time-scale changes in streamflow variability and autocorrelation have been observed in the streamflow records of the western United States. The 1930s–50s can be described as a period of low variability and high persistence, the 1950s–70s as a period of low variability and antipersistence, and the period after 1980 as high variability and high persistence.

These various streamflow characteristics were not necessarily varying on the same time scales or coincidentally; increased variability preceded increased autocorrelation by approximately 5–10 yr, which in turn preceded increased skewness by another 5 yr. Nonetheless, the various phenomena became "in phase," making the most recent 20 yr the only part of the record that was highly variable, highly persistent, and highly skewed.

A period of high persistence, variance, and skewness is perhaps the most challenging scenario for water managers. For example, a series of consecutive wet years (e.g., Fig. 5, 1983–86) may overwhelm reservoirs and inflate stakeholder expectations about the amount of water available. An extended stretch of dry years then exhausts storage reservoirs and does not give them a chance to recover (e.g., 1987–94). Smaller reservoirs that do not have multiple-year storage capacity would be especially vulnerable. In comparison, individual dry years interspersed among wet years are much more tolerable.

These decadal oscillations also have implications for water supply forecasting. Statistical streamflow forecasting techniques that use persisted spring and summer streamflow as a predictive variable for next year's
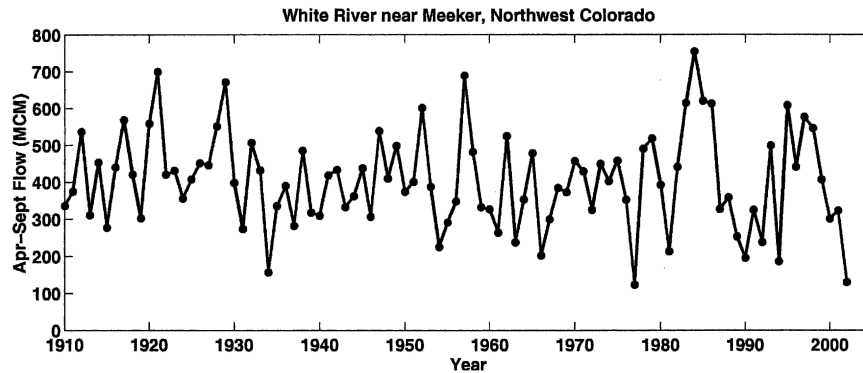
FIG. 5. Time series of Apr–Sep flow at the White River near Meeker, CO (USGS ID 09304500), from 1910 to 2002. (10^6 m^3)

flows will lead the forecaster astray when the climate regime switches between positive and negative autocorrelation. It is unknown at this time whether procedures that use antecedent autumn streamflow (e.g., September–November) as a predictive variable to index the effects of soil moisture and groundwater variability are also vulnerable to this effect. In addition, statistical forecast procedures work best under typical basin conditions; when many consecutive dry years create unprecedented basin moisture deficits, forecast skill may suffer.

The causes of the recent sequence of flows are unknown. The HCDN stations are free of significant human influence, and the signals detected in this study were geographically widespread, ruling out changes in basin characteristics, soil properties, or local management practices as the causes of changes in variability. It is likely that the changes in persistence and variability have climatic origins.

Detecting changes in precipitation and temperature may be more difficult than detecting changes in streamflow because of the temporal and spatial integrative behavior of watersheds. The climate signal may be spread across seasons such that, for example, winter (December–March) precipitation variability in California may be rising while spring (April–June) precipitation variability is rising in Colorado, resulting in an April–September streamflow variability increase in both locations. Coincidentally, the seasonality of the increased precipitation variability has serious implications for water supply forecast accuracy. Given that water supply forecasts are primarily based on existing initial conditions (e.g., current snowpack), if extreme (high or low) precipitation occurs before the forecast issue date (e.g., 1 April), the forecast is more accurate than if the extreme event occurs after the forecast issue date (Pagano et al. 2004).

If the driving factor in this recent variability increase is discovered, it may be a source for long-range decadal climate forecasts. Recently, McCabe et al. (2004) explained almost three-quarters of the spatial and tempo-

ral low-frequency variability of drought across the United States using the Pacific decadal oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and a unidirectional trend possibly due to climate warming. Those authors examined the frequency of average annual precipitation falling below a particular threshold and did not investigate variability or persistence. Nonetheless, future research is necessary to determine if the phenomena are related and if streamflow variability and persistence will continue to increase.

The current region of high streamflow variability (California, Nevada, Utah, and Colorado) is also known for its low seasonal precipitation predictability (Hartmann et al. 2002). In contrast, the El Niño–Southern Oscillation (ENSO) and the PDO typically affect Oregon, Washington, and Idaho as well as Arizona and New Mexico (Redmond and Koch 1991; Mantua et al. 1997). The mechanism driving increased variability could be masking otherwise useful ENSO- and PDO-related climate forecast skill in this highly unpredictable region.

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