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THE RECENT INCREASE IN WESTERN US STREAMFLOW VARIABILITY AND PERSISTENCE

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1. INTRODUCTION

Water managers are increasingly concerned about the expected impacts of anthropogenically induced climate change on the hydrology of the western US. Model simulations suggest that widespread temperature increases will induce changes in the balance between snow and rainfall. Snowpack will melt earlier in the season, and streamflow will occur earlier and have reduced late summer streamflows. Research also hints at the possibility of an intensification of extreme hydrologic events (i.e., droughts and floods; NAST, 2000). Researchers have put forth that climate change will add another layer of complexity in the management of natural resources in an already challenging environment of changing demographics and competing interests.

Several studies have focused on detecting observed trends in mean streamflow and trends in the magnitude of extreme events. Lettenmaier et al. (1994) find upward trends in monthly and annual streamflow volumes across most of the US between 1948-1988. Mauget (2003) identifies 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) find that these increases are due to increasing low and moderate flows, not high flows. McCabe and Wolock (2002) reinforce these studies, finding a dramatic national increase in median and minimum flows after the mid-1970s. These studies together suggest that the hydrology of the US is 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) assert, contrary to other studies, that heavy precipitation events are increasing and the increases in high streamflows are detectable when one regionalizes the data, as opposed to doing a site-by-site analysis. Specifically in the western US, however, Groisman et al. (2001) assert that there are no trends in streamflow volumes because less extensive snow cover is offsetting heavier precipitation.

No previous study, however, investigates the 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 can 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 assume that streamflow persistence is caused by soil moisture carryover and that precipitation is random, stationary, and lacks persistence.

This study documents observed trends in western US streamflow variability and persistence and discusses potential implications for water management and seasonal forecasting.

2. DATA AND METHODS

Slack and Landwehr (1992) identify a subset of “Hydro-Climatic Data Network” (HCDN) streamgages as being free of significant human influences and therefore appropriate for climate studies. In the continental western US, there are 475 such points west of 104.5° west longitude, excluding Alaska and Hawaii. Of these locations, a subset of 140 still-active gages with 50 or more years of data is chosen. HCDN sites with “constant” yet significant irrigation withdrawals or regulation, as indicated by the HCDN metadata, have been removed from the analysis. Monthly streamflow data, obtained from the US Geologic Survey online database (http://waterdata.usgs.gov/nwis/sw) are aggregated into April-September flow volumes. This period corresponds to the snowmelt and irrigation season across most of the interior western US.

At each streamgage, the variance of the April-September flow volumes is computed for a 20-year moving window over the period 1901-2002. This variance is then expressed as a ratio, relative to the period of record variance. If this ratio is

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greater than one, the period's streamflow is more variable than that of other periods. If the ratio is less than one, the period's streamflow volume is less variable than in other periods. The 20-year moving window lag-1 year autocorrelation is also computed. Negative autocorrelation means that wet years tend to be followed by dry years and vice versa ("anti-persistent") whereas positive autocorrelation indicates a tendency for consecutive dry and wet years ("persistent").

To support this analysis, two additional diagnostic parameters are computed. The moving window coefficient of variation (CV, the standard deviation divided by the mean) is calculated. The CV is of interest in that it accounts for changes in variability caused by changes in the mean (i.e., dry periods tend to have low variability). The skewness also is calculated for each moving window and presented as an anomaly relative to the period of record skewness. Most basins in the western US have positive skewness, indicating a tendency for low streamflow years to outnumber high streamflow years.

Data must be serially complete within the 20-year moving window for the variance, CV, skewness, or autocorrelation to be valid; after 1940, at least 100 of the 140 available gages had valid data during any given 20-year period. The 20-year time frame was chosen arbitrarily; future results could be generalized across all timescales using wavelet analysis, which investigates the changes in the power spectrum of data versus time (Torrence and Compo, 1998). An increase in persistence implies a shift from high frequency to low frequency variability. For example, Cahill (2002) uses wavelets to describe the long term increase in short term (< 2 week) streamflow variability across the US.

The objective of this study is to determine if the variability during any given period is different from the variability of the period of record. The null hypothesis can 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 semi-arid western US.

Instead, the significance of the change in variability is evaluated empirically. For each site, 20 years of available data from the period of record are selected at random without replacement, and the ratio of the random years' variance to the period of record variance is computed. This sampling is repeated 10 000 times. The observed variance ratio for each 20-year period is compared to the variance ratios of the synthetic samples to determine the probability of obtaining the observed ratio by chance. This Monte Carlo procedure is then repeated for the CV. This technique, which draws randomly from the entire period of record, may underestimate the statistical significance of the result compared to a technique that only draws from years outside the 20-year window (e.g., an analysis of 1950-1969 flows that only selects random years before 1950 and after 1969). The alternate technique, however, involves almost two orders of magnitude more analysis than the selected technique and thus is prohibitively expensive.

3. RESULTS

Figure 1a shows a time series of the percent of available stations reporting statistically significant (p=0.1) periods of increased variability (solid) and decreased variability (dashed). The period 1945-1964 is the most geographically widespread period of low variability in modern history, with 48% of sites reporting statistically significant decreases in variability. During this period, none of the 104 reporting sites in the western US had significantly increased variability. The variability decrease is most pronounced in Idaho and Montana, with decreases also in the Cascades, central California, the Great Basin, and the Southwest. Increasing variability marks the period after the mid-1960s, with 29% and 27% of sites reporting statistically significant increased variability in 1982-2001 and 1971-1990, respectively. This variability increase is focused primarily in California, the Great Basin, and northwestern Colorado (Figure 2, left).

Incidentally, the 1945-1964 low variability period is also a period of relatively high streamflow skewness, as measured by the 20-year skew anomaly with respect to the skewness of the period of record. A relative minimum occurred in 1964-1983 (80% of sites reporting a negative skew anomaly). The current 20-year period has the highest percentage of stations reporting a positive skew anomaly (62%) of any period in history (not shown).

One might expect that the increase in variability in the recent period is caused by increases in the mean (e.g., the 1950s drought is a period of low variance). As mentioned in the introduction, few authors have been able to detect trends in mean flow in the western US. Additionally, in the analysis performed here, statistically significant changes in the CV are very well correlated with changes in the variance, suggesting that the changes in the mean have a secondary influence on these results, if at all.

Figure 1b shows a time series of the percent of available stations whose lag-1 autocorrelation is greater than (solid) or less than (dashed) +/- 0.30 in a 20-year moving window. This time series shows that in 1936-1955, 26% of sites had high year-to-year persistence. By 1959-1978, 33% of sites had negative autocorrelation, a tendency for wet years to be followed by dry years and vice versa. In the most recent twenty years, 28% of the sites have returned to high year-to-year persistence, the most widespread of any period of history (Figure 2, right).

The results shown in figure 1 are 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. Future research should investigate the field significance of these results, perhaps by using cluster or principal components analysis.

4. DISCUSSION

Decadal timescale changes in streamflow variability and autocorrelation have been observed in the streamflow records of the western US. The 1930s-1950s can be described as a period of low variability and high persistence, the 1950s-1970s as a period of low variability and anti-persistence, and the period after 1980 as high variability and high persistence.

These various streamflow characteristics are not necessarily varying on the same time scales or coincidentally; increases in variability have preceded increases in autocorrelation by approximately 5-10 years, which have in turn preceded increases in skewness by another five years. Nonetheless, the various phenomena have become “in phase”, making the most recent 20 years the only part of the record that is highly variable, highly persistent, and highly skewed.

This triple alignment is perhaps the most challenging scenario for water managers. One possible scenario involves a series of consecutive wet years that overwhelm reservoirs and inflate stakeholder expectations about the amount of water available. An extended stretch of dry years exhausts storage reservoirs and does not give them a chance to recover. 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 flows will lead the forecaster astray when the climate regime switches between positive and negative autocorrelation. The changes in persistence and variability are undoubtedly linked to changes in precipitation and temperature and not changes in basin characteristics or soil properties. 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 are also vulnerable to this effect.

The causes of the current triple alignment are unknown. It is interesting to note that the spatial pattern of increased variability for 1963-1982 (high in the Pacific Northwest and Southwest, Figure 2, left middle) is the inverse of the pattern in 1983-2002 (high in California, Nevada, Utah, and Colorado, Figure 2, left bottom). Both of these patterns bear general resemblance to the north-south dipole associated with the El Niño/Southern Oscillation and the Pacific Decadal Oscillation (Redmond and Koch, 1991; Mantua et al., 1997). Future research is necessary to determine if the phenomena are related and if variability and persistence will continue to increase.

5. ACKNOWLEDGEMENT

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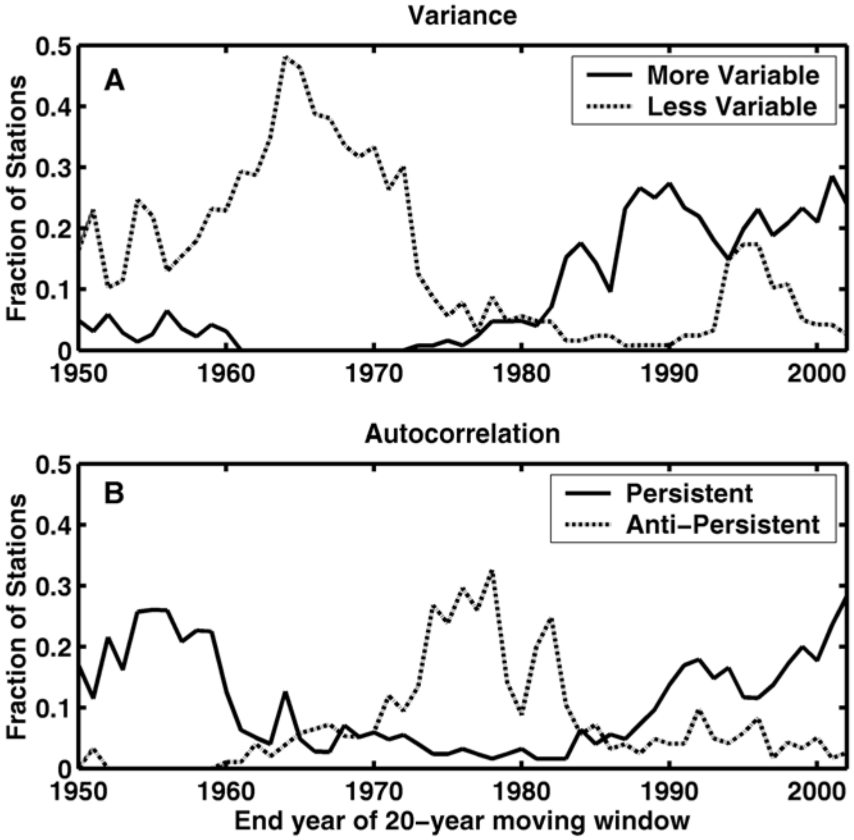

Figure 1. A: Time series of the fraction of western US streamflow stations reporting statistically significant increases (solid) or decreases (dashed) in 20-year moving window variance compared to the period of record. B: Fraction of stations reporting lag-1 year autocorrelation of greater than 0.3 (solid) or less than –0.3 (dashed). All data are plotted at the end year of the 20-year moving window.

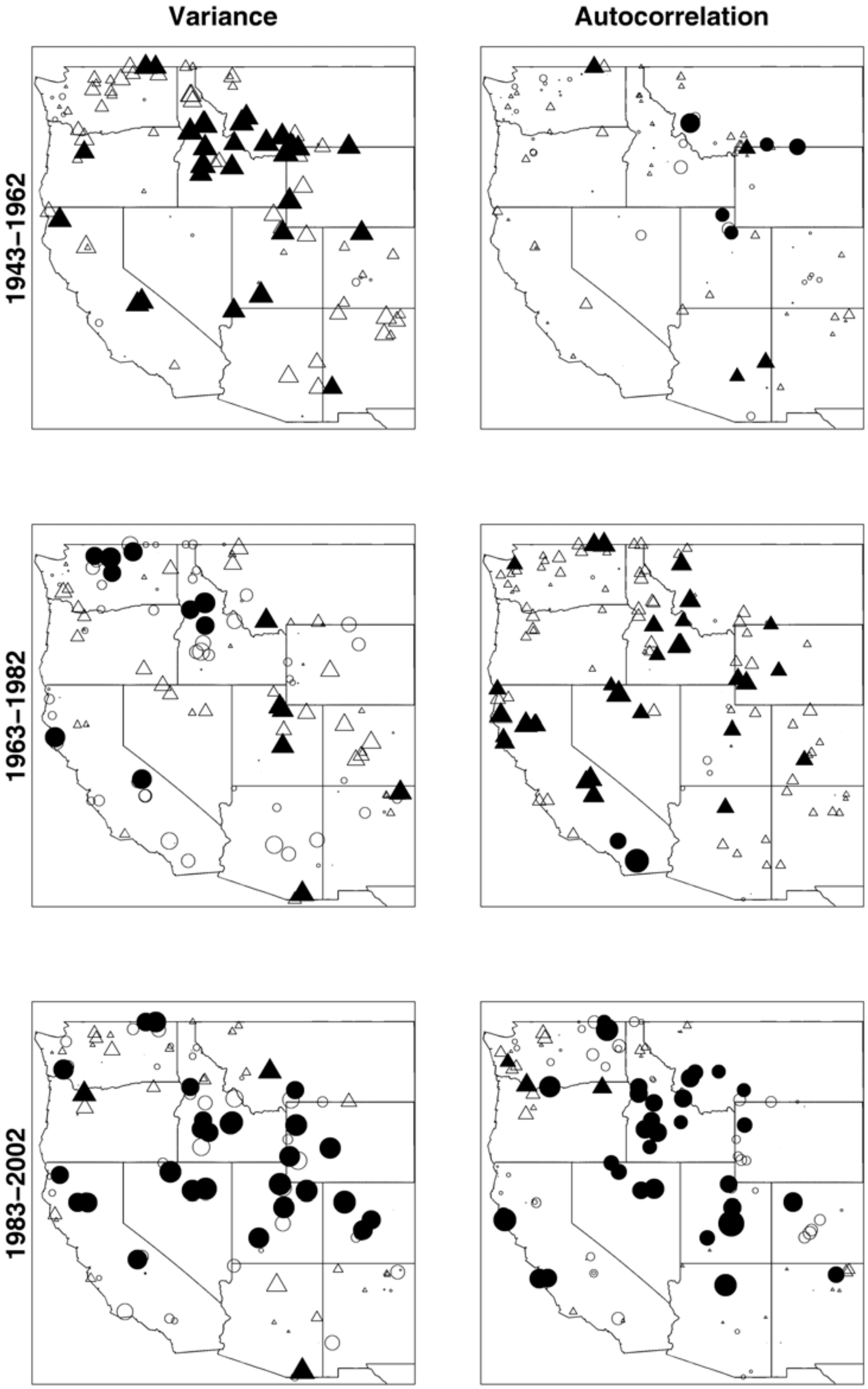

Figure 2 Maps of streamflow variance ratio significance (left) and autocorrelation (right) for three 20-year epochs (top, middle and bottom). Circles indicate positive autocorrelation or increased variance relative to the period of record. Triangles indicate negative autocorrelation or decreased variance. 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.