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LETTERS

Decreasing Reliability and Increasing Synchroneity of Western North American Streamflow

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ABSTRACT

Assessing climate-related societal vulnerability and mitigating impacts requires timely diagnosis of the nature of regional hydrologic change. A late-twentieth-century emergent trend is discovered toward increasing year-to-year variance (decreasing reliability) of streamflow across the major river basins in western North America—Fraser, Columbia, Sacramento–San Joaquin, and Upper Colorado. Simultaneously, a disproportionate increase in the incidence of synchronous flows (simultaneous high or low flows across all four river basins) has resulted in expansive water resources stress. The observed trends have analogs in wintertime atmospheric circulation regimes and ocean temperatures, raising new questions on the detection, attribution, and projection of regional hydrologic change induced by climate.

Recent floods and droughts in the western North American (WNA) region have underscored the need to understand the consequences of climate variations and change for hydrologic systems (CDWR 2000; NCDC 2002; NOAA 1997). A diagnosis of the changes in streamflow regimes (most often characterized by the annual mean and interannual variability) is useful in efforts to detect regional hydrologic change. The attribution for such changes is then essential in distinguishing natural from anthropogenic origins, and thereby clarifying the probability that any detected change may persist. For existing water resources infrastructure, changes in the flow regimes imply that a design based on historical flow statistics may no longer be suitable to respond to the present and future flows, thus bringing into question the reliability and the level of protection such systems may offer for critical objectives, such as flood control (Jain and Lall 2001). It has been shown that the changes in the runoff variance are at least as important as the changes in the mean statistics in engendering shortfalls in a reservoir's capacity to meet water demands for multiple, competing objectives, including agriculture, consumptive use, hydropower generation, flood control, and fisheries (Jain et al. 2002). In contrast with other studies that assessed annual runoff trends (Lettenmaier et al. 1994; Zhang et al. 2001; McCabe and Wolock 2002), we investigate the changes in year-to-year streamflow variability, together with an analysis of the synchroneity of flow regimes over WNA as a whole. Both are useful metrics of the extent and severity of regional hydrologic stress. Because large river basins are excellent integrators of hydroclimatic variability, our analysis highlights the coherent variations in runoff volumes due to large-scale climatic variations and change, while limiting the influence of land-use changes on runoff volumes.

A nearly century-long record of water year runoff volumes for the four river basins in WNA is analyzed (Fig. 1). A water year is a 12-month period with 1 Oc-

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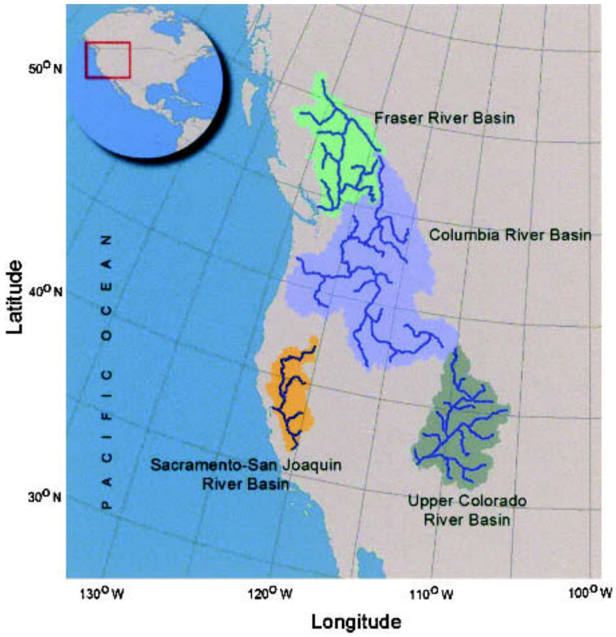

FIG. 1. Map of the WNA region showing the four major river basins—Fraser, Columbia, Sacramento–San Joaquin, and Upper Colorado. The annual cycle of streamflow, driven dominantly by wintertime precipitation and snowpack, reflects an integration of regional hydroclimatic variability across the river drainages [contributing drainage area for the streamflow records investigated here are (km^2) 217 000 (Fraser), 614 000 (Columbia), 54 000 (Sacramento–San Joaquin), and 289 000 (Upper Colorado)]. River basin–wide precipitation for winter (Oct–Mar) is highly correlated with the water year (Oct–Sep) runoff volumes [correlations for the 1948–2001 period: 0.71 (Fraser), 0.92 (Columbia), 0.91 (Sacramento–San Joaquin), and 0.66 (Upper Colorado)].

tober as the start date. For example, the 2001 water year considers total flow volume for the October 2000–September 2001 period. Throughout this letter, the terms annual and water year runoff volumes are used interchangeably. Furthermore, the runoff volumes for the Columbia River Basin, Sacramento–San Joaquin River Basin, and Upper Colorado River Basin are the naturalized runoff estimates that account for major flow diversion and storages. The runoff data for the Fraser River Basin is affected by some upstream storages (and diversions); however, a large fraction of the water diverted for hydropower generation is returned to the river.

Our trend analysis of these records yielded no conclusive results regarding changes in the mean annual runoff volumes. On the other hand, the year-to-year variations within sliding 30-yr windows have materially increased. Figure 2a shows the raw annual time series of runoff volumes for the individual river basins, and the substantial decadal variations are highlighted. Especially noteworthy are the recent variations (1972–2001 period, shaded gray) in runoff volumes—those marked by an apparent coherency of swings across the four river basins (cf. smoothed solid curves). Figure 2b compares the empirical runoff probability distributions for the common period of record. Empirical probability density functions are computed using a nonparametric kernel density estimator with an optimal normal smoothing parameter (Bowman and Azzalini 1997). Probability density estimates shown in Fig. 2b are based on standardized runoff volumes to allow a common scale for all four river basins. The last three decades (red curves) show an increase in extreme event (in terms of water year runoff volumes) occurrences as indicated by a higher frequency of the tail probabilities (high and low flows) compared to the earlier period of record. This increase in extreme flow statistics since 1972 is consistent across all river basins.

We thus further investigate the unusual nature of recent variance increases by computing overlapping 30-yr estimates of the coefficient of variation (CV) for the full length of the individual runoff volume records. A 30-yr time period is widely used in planning and design as a reasonable averaging period for obtaining the climate normal. This is based on the assumption that the embedded variability is representative of a climate normal (Guttman 1989). Here, CV is defined as the ratio of sample standard deviation to the sample mean, expressed as a percentage. The estimates in Fig. 2c corroborate the near-monotonic increase in the variability of streamflow in the post-1970 period. Note that the increase in the CV is occurring predominantly through an increased variability of the annual flow volumes. The CV estimates from precipitation data for the four basins confirm the recent streamflow trends (not shown). As such, these measured increases in the CV imply corresponding decreases in reliability and resilience of storage reservoirs (Vogel et al. 1999).

A primal concern in WNA water resources management is the incidence of water excess or deficit spanning all four river basins simultaneously. This is due to the increasing interdependence between the river basins for hydropower, agriculture, and fisheries products, which permit mitigation of impacts from water resources deficits in one basin by surpluses in a neighboring basin. Furthermore, adequate resource allocation for drought relief and flood protection becomes a major challenge when all four river basins experience water shortages or flooding. It is thus important to ascertain whether the consistent signature for increased extreme flows for WNA during the last three decades has been manifest in precisely the same years across the four basins. A principal component analysis (PCA; Lebart et al. 1984) of the ranked historical streamflow record reveals two dominant spatial patterns of variability (Table 1). The first principal component (PC1) has loadings of the same sign across all four river basins, reflecting synchronous variations. The second principal component (PC2) is characterized by a north–south pattern, with Fraser and Columbia annual flows varying out of phase with the Sacramento–San Joaquin and Upper Colorado annual flows. This pattern has been

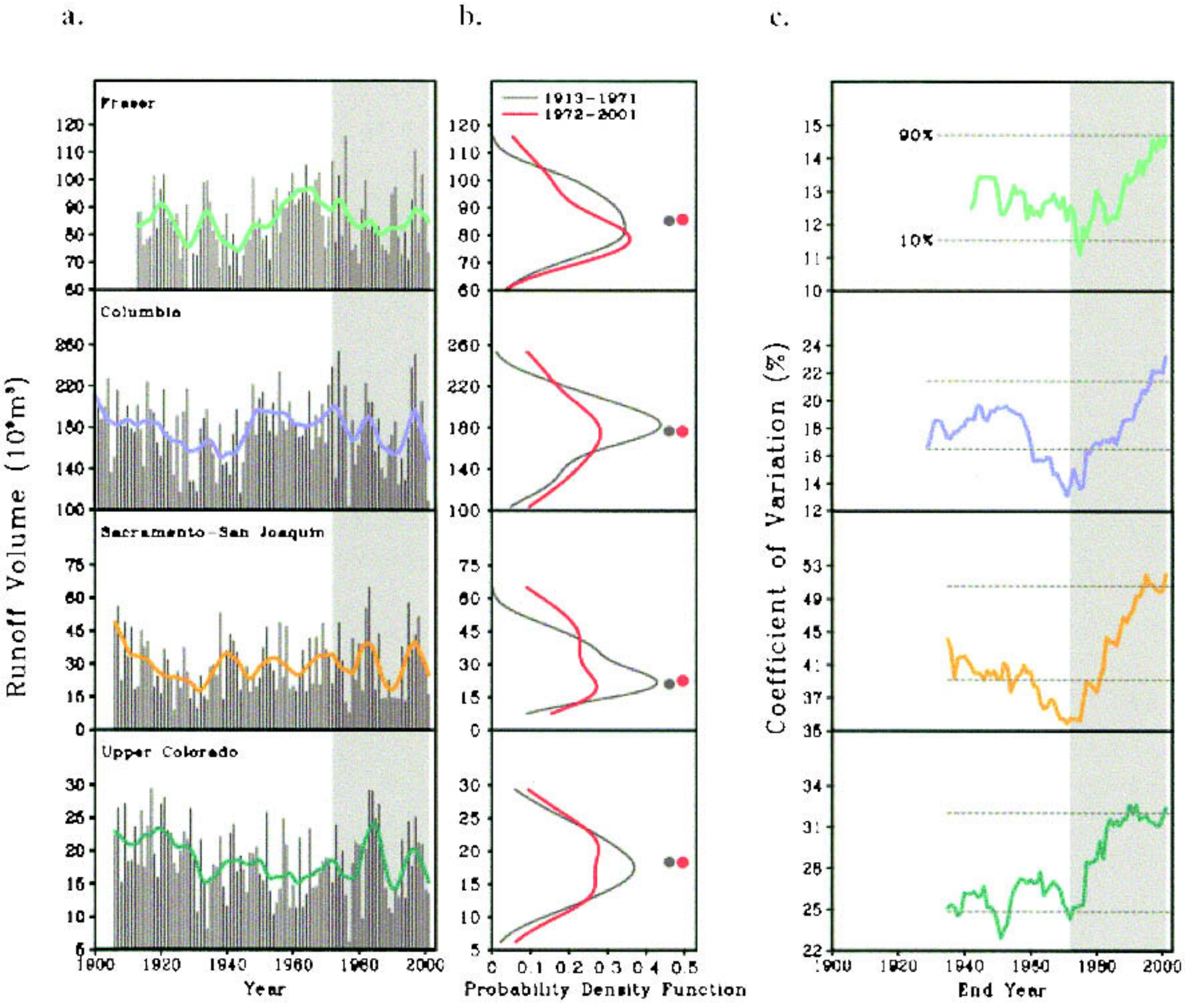

FIG. 2. Historical variability and change in the water year (Oct–Sep) runoff volumes. (a) Vertical bars represent water year runoff volumes for the individual years. A robust linear smoother with 11-yr span (solid line) provides an estimate of the decadal and longer-term variations in streamflow. The gray-shaded region highlights the last three decades of the record (1972–2001). (b) Empirical probability density function for the common period of record (1913–2001) for the four river basins. The dots represent the corresponding mean runoff volume for the two periods. (c) Time variations (based on 30-yr moving-window estimate) in the CV provide an assessment of the temporal changes in the variability of flow regimes. Each CV estimate is plotted at the last year of the respective 30-yr moving window. Statistical significance is assessed based on 1000 CV estimates obtained by resampling without replacement; the 10% and 90% levels are shown (gray lines).

previously identified as a preferred spatial pattern for interannual and decadal fluctuations (Dettinger et al. 1998; Cayan et al. 1998). A striking feature of the temporal variations in PC1 and PC2 (Fig. 3) is the multidecadal swings between north–south dipole (PC2) and synchronous (PC1) flow regimes. In particular, there has been a substantial increase in the variance of the PC1 during the recent three decades (a 45% increase in the standard deviation during the 1972–2001 period relative to the 1913–71 period), and this occurred in tandem with reduced occurrences of the dipolar PC2 pattern. The occurrence of synchronous flows (red and blue bars in Figs. 3a,–b) throughout the historical record has been concentrated in the pre-1940 and post-1970 periods. Out of the 11 synchronous high- and low-flow years identified, that is, water year runoff volumes above the 60th percentile (high) and below the 40th percentile (low) for the common period of record (1913–2001), 7 have occurred in the last three decades. These selected years project strongly on the PC1, while having virtually no projection onto PC2 (Fig. 3b, color bars).

TABLE 1. Principal component loadings for the runoff volumes.

	Fraser	Columbia	Sacramento–San Joaquin	Upper Colorado
PC1	−0.31	−0.64	−0.57	−0.40
PC2	0.68	0.34	−0.37	−0.53

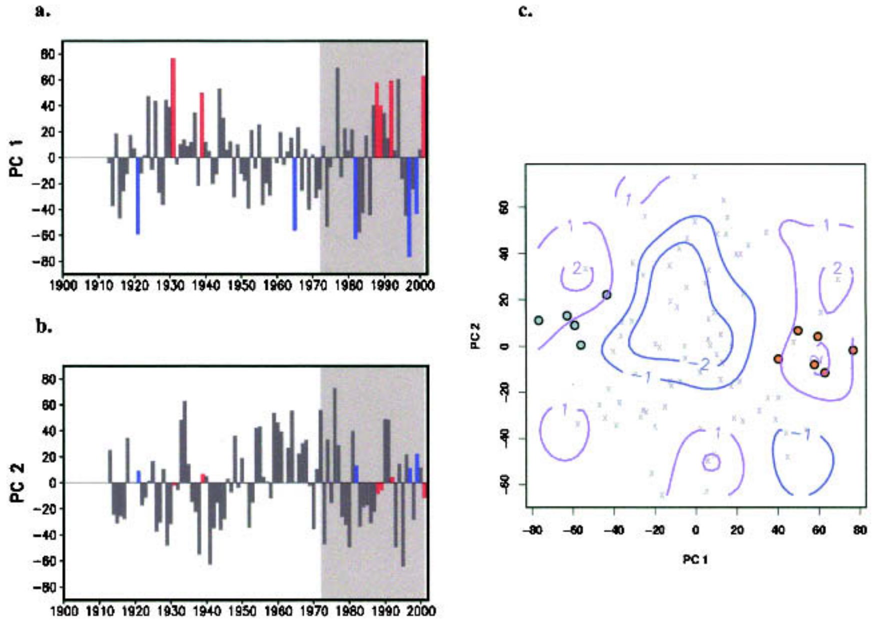

FIG. 3. Leading principal components (PCs) for the WNA streamflow for the 1913–2001 period: (a) PC1 and (b) PC2. The two leading PCs explain 79% of the total variance of streamflow (PC1: 42%; PC2: 37%). Table 1 shows the eigenvectors corresponding to the leading PCs. Blue and red vertical bars show the synchronous high streamflow (blue, water years: 1921, 1965, 1982, 1997, 1999) and low streamflow (red, water years: 1931, 1939, 1988, 1989, 1992, 2001) from the historical record. (c) Changes in the joint probability density of the two leading PCs. The contours show the standardized density difference surface based on the 1972–2001 and 1913–71 periods (Bowman and Azzalini 1997). The contours show the density difference as increase (decrease) in standard deviation units. Synchronous high (orange circles) and low (blue circles) flow years contribute significantly to the changing probabilities. All other years are shown by "×" symbols (gray).

Figure 3c quantifies the temporal change (1972–2001 versus 1913–71) in the occurrence of flow regimes that are synchronous versus dipolar in their spatial signatures. A simple assessment of variability is done based on the difference of two probability densities (1913–71 and 1972–2001 periods). Standardized density differences exceeding two standard deviations are of particular interest (Bowman and Azzalini 1997). The standardized difference in probability density exceeds two standard deviations for the extreme phases of the PC1, confirming a highly detectable increase in the incidence of synchronous high and low flows in the last three decades. The recent increase in frequency of large-amplitude and synchronous variations in PC1 has occurred alongside the decreases in the middle portion of the PC1 density surface.

These changes in the reliability and synchroneity of annual flows reflect large-scale climate controls, as opposed to being artifacts of local land-use and management practices. Evidence for a planetary climate link comes from a correlation analysis of wintertime 500-hPa geopotential height and sea surface temperature (SST) patterns associated with the two leading PCs for runoff volumes (Fig. 4). The atmospheric circulation pattern (Fig. 4a) corresponding to synchronous flows in the WNA region consists of a wavy structure spanning the entire Pacific North American (PNA) region, with synchronous low flows associated with a high pressure center over the entire Pacific Northwest region, together with an apparent quadrupole covering the North Pacific region. Interestingly, this geopotential height pattern is also reminiscent of the trends in 500-hPa geopotential heights during the 1950–2001 period (pattern correlation: 0.59). The question remains open as to the physical causes of the circulation trend; however, our analysis suggests that a regional manifestation of such changes is an increased incidence of synchronous flows for the four river basins in WNA.

The atmospheric circulation associated with PC2 consists of a zonal band of alternating height anomalies that appear rooted in the Tropics. Indeed, the strong correlations in the deep Tropics are consistent with the fact that this pattern is related to tropical Pacific SST variability, closely resembling the El Niño–Southern Oscillation (ENSO) teleconnection pattern identified in previous studies (pattern correlation between the 500-hPa geopotential height pattern in Fig. 4b and the ENSO height pattern: 0.88; Trenberth et al. 1998).

The efficacy of tropical SST anomalies in forcing the WNA precipitation anomalies has been noted in previ-

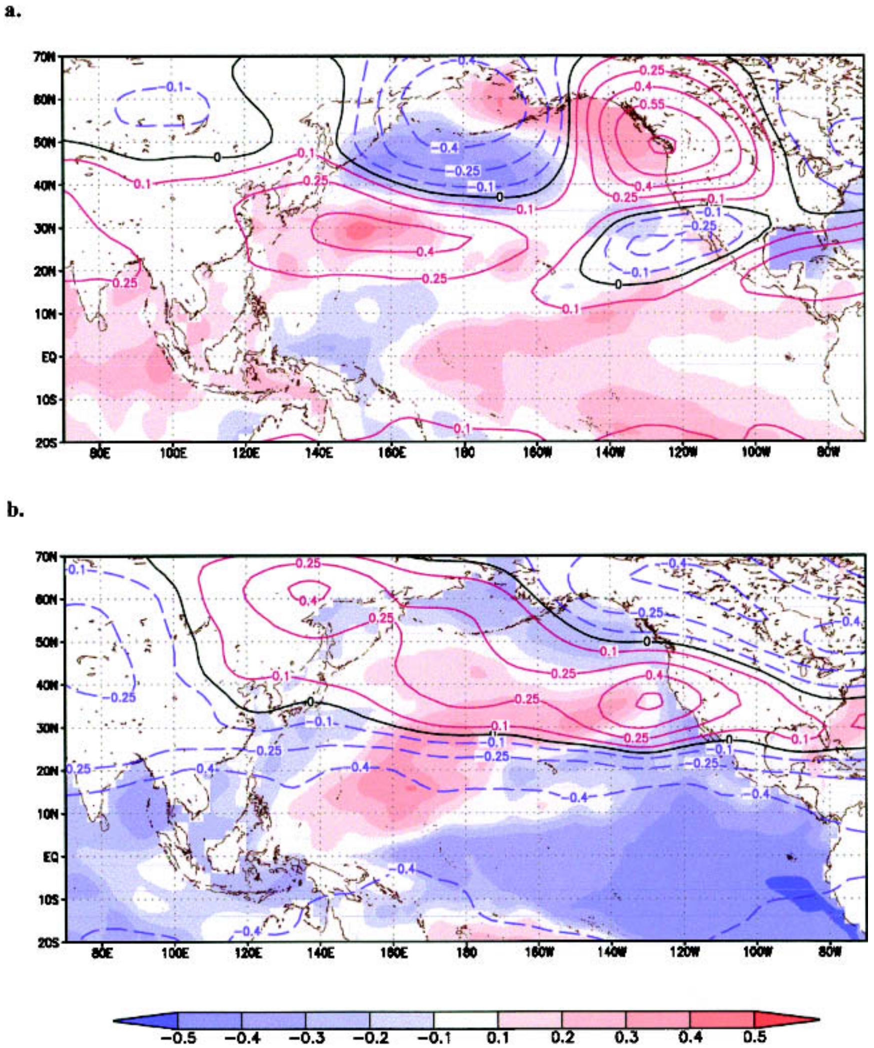

FIG. 4. Correlation fields associated with the two leading PCs of the WNA streamflow. Correlation between the streamflow PC time series and wintertime (Oct–Mar) 500-hPa geopotential height (contours) and SSTs (shaded) are computed for the 1950–2001 period. (a) PC1 and (b) PC2. The two leading PCs explain 79% of the total variance of streamflow (PC1: 42%; PC2: 37%). Table 1 shows the eigenvectors corresponding to the leading PCs.

ous ENSO studies, and it is also seen here that generally warmer Indo-Pacific oceans are linked with a preference for synchronous low flows in WNA. An important open question is whether continued further warming of the SSTs would bias WNA streamflow volumes to synchronous low-flow regimes. We note especially that the SST of Fig. 4a resembles the 1950–2001 warming trend (Knutson et al. 1999), one that is projected to continue throughout the twenty-first century (Watson et al. 2001). We thus propose that the spatial patterns and temporal variations identified in this study provide a reduced set of atmospheric and SST archetypes of particular relevance in modeling efforts to attribute and project WNA regional hydrologic change.

Societal vulnerability and impacts stemming from regional hydrologic change will permeate numerous human and natural systems that rely on water supplies. Our work points to decreasing runoff reliability and increased incidence of wet and dry regimes occurring in lockstep across the four river basins. The coherent nature of changes diagnosed here also points to the important role of casting the problem of regional hydrologic change based on metrics of great consequence to resource management (e.g., Cayan et al. 2003). Are the changing hydrologic regimes symptomatic of regional-scale climate change? The Intergovernmental Panel on Climate Change (IPCC) synthesis for greenhouse warming scenarios and the associated regional hydrologic change for WNA water supplies show large uncertainties in the magnitude and direction of changes (Watson et al. 2001). Based on results from this work, it is clear that the detectability and projection of regional hydrologic change likely hinges on the sensitivity of identified sets of climatic analogues to climate change, and focused climate model simulation studies will be necessary to advance predictions (e.g., Hoerling and Kumar 2003; Schubert et al. 2004). If the recent trends in variance and synchroneity persist, a revisitation of water resources operations and planning strategies becomes imperative.

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