Cross-Basin Decadal Climate Regime Connecting the Colorado River with the Great Salt Lake

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ABSTRACT

The 2013 federal Colorado River Basin Water Supply and Demand Study projected the water imbalance between future supply and demand to increase. The Colorado water supply (WS) exemplifies a pronounced quasi-decadal oscillation (QDO) of 10–20 years throughout its historical record; however, this QDO feature is unaccounted for in the climate models used to project the future WS. Adjacent to the Colorado River, the large watershed of the Great Salt Lake (GSL) in Utah records the hydrologic QDO signal in its water surface, leading previous studies to explore the cause of decadal fluctuations in the lake elevation and assess predictability. This study reports a remarkable coherence between the Colorado WS and the GSL elevation at the 10–20-yr time scale. Analysis of precipitation and terrestrial water storage anomalies suggests a cross-basin connection in the climate and hydrometeorological variations of the Colorado WS and the GSL. The 160-yr-long and well-kept GSL elevation record makes it an effective indicator for the Colorado WS.

1. Introduction

The Colorado River spans seven states in the western United States and is a leading provider of water for municipal use, agriculture, and power in the Southwest. In the face of the warming climate, numerous papers have warned about sizable water shortages of the Colorado River (Barnett and Pierce 2008, 2009; Christensen et al. 2004; McCabe and Wolock 2007; Rajagopalan et al. 2009). In 2013, the Bureau of Reclamation (BOR) released a comprehensive Colorado River Basin Water Supply and Demand Study (BOR 2013), hereafter ''the BOR study.'' Figure 1a displays the Colorado River water supply (herein Colorado WS), which was computed mainly from streamflow and water use information that is illustrated in the BOR study. The supply and demand curves have intersected in the early 2000s, suggesting that the water supply may no longer meet demand. To facilitate water resources management, the BOR study projected the future water supply from 112 downscaled global climate model (GCM) simulations from 2013 onward. The derived water supply initially maintains an upward trend extrapolated from the 2011 increase and then levels off around 2018 (Fig. 1a). Afterward, the projection is ''blurred'' by the broad range of uncertainty due to the cancelation of internal model variability, whereas the water demand continues to increase with less uncertainty.

One prominent feature that is missing from the ''flattened'' water supply projections in Fig. 1a is the low-frequency variability that is evident throughout the historical record, reflecting the recurrent shifts between persistently dry and wet regimes at a decadal time scale (Gangopadhyay and McCabe 2010). This decadal-scale variability also reflects the prevailing climate cycles of the intermountain region (DeRose et al. 2012, 2015; Gray et al. 2004; Smith et al. 2015; Wang et al. 2009, 2010). The BOR study does emphasize such shifts

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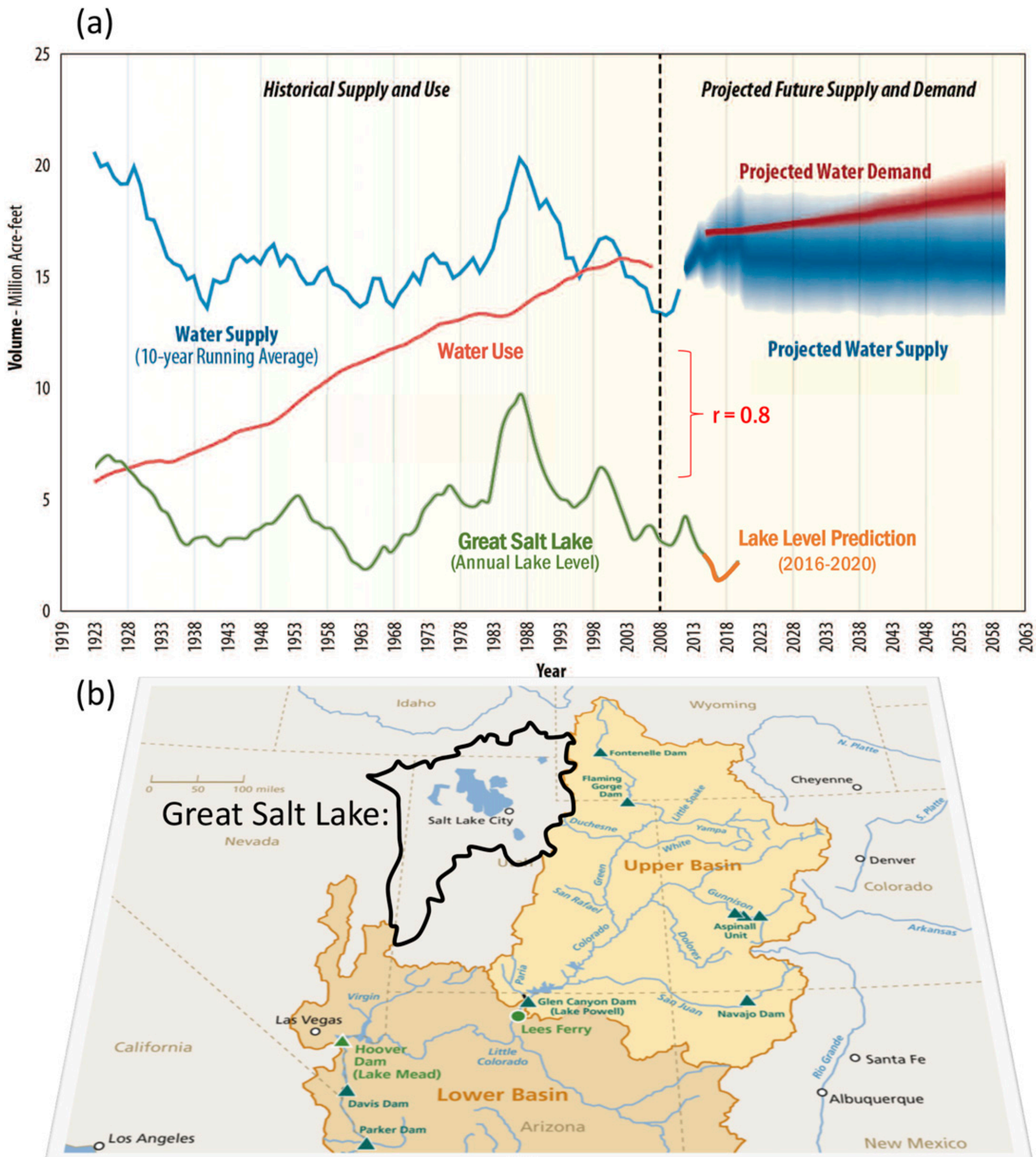

FIG. 1. (a) Historical and projected water supply and water use of the Colorado River basin smoothed by a 10-yr running mean, adopted from the BOR study (BOR 2013), overlaid with the annual-mean GSL elevation (green, without smoothing) and its forecast for 2016–20 (orange) derived from Gillies et al. (2015). Note the apparent low-frequency variations and strong temporal coherence illustrated by the high correlation coefficient *r* of 0.8 between the GSL elevation and water supply. (b) Map outlining the UCRB (light yellow) and the GSL and its watershed (thick black outline). The Wasatch Range in Utah separates the two watersheds. (Map source: http://www.rand.org/content/dam/rand/www/external/jie/projects/RR242fig3-3.png.)

between persistently dry and wet regimes and associated impacts on the water supply and water management (Gangopadhyay and McCabe 2010). However, current GCM projections could not have captured such decadal climate fluctuations in the Great Basin and Colorado River basin due to model insufficiencies, cancelation of natural variabilities, and ocean biases (Barandiaran 2016; Smith et al. 2015). The purpose of this paper is to review and examine the role of decadal climate oscillations in the water supply over the two neighboring water storage systems.

2. Background knowledge

As a shallow closed-basin lake, the Great Salt Lake (GSL) integrates hydrological forcings over a vast watershed that extends to the upper Colorado River basin (UCRB; Fig. 1b). The aforementioned quasi-decadal oscillation (QDO) signal that prevails in the intermountain hydroclimate variability is well recorded by the GSL elevation (DeRose et al. 2014; Gillies et al. 2015; Mann et al. 1995; Wang et al. 2012, 2010), as shown by the green line in Fig. 1a. The prominent QDO manifest in the GSL elevation has been studied extensively through statistical analysis (Gillies et al. 2011; Mann et al. 1995; Moon and Lall 1996), climate diagnostics (Wang et al. 2012, 2010), GCM simulations (Hakala 2014; Smith et al. 2015), and tree-ring reconstructions of streamflow (Allen et al. 2013; Bekker et al. 2014; DeRose et al. 2015) and lake level (DeRose et al. 2014). Similarly, the Colorado River flow is also characterized with a QDO signal (Gangopadhyay and McCabe 2010; Lamb et al. 2011). Previous studies (Hidalgo and Dracup 2003; Lamb et al. 2011; Scanlon et al. 2015) have noted the pronounced decadal variations revealed in the Colorado WS. Thus, the Colorado WS and GSL time series in Fig. 1a are highly coherent, evidenced by their significantly high correlation coefficient of 0.8 (with $p < 0.001$).

Given that the Colorado WS data used in the BOR study embody a 10-yr backward running mean (Fig. 1a), their marked correspondence with the annual GSL elevation echoes the observation that the two basins share a similar climate regime (DeRose et al. 2013; Herweijer et al. 2007; Wang et al. 2010). The atmospheric process modulating the GSL involves the so-called "Pacific QDO" (Wang et al. 2012, 2010), which describes cyclic, coupled evolutions of sea surface temperature (SST) and atmospheric circulation anomalies at the 10–20-yr time scale (Hsu and Chen 2011; White and Liu 2008a,b). Hereafter, the term "QDO" refers to any quasi-decadal variability (10–20 years) revealed in any variable, while the term "Pacific QDO" specifies the coupled SST–atmospheric mode in the Pacific Ocean.

The Pacific QDO resembles the broadened El Niño/La Niña SST anomalies and is loosely interchangeable with the North Pacific Gyre Oscillation (Di Lorenzo et al. 2015). The maximum quasi-decadal power of the various Pacific SST indices occurs in the equatorial central Pacific known as the Niño-4 region (160°E–160°W, 5°S–5°N; Tourre et al. 2001; Wang et al. 2011). Wang et al. (2010) found that the 10–20-yr oscillation in the GSL elevation is strongly modulated by the atmospheric teleconnection that is induced at the transition point of the Pacific QDO, which lies approximately halfway between the warmest and coldest SST anomalies in the equatorial central Pacific. The unique teleconnection, triggered during the transition phase of the Pacific QDO through latent heating in the western tropical Pacific, forms the low/high pressure anomaly upstream of the GSL watershed causing a precipitation surplus/deficit. Since the short atmospheric memory would not support such a long time lag, the teleconnection induced during the transition point of the Pacific QDO explains why the precipitation anomaly in the GSL watershed would appear to lag the peak Niño-4 SST (Wang et al. 2011). In other words, the "atmospheric teleconnection" does not have a long memory or lag (i.e., triggering hydrologic anomalies by an atmospheric state that occurred months or years ago), but the long lag is a combined result of both the slow/predictable evolution of Niño-4 SST and their concurrent impact on the GSL climate. Such a sequential process creates consistent time lags, on the order of ~6 years, between the Pacific QDO's Niño-4 index and the GSL elevation.

Based upon this implied predictability, Gillies et al. (2011) showed skillful prediction of the GSL elevation out to 8 years by using the Niño-4 index and local precipitation as predictors. Later, Gillies et al. (2015) refined this decadal prediction by using an additional 800 years of the tree-ring-reconstructed GSL elevation constructed by DeRose et al. (2014). The published GSL elevation prediction of 2016–20 is shown in Fig. 1a as the orange line.

3. Data sources

We used the Colorado WS data directly from the 2013 BOR study (https://www.doi.gov/water/owdi.cr.drought/en/). The WS illustrated in Fig. 1a was subjected to a backward 10-yr moving average (MA) in the BOR study, and these MA-applied data are denoted as the Colorado $\widetilde{\mathrm{WS}}$. The SST data and the Niño-4 time series were obtained from the Kaplan global analysis (Kaplan et al. 1998). The GSL annual elevation data up to June 2016 were obtained from http://waterdata.usgs.gov/. We also used the gridded monthly precipitation provided by the PRISM Climate Group at a 1/8° resolution (http://www.prism.oregonstate.edu/). For the estimation of water storage change, we utilized the level-3 Gravity Recovery and Climate Experiment (GRACE) monthly liquid terrestrial water storage anomalies (TWSA) data (Landerer and Swenson 2012; http://grace.jpl.nasa.gov/).

4. Analysis results

For the examination of temporal and spectral properties of the Colorado WS and GSL elevation, the magnitude-squared spectral coherence was computed to identify significant frequency-domain correlation across different frequencies and the phase lag between sinusoidal components. Figure 2a shows the spectral coherence between the original (unsmoothed) Colorado WS and GSL annual elevation, overlaid with the 95%

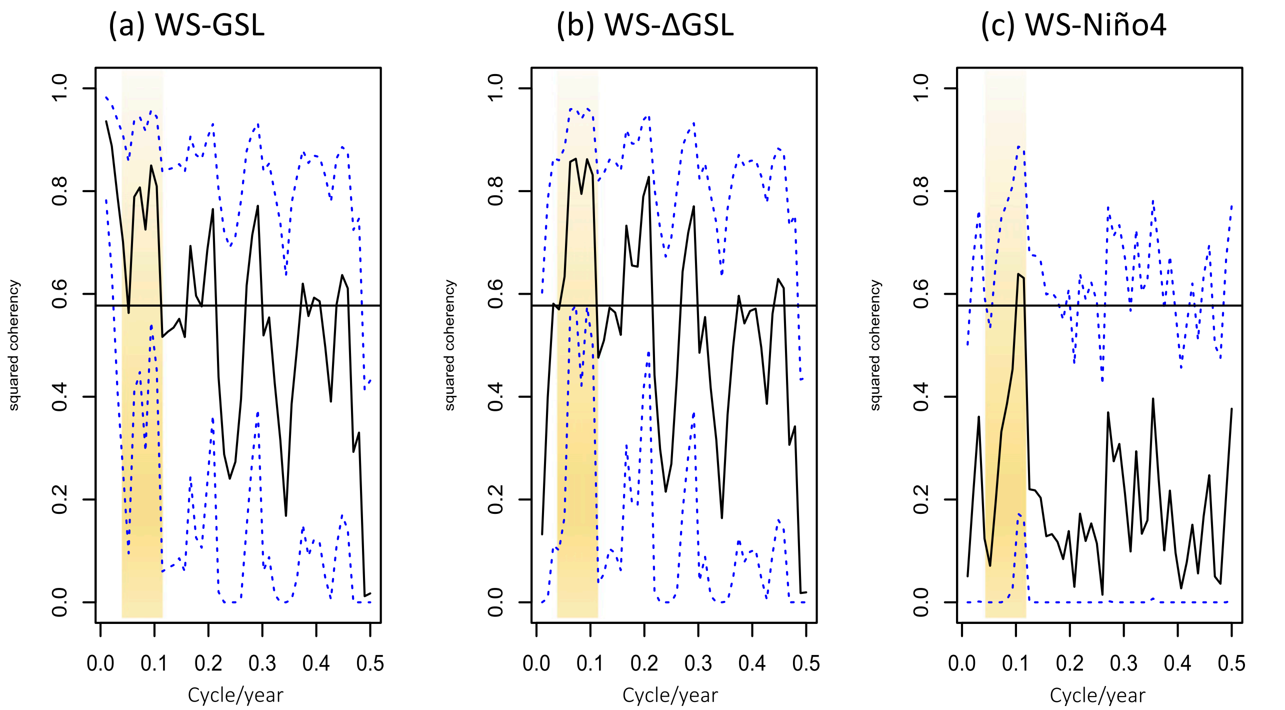

FIG. 2. Spectral coherence (solid black) with 95% confidence bounds (dashed blue) of the unsmoothed Colorado WS with the (a) GSL elevation, (b) GSL elevation tendency (ΔGSL), and (c) Niño-4 SST index using raw annual data. The horizontal line depicts the critical value $\alpha = 0.05$. Yellow shaded strips indicate the quasi-decadal frequency range of 9–16 years.

confidence bounds. Since the hydrological input of the GSL is directly related to the change in GSL elevation, we further computed the spectral coherence of the GSL elevation annual *tendency* (ΔGSL) with the Colorado WS, which is shown in Fig. 2b. Both plots reveal significant spectral coherence peaking within the quasi-decadal frequency (9–16 years), and this echoes the primary variation frequency found in the GSL elevation (Gillies et al. 2011; Mann et al. 1995; Wang et al. 2010) and northern Utah's groundwater storage (Hakala 2014; Masbruch et al. 2016).

The stronger coherence magnitude between the Colorado WS and the ΔGSL is likewise influenced by the quasi-decadal climate driver of hydrologic input over both watersheds. Correspondingly, Fig. 2c shows the spectral coherence between the Colorado WS and the Niño-4 SST anomaly averaged in the calendar year. The plots indicate significant coherence in the quasi-decadal frequency, which is not surprising given the high correlation of WS with the GSL elevation (Fig. 1a) and the documented link between the Niño-4 SST anomaly and the GSL elevation (Wang et al. 2010). Significant coherence is only revealed in the quasi-decadal frequency, not the interannual time scale, and this reflects the weak UCRB–El Niño linkage reported in previous studies (Hidalgo and Dracup 2003; Lamb et al. 2011). However, since the 95% confidence lower bound does not cross the critical alpha line, there is a ~30% chance that the spectrum of decadal signals between WS and Niño-4 is insignificant.

To delineate the association of precipitation and its geographical distribution with the hydrologic input depicted by ΔGSL, we computed the one-point correlation map of the annual ΔGSL with the water-year precipitation (August–July) from 1900 to 2015, applied with a 5-yr MA to focus on the low-frequency regime. Figure 3a shows that significant correlations ($r > 0.4$, $p < 0.01$) cover not only the GSL but also the UCRB, suggesting that the two basins share similar precipitation variations in the low-frequency time scale. Likewise, the correlation map of the annual Colorado WS and precipitation (not shown) revealed high coefficients encompassing the GSL, as well.

A further analysis of TWSE in the UCRB reveals significantly positive 1-month-lag autocorrelation, suggesting a smooth seasonal distribution of the water storage (Fang and Shen 2017). By constructing the one-point correlation map of GRACE TWSA centered in the UCRB with TWSA elsewhere, based on the annual means (so that it depicts interannual variation rather than the seasonal cycle), the result in Fig. 3b shows that the significant correlations ($p < 0.01$) cover the entire GSL watershed, suggesting a cross-basin connection in the variations of TWSA. Although GRACE has a large

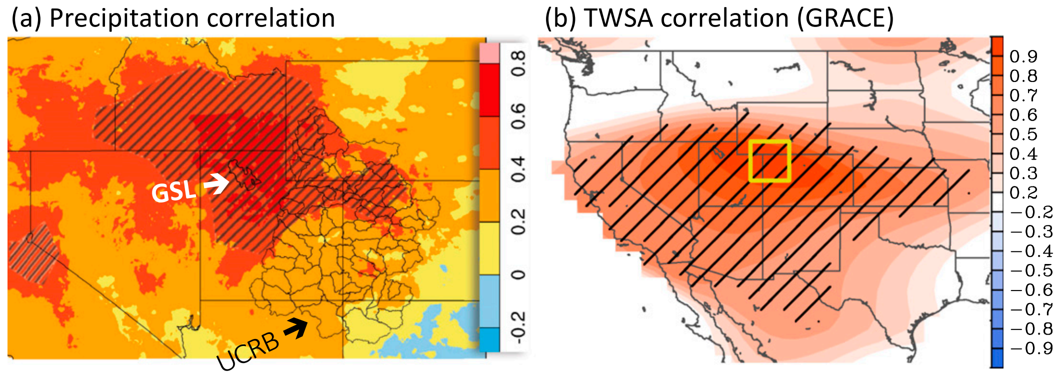

FIG. 3. (a) One-point correlation map of ΔGSL with the PRISM water-year precipitation over the period of 1900–2015, both of which were smoothed by a 5-yr MA to focus on the low-frequency time scale. (b) Correlation map of the annual mean GRACE TWSA correlated with itself averaged within the UCRB (yellow box), using unsmoothed data. Hatched areas indicate significant values with $p < 0.01$. The UCRB and its tributaries are outlined as subregions in (a).

spatial footprint (~200 000 km^2), the size of the autocorrelated area has exceeded this value, and so the result can be translated to the groundwater recharge/depletion processes that influence streamflow over both sides of the Wasatch Mountain Range (which separates the GSL watershed and UCRB).

Using GRACE data, Castle et al. (2014) found that approximately 77% of the total freshwater loss in the Colorado River during the recent sustained drought (2004–13) was due to groundwater depletion. The concurrent downtrend in the GSL elevation (Fig. 1a) during the same period as analyzed by Castle et al. (2014) lends support to possible synchronized water storage changes between the GSL elevation and the Colorado WS. Scanlon et al. (2015) further found that the decadal-scale changes in total water storage of the UCRB are controlled mostly by surface reservoir and soil moisture changes, reflecting the Colorado $\widetilde{\mathrm{WS}}$. Meanwhile, the GSL has undergone considerable diversions leading to a long-term decline in the lake level (Bedford 2009; Mohammed and Tarboton 2012). Quantification of the GSL diversions is by no means straightforward as groundwater withdrawal that reduces lake recharge also plays a role (Hakala 2014; Masbruch et al. 2016).

5. Discussion

While the connection between Niño-4 SST and regional precipitation reflects the atmospheric forcing through the Pacific QDO's transition-phase teleconnection, the lag between precipitation and the GSL elevation is due to hydrologic buffering. The Great Basin and the UCRB exhibit a rather high baseflow index of 60%–90% (fraction of streamflow from groundwater contribution) (Miller et al. 2016; Wolock 2003). Consequently, a majority fraction of the surface water is contributed by groundwater, which has undergone the processes of infiltration, subsurface storage and transmission, and convergence toward the channels. Apparently, the combined buffering of these processes lags baseflow contributions by approximately 3 years behind the precipitation input. Fang and Shen (2017) showed that the annual streamflow–storage correlation in this region is medium-high, depicting a high baseflow fraction that normally leads to a high annual correlation between streamflow and storage correlation (though the lagging effects reduce such correlation). Anecdotal evidence in Las Vegas Valley shows that precipitation in any one year would affect the water levels in artesian wells 3 years later (Thomas 1963). Since the same processes underscore the contribution of base flow to the Colorado River, similar lagging effects are expected for the Colorado $\widetilde{\mathrm{WS}}$. As a result, the GSL elevation and Colorado $\widetilde{\mathrm{WS}}$ are highly coherent and the former can, in theory, serve as a proxy for the latter.

6. Concluding remarks

The remarkable temporal coherence between the low-frequency variations of the Colorado $\widetilde{\mathrm{WS}}$ and the GSL elevation is an undocumented feature that was examined herein. The illustrated high spectral coherence and significant correlation between the GSL elevation and $\widetilde{\mathrm{WS}}$, their shared climate regime in response to the Pacific QDO, and their interconnectivity vis-à-vis water storage systems (as inferred by GRACE data) all point to the feasibility of using the GSL elevation as a proxy to estimate Colorado $\widetilde{\mathrm{WS}}$. Previous studies have reconstructed Colorado River flows using tree-ring data prior to instrumentation to assess historical flow conditions, which could infer the future water supply (Hidalgo et al. 2000; Meko et al. 2007; Stockton and Jacoby 1976; Woodhouse et al. 2006). In those studies, tree-ring reconstructions only explained up to 38% of the variance of the gauged flows. By comparison, the GSL elevation explains 64% of the variance in the Colorado $\widetilde{WS}$ (see Fig. 1a), and so it is complementary to the tree-ring reconstructions of the river flows. Thus, it would be pragmatic to periodically assess future Colorado $\widetilde{WS}$ through the development of decadal prediction schemes in parallel with those applied to the GSL elevation.

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