# Decadal-to-Centennial-Scale Climate Variability: Insights into The Rise and Fall of the Great Salt Lake

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**Abstract.** We demonstrate connections between decadal and secular global climatic variations, and historical variations in the volume of the Great Salt Lake. The decadal variations correspond to a low-frequency shifting of storm tracks which influence winter precipitation and explain nearly 18% of the interannual and longer-term variance in the record of monthly volume change. The secular trend accounts for a more modest ~1.5% of the variance.

## Introduction

Prospects of anthropogenic climate change have renewed interest in the study of low frequency variability in hydro-climatic processes [*Aguado et al.*, 1992; *Rasmusson and Arkin*, 1993; *Lins and Michaels*, 1994]. Permanent closed basin lakes are unique in that they reflect a precarious long term balance of precipitation and evaporation in an arid region. Several studies have established linkages between regional hydrological patterns and large-scale atmospheric circulation [*Rasmusson and Arkin*, 1993; *Lins*, 1985; *Cayan and Peterson*, 1989; *Ely et al.*, 1994]. Here, we demonstrate the connection between climatic signals and the fluctuations in the volume of the closed-basin Great Salt Lake (GSL). The GSL (Figure 1a) provides a useful case study because of its dramatic historical fluctuations (Figure 1b). The monthly volume change ($\Delta V$–Figure 1c) is a measure of the response to hydrological fluxes. We use monthly streamflow and precipitation records to measure the hydrological forcing of the GSL, and employ a spatiotemporal analysis of gridded, century-



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long records of monthly surface temperature ($T_s$) and sea level pressure ($P_s$) to isolate quasiperiodic climatic signals. Variations in $P_s$ reflect changes in atmospheric circulation that affect $\Delta V$ largely through precipitation. Evaporation is associated with $T_s$, as well as moisture transport, cloud cover, and wind patterns tied to the $P_s$ field. Our spatiotemporal analysis of hydro-climatic data contrasts with conventional distributed approaches to modeling hydrological systems.

## Data and Methods

The Silver-Lake Brighton (SLB) station provides a long record of precipitation in the GSL basin immune from local lake and rain shadow effects. The Blacksmith Fork at Hyrum (BFH) river gauge provides the longest record of streamflow which enters into the GSL, free of regulation or diversion. SLB and BFH are located near the south and north ends, respectively, of the GSL basin (see Figure 1a). The at-site records ($\Delta V$, SLB precipitation, and BFH streamflow) indicate broad power on interannual, interdecadal, and secular time scales [*Lall and Mann*, 1993]. To identify large scale climatic signals that may lead to regional hydrological variability, we perform spatiotemporal analyses of the $P_s$ and $T_s$ fields. We used gridded $P_s$ (from 1899-1990, on a $5^o$ by $5^o$ grid) over the continental U.S. and surrounding region [see *Jenne*, 1975]. and global gridded $T_s$ (land air and sea-surface temperature anomaly from 1890-1990, $5^o$ by $5^o$ grid) [see *Jones and Briffa*, 1992]. The $T_s$ analysis is taken from *Mann and Park* [1994] who describe the analysis technique (summarized below) that is applied here independently to the $P_s$ dataset.

The analysis is performed on standardized time series ${x_n}^{(m)}$ ($n = 1, \ldots N$ indexes time, $m$ indexes the grid-point) for which the long-term mean is removed and the time series is divided by its long-term standard deviation. Standardized time series are transformed by multitaper spectral analysis [*Thomson*, 1982], calculating $K$ independent spectral estimates of each time series at each frequency $f$. The $K$ eigenspectral estimates are confined within the frequency band $f \pm p/N\Delta t$ where $p = 2K - 1$. We use $K = 3$ (bandwidth $2/N\Delta t$, $\Delta t$=1 month). A complex singular-value decomposition (SVD) of the the $M \times K$ matrix of spectral estimates, $\mathbf{A}(f) = \left[{Y_k}^{(m)}\right]$ is performed at each frequency $f$ in the range $0 < f < 0.5$ cycles/year, each row calculated from a different grid-point time series, each column using a different taper. At each frequency, the SVD returns $K$ orthogonal modes. Potential signals are indicated by a narrow frequency band ($f \pm p/N\Delta t$) within which the principal mode explains a large fraction of the variance in the band. Statistical signficance is determined from Monte Carlo simulations.

The left eigenvectors of the principal mode determines the slowly-varying complex time envelope $E(t)$, describing a quasiperiodic oscillation of the form, $y(t) = \Re\{E(t)\exp(ift)\}$ at frequency $f$. $E(t)$ is described by $K = 3$ complex spectral degrees of freedom. The right eigenvector determines relative amplitude and phase of the oscillation spatially. A chosen phase of the cycle describes a particular pattern of positive and negative anomalies.

Signals in *both* $P_s$ and $T_s$ are observed on 2.2 year quasibiennial, 4-5 year interannual, 10-11 year quasidecadal and secular time scales (Figure 2). These signals are found to be seasonally-robust based on independent warm and cold season analyses, but are most influential during the cold season when synoptic variance is greatest. Statistical significance is insensitive to dropping the first/last 10 years of data from the analysis. We have less confidence in peaks that are significant for only one of the climatic fields. These include the 16-20 year peak in global $T_s$ [see *Mann and Park*, 1993;1994] associated with *interdecadal* variability that may have a source region in the Pacific [e.g., *Trenberth*, 1990; *Graham*, 1994; *Latif and Barnett*, 1994] but for which we can not as yet determine a consistent influence on continental U.S. climate. We focus on quasidecadal and secular signals; interannual variability in the GSL and its relation to the El Nino/Southern Oscillation is discussed elsewhere by *Lall and Moon* [1994].

We independently reconstruct [see *Park and Maasch*, 1993] the quasiperiodic oscillation present in the at-site records at the significant quasidecadal and secular frequencies. Each time-reconstruction ($P_s$, $T_s$, and the three at-site records) is statistically independent, and mutual correlation is determined from the spectral coherence [e.g., *Mann and Park*, 1993].

## GSL and climatic signals

Quasidecadal (10-11 year period) signals have been observed in gridded global surface temperature [*Mann and Park*, 1994], North Atlantic sea level pressure, winds, and marine and air temperature [*Deser and Blackmon*, 1993] U.S. temperature [*Dettinger and Ghil*, 1991], U.S. streamflow [*Guetter and Georgakakos*, 1993], and equatorial Atlantic sea surface temperatures [*Houghton and Tourre*, 1992] as well as Great Basin precipitation [*Eischeid et al.*, 1985]. While a connection has been suggested between the ~11 year sunspot cycle and decadal variability in atmospheric circulation [*Labitzke and van Loon*, 1988], U.S. precipitation [*Currie and O'Brien*, 1992], and GSL volume [*Willet and Prohaska*, 1987], our analysis argues against such an explanation for the variability described here (Figure 3a). Empirical [e.g., *Deser and Blackmon*, 1993; *Mehta and Delworth*, 1994] and theoretical [*Mehta and Delworth*, 1994; *Weaver et al.*, 1991] evidence suggests that such climate variability may have its origins in North Atlantic ocean-atmosphere interaction The quasidecadal global $T_s$ pattern of *Mann and Park* [1994] displays greatest amplitude there with teleconnections that may perturb storm tracks throughout the Northern hemisphere. This signal is coherent with quasidecadal $P_s$ variations over the continental U.S. (both shown in Figure 3b) at $> 95\%$ confidence level.

Variations in $\Delta V$, local precipitation, and streamflow on this time scale are significantly correlated, and are anticorrelated with the local projection of the quasidecadal $P_s$ mode (Figure 3c,d). $\Delta V$ lags precipitation slightly, consistent with the expectation of a lagged response between precipitation and snowmelt runoff. The spatial pattern (Figure 3e) [derived from the spatiotemporal analysis of $P_s$] coincident with these conditions indicates a low pressure anomaly from the Great Basin through the Gulf of Mexico. This pattern is associated with an increased likelihood for the winter storm track to shift southward from its typical location to the north (e.g., Montana/Idaho) into the GSL region [*Benson and Thompson*, 1987], leading to enhanced precipitation. The precipitation response appears to be non-linearly related to the $P_s$ variations. For example, the $P_s$ fluctuations of the 1970's, only slightly larger than those of the 1940's, are associated with a dramatically higher response in precipitation, streamflow, and $\Delta V$ (Figure 3c). The opposite phase, when $\Delta V$ and local precipitation/streamflow are minimum, is associated with high pressure and a diversion of storms from the Great Basin. Relatively moist, cloudy (dry, clear) conditions during the high (low) precipitation phase might serve to inhibit (enhance) evaporation slightly, thus positively reinforcing the signal. Associated temperature variations are locally weak (see Figure 3e) and these $\Delta V$ variations are likely driven largely by precipitation rather than evaporation changes [*Lall and Mann*, 1993]. Consistency between $T_s$ and $P_s$ is indicated, for example, by anomalous southerly (northerly) flow about the large cyclonic pressure anomaly associated with warm (cold) anomalies.

On secular time scales, increasing SLB-precipitation is highly correlated with the local decreasing $P_s$ (Figure

4a). The secular temperature mode exhibits the greatest warming before 1940, leading these trends somewhat. Such warming could be expected to lead to enhanced evaporation. Other work [e.g., *Karl et al.*, 1993] suggests that recent warming in this region is marked mostly by higher minimum rather than maximum daytime temperatures which might argue against a strong effect on evaporation. These results, based on linear trends over a shorter time interval (1951-1980), may not, however, extrapolate to the secular variations examined here. Inconsistencies between temperature, precipitation, and streamflow trends over the U.S. [see *Lins and Michaels*, 1994] and influences of long-term changes in cloud cover on evaporation need to be better understood. Consistent, nonetheless, with increased evaporation in the region that accompanies the abrupt secular warming, $\Delta V$ tends to decrease until about 1940. Thereafter, increasing precipitation seems to counteract the decline and $\Delta V$ increases. The local $P_s$ decrease is associated with a trough that develops over much of the U.S., particularly in the west (Figure 4b), implying increased frequency of mid-latitude storms.

## Conclusions

Climatic signals appear to be responsible for some of the historical variation in the GSL volume. Quasi-decadal atmospheric circulation variations appear to drive particularly high amplitude oscillations in the lake through precipitative forcing. Hydrological forecasting may be improved by a shift in emphasis from high frequency, distributed modeling to incorporating effects of low frequency carrier climatic signals.

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**Figure 1.** (a) Site Map showing Great Salt Lake (GSL), Silver-Lake Brighton (SLB) station monthly precipitation, and the Blacksmith Fork at Hyrum (BFH) river gauge of monthly streamflow. (b) Great Salt Lake volume record from 1899-1990 (in units of $m^3$). The most notable feature observed is the large fluctuation of the 1980s. (c) $\Delta V$ monthly time series (dotted–units of $m^3$/month) from 1899-1990. The annual cycle is the most prominent feature in the record, but note the interannual and longer time scale variability revealed by the 2-year lowpassed curve (thin solid) and the specific contributions indicated by the trend (dashed curve) and trend combined with the quasidecadal (thick curve) signal reconstruction (see "Data and Methods"). The 1980's peak may largely be associated with constructive interference of the secular trend, quasidecadal and interannual oscillations.

**Figure 2.** Spectrum of fractional variance explained by the principal mode of the SVD on time scales $\tau > 2$ year for both the $P_s$ data set (dashed) and global $T_s$ data set (solid). The scales (right–$P_s$, left–$T_s$) are aligned at the 95% confidence level as calculated from Monte Carlo simulations.

**Figure 3.** Quasidecadal signal. (a) Variations in $\Delta V$ (solid, in units of $2.5 \cdot 10^8$ m$^3$/month) and sunspot numbers (dashed-vertical scale normalized). The spectral coherence between the two records in this frequency band ($C^2 = 0.03$) is statistically insignificant. (b) Time-domain signals in $P_s$ (dashed) and global temperature (solid) projected onto GSL region. The $P_s$ signal is shown in units of millibars (mb). The temperature oscillation, shown in units of $0.01^o$C, nearly vanishes locally in the GSL region (see spatial pattern below). (c) Variations in $\Delta V$ (solid–units of $2.5 \cdot 10^8$ m$^3$/month), SLB-precipitation (dashed–units of 2.5 mm/month), and BFH streamflow (dot-dashed–units of 1.5 m$^3$/s). (d) Variations in SLB precipitation (solid, same units as above) and local projection of $P_s$ mode (dashed–units of mb). The above signals are each correlated at $> 95\%$ confidence levels. Phase discontinuities (during 1930s and near 1960) occur when the complex envelope of the oscillation vanishes, and at-site reconstructions may be contamined by background noise at these times. (e) Large-scale pattern when SLB precipitation is maximum. Position of GSL is indicated (small rectangle with approximate dimensions of the lake). $P_s$ is contoured in units of millibars (mb) with a peak amplitude of about 0.6 mb (peak-to-peak amplitude of 1.2 mb). The global $T_s$ pattern is shown over the same domain. Rightward (leftward) arrows indicate warm (cold) anomalies. Size of arrows scales relative amplitude. Pattern has maximum peak-to-peak amplitude $\sim 0.6^o$C.

**Figure 4.** Secular signal. (a) Trends of $\Delta V$ (dotted–units of $2.5 \cdot 10^8$ m$^3$/month), SLB-precipitation (dashed–units of 2.5mm/month), and secular $P_s$ (dot-dashed–units of mb) and $T_s$ (solid–units of $^o$C) modes projected onto GSL region. (b) Large-scale pattern of secular modes. Pattern peak amplitude is -3.3 mb in central Mexico, and nearly as large (-2.6 mb) just north-east of the GSL. Temperature trends are indicated by same convention as above, showing a spatially-varying warming. Maximum amplitude warming in the pattern is $0.85^o$C off the mid-Atlantic coast, with $\sim 0.4 - 0.5^o$C warming over the great basin.