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Short communication

Magnitude and frequency of wet years under a megadrought climate in the western Great Basin, USA

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ABSTRACT

Megadroughts are not devoid of interannual precipitation variability. However, the frequency and magnitude of occasional wet years must be limited in order to be consistent with geologic evidence indicating terminal lake lowstands during past megadroughts. We present a series of hydrologic model simulations of Walker Lake, a western Great Basin terminal lake, where varying return intervals of increased cool-season (October–April) precipitation are superimposed upon a megadrought climate. Estimated megadrought lowstands are achieved with wetter years returning every 5–10 years. Total cool season moisture transport derived from the 20th Century Reanalysis between 1895 and 2012 A.D. was positively correlated with cool-season precipitation during the corresponding year (0.49, $p < 0.01$). Daily moisture transport exceeding the 95th percentile is used as a surrogate for atmospheric river events. Wetter (drier) years had a greater (lesser) fraction of total cool season transport occurring on atmospheric river days, indicating their important role in driving western Great Basin hydroclimate variability.

1. Introduction

Severe multidecadal droughts (hereafter megadroughts) in the western United States are well documented by paleoproxy evidence during the middle-late Holocene (Stine, 1994; Benson et al., 2002; Adams, 2007; Mensing et al., 2013). Despite interannual precipitation variability during megadroughts (Cook and Krusic, 2004), the frequency and magnitude of occasional wet years must be limited in order to be consistent with geologic evidence of drought conditions (Stine, 1994; Adams, 2007). Great Basin terminal lakes such as Walker Lake (Fig. 1a) offer ideal locations to study changes in regional hydroclimate because as closed hydrologic systems their surface area and elevation represents the balance between gains from direct on-lake precipitation and watershed-derived runoff and losses due to evaporation. For example, to achieve Walker Lake levels consistent with two extreme lowstands that took place during the megadroughts of the Medieval Climatic Anomaly (MCA; 850–1300 A.D., Stine, 1994), cool-season (October–April) precipitation reductions on the order of 30–40% compared to a baseline climate of 1971–2000 A.D. averages are required (Hatchett et al., 2015). These values are comparable with other estimates of MCA precipitation reductions (Stine, 1994; Graham and Hughes, 2007; Kleppe et al., 2011). In their simulations, Hatchett et al. (2015) assumed that the drought climates were persistent and each year had similar precipitation. Walker Lake is sensitive to interannual precipitation variability, however decadal-multidecadal persistence of climate conditions is required for complete hydrologic oscillations to occur (Hatchett et al., 2015).

Known modulators of interannual-decadal climate variability in the Walker Lake region include Pacific and Atlantic extratropical and tropical sea surface temperature (SST) variability and the associated atmospheric teleconnections (Wallace and Gutzler, 1981), with the El Niño-Southern Oscillation (ENSO) of particular importance (Dettinger et al., 1998; Cayan et al., 1999). However, the Walker Lake region sits near the inflection point of the western United States ENSO dipole (Dettinger et al., 1998; Wise, 2010)

Abbreviations: 20CR, 20th Century Reanalysis; ENSO, El Niño-Southern Oscillation; MCA, Medieval Climate Anomaly; PRISM, Parameter Regression Independent Slopes Model; WL, Walker Lake.

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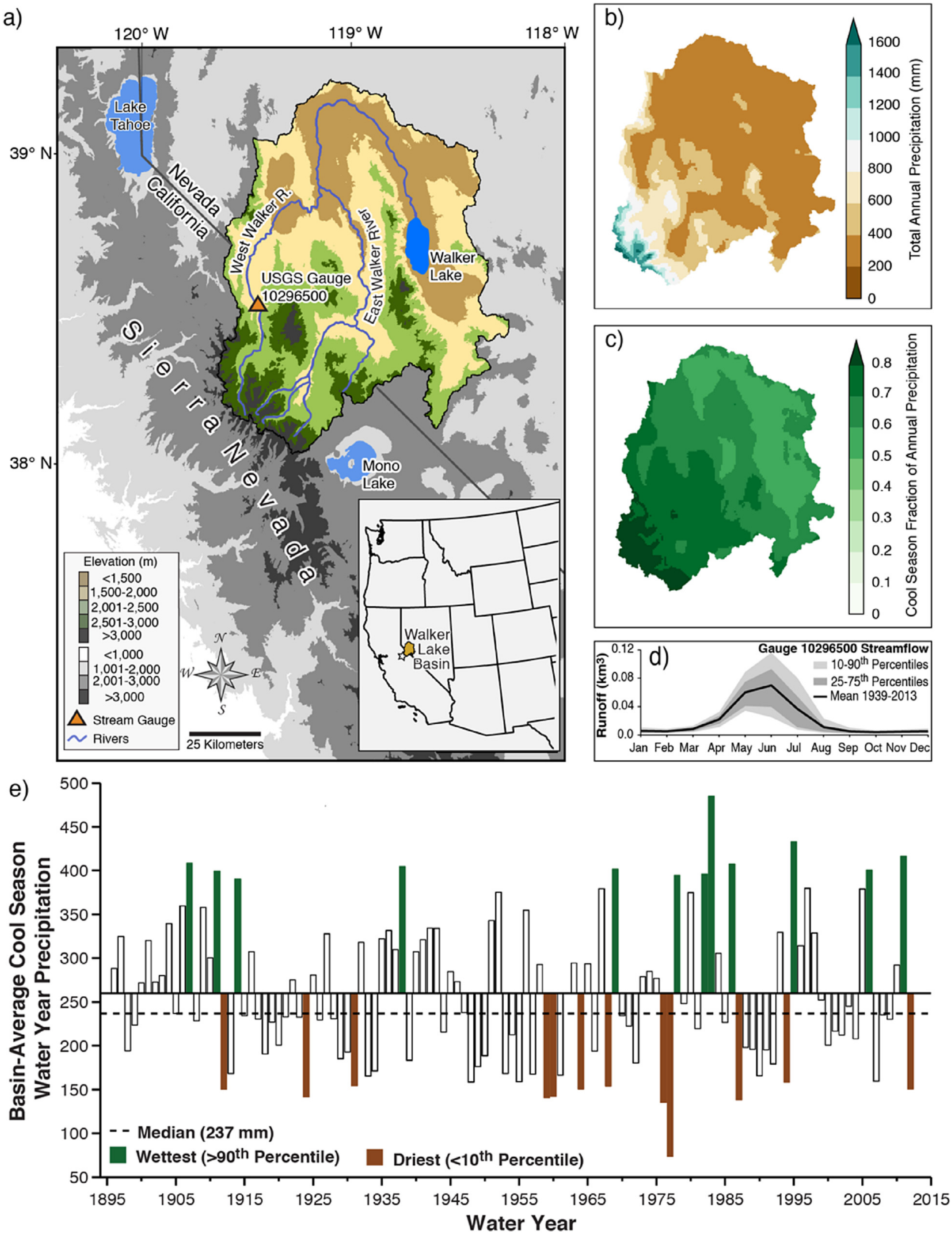

Fig. 1. a) The Walker Lake Basin study area (elevations within basin are colored, outside are grayscale) showing the forks of the Walker River and USGS stream gauge 10296500 along the West Walker River (triangle). The star on the inset map shows the grid point where upstream moisture fluxes were calculated. b) PRISM-estimated total annual precipitation in mm. c) Fraction of total annual precipitation occurring during the cool season (October–April). d) Observed monthly mean streamflow (km^3) at the USGS gauge. e) Walker Lake Basin average cool-season precipitation for water years 1896–2012.

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meaning that either ENSO phase can favor a wet or dry winter. At shorter timescales, atmospheric rivers (Ralph et al., 2004), or elongated regions of intense moisture transport located within the warm sector of extratropical cyclones, favor heavy to extreme precipitation (Ralph and Dettinger, 2012) and produce nearly double the precipitation as all storms (Neiman et al., 2008). The wettest days in the Sierra Nevada are associated with atmospheric rivers (Dettinger et al., 2011; Dettinger and Cayan, 2014; Backes et al., 2015). Atmospheric rivers have disproportionate roles in interannual hydroclimatic variability in the Walker Lake region and throughout the far western United States (Dettinger et al., 2011; Rutz et al., 2014). In the Walker Lake basin they occur on 10% of cool-season precipitation days but provide 30–40% of total cool-season precipitation (Backes et al., 2015) and thus provide an important linkage between weather and climate.

Here we use a series of hydrologic simulations and analyses of moisture transport during the historic period (1895–2012 A.D.) to extend the work of Hatchett et al. (2015) and estimate plausible frequencies and magnitudes of wetter years that can interrupt MCA-like megadroughts while producing lake level falls consistent with MCA lake levels and drought durations. We hypothesize that lake regressions can be achieved by the occurrence of occasional (approximately every 5 years) wetter years. By examining cool-season moisture transport into the Walker Lake basin, we also link the basin's hydroclimate variability to both total moisture transport and atmospheric river events.

2. Data and methods

The Walker Lake basin is located in the western Great Basin (Fig. 1a). Lake inflow is derived primarily from precipitation in the form of snow and accumulated on the 3500 m high Sierra Nevada during the cool season (Fig. 1b,c). Runoff from snowmelt flows to Walker Lake via the West and East forks of the Walker River (Fig. 1a) with peak streamflow occurring between April and June (Fig. 1d). Our watershed simulations are performed using a semi-distributed, calibrated water balance model with 800 m^2 horizontal resolution that simulates key surface hydrologic processes (e.g., snowpack accumulation and melting, evapotranspiration, and runoff generation). Groundwater was not explicitly simulated. The lake evaporation model uses a rating curve to estimate lake surface area, elevation and volume change as functions of inflow from runoff and direct on-lake precipitation and outflow from evaporation. The models are applied using a monthly time step. Inputs to the models include monthly minimum and maximum temperature and precipitation from PRISM (Parameter Regression Independent Slopes Model; Daly et al., 1994). For further model information the reader is referred to Hatchett et al. (2015), Barth (2013), and Barth et al. (2016). Estimates of Walker Lake paleoshoreline elevations are from Adams (2007). Wet (dry) years are defined as $>90^{th}$ ($<10^{th}$) percentiles of cool season basin-averaged PRISM precipitation estimates between 1895 and 2012 A.D. (water years 1896–2012; Fig. 1e). We calculated vertically integrated moisture transport at daily time steps on fifteen isobaric surfaces from 1000 to 300 hPa using winds and specific humidity from the 2° horizontal resolution 20th Century Reanalysis (20CR; Compo and coauthors, 2011) between 1895 and 2012. Atmospheric river days were defined by daily moisture transport exceeding the cool season 95th percentile. This simple surrogate method captures 90% of atmospheric river days cataloged by Rutz et al. (2014).

Our model experiments are performed as follows:

1. The watershed-lake model is initialized at baseline precipitation for 10 years to either a relative Holocene highstand (1247 m) or lowstand (1225 m).
2. A megadrought climate derived by Hatchett et al. (2015) and consistent with the most severe MCA drought (G-1, ca. 850–1075 A.D.; Stine, 1994) is applied as a multiplier across the model domain ($\Delta P = 0.625$). The drought simulation runs 140 years, which is the duration of the shorter, second MCA drought (G-2, ca. 1125–1300 A.D.).
3. A series of simulations are performed using either baseline ($\Delta P = 1$) or wet ($\Delta P = 1.46$) climates applied for one cool season at frequencies of every 3rd, 5th, and 10th year. Warm season (May–September) precipitation is unchanged.
4. We repeated each precipitation scenario simulation twice, once using baseline values of temperature and again with annual temperatures increased by 2°C to represent maximum late Holocene temperature departures (Salzer et al., 2014).

3. Results

Under continuously dry conditions with no wetter years, Walker Lake falls to low levels consistent with G-1 drought lowstands regardless of initial state (Dry simulations; 1207–1208 m; Fig. 2). Under continuous dry and warmer conditions (Dry+2°C) lake levels below those estimated during the G-1 drought were simulated (1196–1198 m; Fig. 2). When Walker Lake is initialized at a relative highstand elevation (1247 m) consistent with historic and late Holocene highstands (Adams, 2007); Fig. 2a), regression to the estimated G-2 elevation (~1223 m) is achieved by the baseline years that recur every five and 10 years (Baseline_5 and Baseline_10). By increasing annual temperatures 2°C, wet years could recur every 10 years (Wet_10+2°C) while baseline years could occur no more than every three (Baseline_3+2°C). The Baseline_10+2°C climate was sufficient to drive the lake to the estimated minimum G-1 elevation (~1209 m). Starting with an initially low lake level (1225 m), all simulations (Baseline, Wet, and +2°C) satisfied the G-2 elevation with the exceptions of the Baseline_3 and Wet_10 runs (Fig. 2b). The G-1 drought elevation is only achieved by the Baseline_10+2°C run. In agreement with previous studies that found that different lake levels can result from stochastic versus mean-state precipitation forcing (e.g., Steinman et al., 2010a,b), we also found that stochastic spacing of wet years did change the likelihood of satisfying the target lake level. Applying additional variability to magnitudes of intervening drought years by randomly selecting from the driest (bottom) 10th, 15th, 20th, and 25th percentile years yielded lower lake levels (not shown). Together, these findings provide confidence that our estimated return intervals of wetter years are reasonable upper bounds of the frequency for occasional wet years to occur amidst an average background megadrought climate.

Total cool-season moisture transport for the 20CR gridpoint immediately upstream of the Walker Lake basin (star in Fig. 1a) is moderately positively correlated with observed cool-season precipitation ($R^2 = 0.49$, $p < 0.01$; Fig. 3a). The number of atmospheric river days increases with cool-season precipitation total, shown as three populations grouped by k-means clustering. The fraction of total transport on atmospheric river days increases from 1.4% (dry) to 32.5% (wet). Using the driest 10th percentile years (dry_{10}) as analogs for drought years (Fig. 1e), anticyclonic turning of moisture transport vectors is observed offshore of southern California (Fig. 3b) and throughout California. The dry_{10} have half the transport magnitude compared to the wet analog (wet_{10}) over California and Nevada. The orientation of mean total moisture transport during the wet_{10} is more orthogonal (southwesterly) to the northwest-southeast orientation of the Sierra Nevada, whereas the dry_{10} are more range parallel (northwesterly). The differences in magnitude and direction between the dry_{10} and wet_{10} are reduced in eastern Utah, northeast towards Idaho, and along the Oregon-Washington border. Similar magnitudes but differing directions

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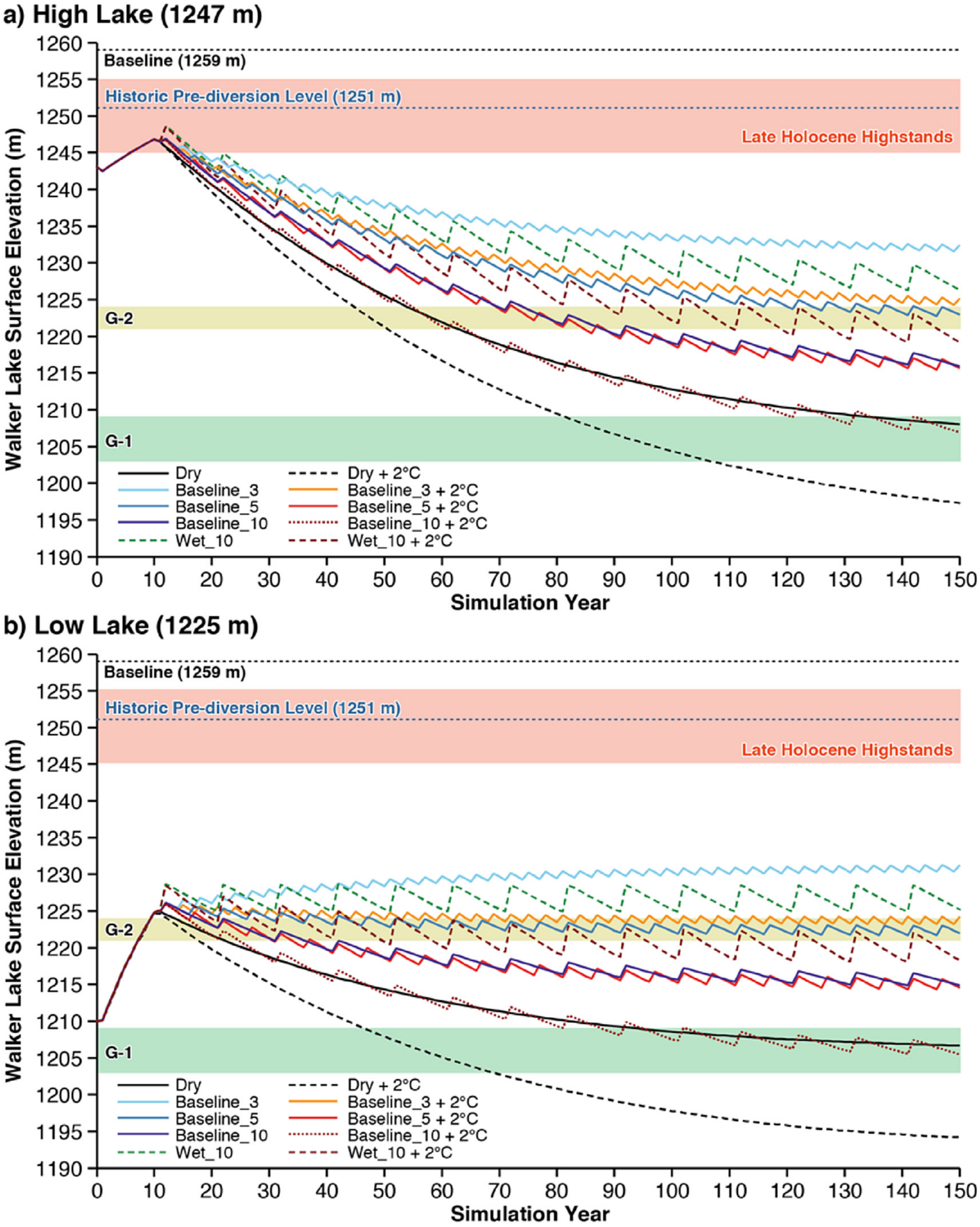

Fig. 2. Model simulations using High (a) and Low (b) initial lake levels. Adams (2007) dated the pre-diversion historic and late Holocene highstand levels (red) of Walker Lake. Steady state results for the baseline climate (thin dashed black line) shows that the baseline period is wet relative to late Holocene (red bar) and pre-diversion climates (dashed thin blue line). Estimated lake levels dated by Adams (2007) and corresponding to the G-1 and G-2 droughts identified by Stine (1994) are shown. Underscored numbers refer to the return frequency of baseline or wet years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are evident in Washington/southern British Columbia.

4. Discussion

Megadroughts can be interrupted by infrequent baseline or wet years while remaining consistent with geologic indicators of drought duration and lake level fall, independent of initial lake level (Fig. 2). This is consistent with the interannual variability evident from occasional positive departures in the tree-ring reconstructed Palmer Drought Severity Index (PDSI) for the Walker Lake region during the MCA (Cook and Krusic, 2004). Historically, these wetter years are associated with increased moisture transport, more favorable trajectories of transport, and a greater frequency of atmospheric river days (Fig. 3; Backes et al., 2015). In the Sierra Nevada, a small number of heavy precipitation events associated with atmospheric rivers can terminate droughts (Dettinger, 2013) or produce average to above-average cool-season precipitation despite otherwise dry conditions (Backes et al., 2015). Our calculated fraction of total moisture transport from atmospheric river days is consistent with other estimates of cool-season precipitation

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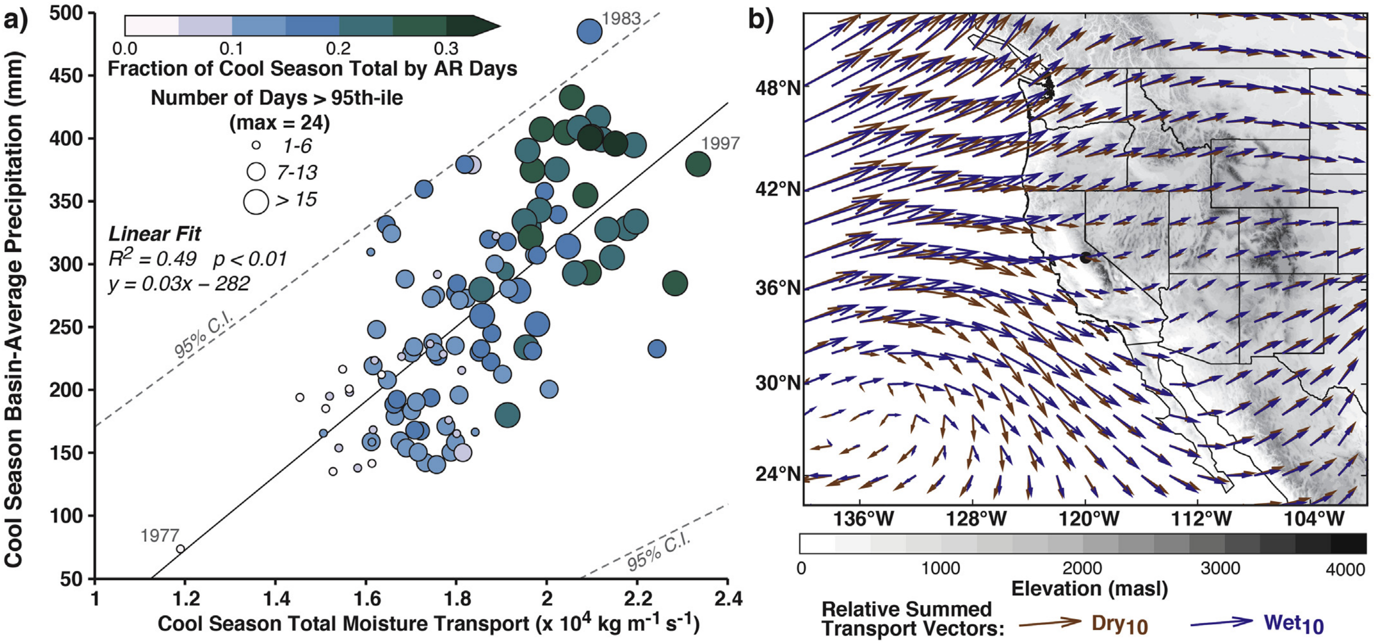

Fig. 3. a) Scatterplot of cool season (October–April) total moisture transport with dot size corresponding to the number of atmospheric river days (>95th percentile transport days). Dot coloring corresponds to the fraction of total moisture transport contributed by atmospheric river days. The years of lowest transport (1977), highest transport (1997), and wettest overall (1983) are shown. b) Mean total transport vectors for driest (<10th percentiles, brown) and wettest (>90th percentiles, blue) years. The black circle shows the grid point used in (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

contributions from atmospheric rivers (Backes et al., 2015; Rutz et al., 2014). Our results support the importance of atmospheric rivers in driving western Great Basin hydroclimate as more (less) of these events occur during wetter (drier) years (Fig. 3a). The lake responds to wetter years by rising on the order of 1–4 m (Fig. 2; Hatchett et al., 2015). The moderate positive correlation between moisture transport and observed cool-season precipitation indicates that moisture transport can be used to evaluate past or future hydroclimate variability from global climate model output (e.g., Lavers et al., 2016) in addition to measures of extratropical cyclone activity (Chang et al., 2015). As we have focused on a single lake basin, regional comparisons of terminal lake systems are encouraged to better constrain regional climate sensitivities.

The orthogonal moisture transport direction with respect to the Sierra Nevada during the wet$_{10}$ years (Fig. 3b) favors increased precipitation efficiency along the Sierra Crest (O'Hara et al., 2009) and a weakening of the Sierra Nevada rain shadow compared to dry$_{10}$ years. The differing vector patterns between the wet$_{10}$ and dry$_{10}$ years are centered in the same region as the second empirical orthogonal function shown by Graham and coauthors, 2007 that explains 20% of the variance in PDSI of the last millennium. This further suggests the importance of moisture transport anomalies in driving hydroclimate variability in this region. The difference in mean transport direction between wet and dry years appears consistent with changes in the poleward extent and strength of the subtropical high (Fig. 3b). Anomalous positive (negative) surface pressures and anticyclonic (cyclonic) flow in the eastern north Pacific promote the blocking (passage) of midlatitude cyclones and associated moisture transport into California and Nevada, consistent with Fig. 3a.

Drought conditions in the southwestern US are favored by persistent La Niña-like conditions in the equatorial tropical Pacific (Hoerling and Kumar, 2003; Seager et al., 2005). La Niña-like conditions are thought to have persisted during the MCA (Herweijer et al., 2007; Burgman et al., 2010). However, high amplitude phases of ENSO can produce a wet year (Dettinger et al., 1998) if the correct phasing with other modes of interannual or intraseasonal variability exists (Seager et al., 2007; Guan et al., 2012, 2013). We define high amplitude phases as when the standardized Tahiti-Darwin Southern Oscillation Index (Ropelewski and Jones, 1987) is less than −1 or greater than 1. Tree-ring chronologies in the southern Sierra Nevada show that ENSO periodicity during the last 2000 years completes one cycle every 2–8 years (Adams et al., 2015). It seems reasonable to assume that ENSO teleconnections would occasionally produce a wetter year despite possible prolonged La Niña-like conditions during MCA-like megadroughts. Our results show that continuous lake regressions would remain possible provided that all high-amplitude ENSO years produce baseline precipitation. Similarly, necessary lake regressions can occur if one in two high-amplitude ENSO events yields a wet year despite otherwise megadrought conditions. This is consistent with the geographical proximity of Walker Lake to the ENSO dipole inflection point (Dettinger et al., 1998; Wise, 2010).

5. Conclusions

We applied hydrologic modeling to test how frequently baseline and wet conditions could occur in the Walker Lake Basin when superimposed upon a megadrought climate and remain consistent with estimated lake levels. Independent of initial lake level, baseline (wet) years could occur once every five (10) years. These results provide plausible bounds on the magnitude and frequency of wetter years amidst otherwise megadrought conditions. Historically, wet (dry) years are produced by increased (reduced) total moisture transport and increased (reduced) numbers of atmospheric river days. We recommend using moisture transport as an additional method to evaluate global climate model simulations of past environments in order to better understand the large-scale drivers of hydroclimate regimes in dryland regions.

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