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Multi-year climate variability in the Southwestern United States within a context of a dynamically downscaled twentieth century reanalysis

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Abstract This investigation evaluates whether there is coherency in warm and cool season precipitation at the low-frequency scale that may be responsible for multi-year droughts in the US Southwest. This low-frequency climate variability at the decadal scale and longer is studied within the context of a twentieth-century reanalysis (20CR) and its dynamically-downscaled version (DD-20CR). A spectral domain matrix methods technique (Multiple-Taper-Method Singular Value Decomposition) is applied to these datasets to identify statistically significant spatiotemporal precipitation patterns for the cool (November–April) and warm (July–August) seasons. The low-frequency variability in the 20CR is evaluated by exploring global to continental-scale spatiotemporal variability in moisture flux convergence (MFC) to the occurrence of multiyear droughts and pluvials in Central America, as this region has a demonstrated anti-phase relationship in low-frequency climate variability with northern Mexico and the southwestern US By using the MFC in lieu of precipitation, this study reveals that the 20CR is able to resolve well the low-frequency, multiyear climate variability. In the context of the DD-20CR, multiyear droughts and pluvials in the southwestern US (in the early twentieth century) are significantly related to this low-frequency climate variability. The precipitation anomalies at these low-frequency timescales are in phase between the cool and warm seasons, consistent with the concept of dual-season drought as has been suggested in tree ring studies.

1 Introduction

Drought in the southwestern US is a recurrent stress to natural and human systems in this region (e.g., Garfin et al. 2013). Long-term droughts, lasting on the order of several decades, can have especially profound consequences in terms of causing major and possibly permanent changes. A well-known historical example, from the Pre-Columbian era, is the extreme and prolonged drought that occurred during the middle-12th and late-thirteenth centuries. These particular severe droughts likely forced the Anasazi people to migrate from their lands, located in the present-day Four Corners region of the southwestern US, and triggered their eventual demise (Benson et al. 2007). In a rapidly changing climate of the twenty-first century under the influence of anthropogenic-induced global warming, these types of droughts in the southwestern US are likely to be even more extreme (Ault et al. 2014); threatening fragile ecosystems and the water supplies within the Colorado River and Rio Grande basins. A better understanding about the variability and nature and causes of American southwestern droughts

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is critically needed to inform resilient strategies for natural hazard management, agriculture, public heath, and water management (Ray et al. 2007).

One major limitation in the physical understanding of long-term drought is the absence of instrumentally-based information that can temporally well resolve long-term climate variability, at the decadal to centennial timescale. The use of natural paleoclimate proxies has been an effective way to characterize this type of long-term climate variability. (e.g., Woodhouse and Overpeck 1998). In the study of the paleoclimate of the southwestern US, historical documents, lake-core sediments (Laird et al. 1996), geomorphic data, and tree-ring chronologies (Grissino-Meyer 1996) have all been employed. Each of these data sources has unique advantages and disadvantages with respect to their ability to characterize climate variability in both space and time. Tree-ring chronologies are particularly robust climate proxy for the southwestern US because of their ability to record annual and sub-annual variations in climate and their availability from forests located in various mountain ranges within the region (Griffin et al. 2013). Dendrochronologic analysis techniques can reconstruct climate conditions as far back as several millennia (D'Arrigo and Jacoby 1991; Herweijer et al. 2007; Meko et al. 2007; Stahle et al. 2009).

In the southwestern United States, cool and warm season climate variability during multiyear droughts has been identified by respectively using earlywood (EW) and latewood-adjusted (LW$_{adj}$) tree-ring chronologies, available for the most recent five centuries. The ability to parse the cool and warm season contributions to the overall climate variability is very important because of the differences in (1) the physical mechanisms and precipitation generation (synoptic-scale mid-latitude cyclones versus monsoon thunderstorms on the mesoscale) and (2) large-scale teleconnective mechanisms related to variability of precipitation at intraseasonal to interannual timescales, at least in the context of the modern instrumental record since the late twentieth century (e.g. Castro et al. 2007b, 2009). Griffin et al. (2013) showed that the 1570s, 1660s, 1770s, 1820s, 1890s, and early 2000s droughts experienced anomalously low precipitation during the cool and warm seasons, or dual-season drought. Unique to their study, they specifically explored the ability of LW$_{adj}$ to explain the warm season (monsoon) precipitation variability (Meko and Basin 2001; Griffin et al. 2011) and discovered that warm season drought events in the previous centuries were more extreme than during the modern instrumental era since the mid-twentieth century. Drought in the southwestern US is not an isolated phenomenon, but part of a larger, continental to global-scale pattern of climate variability. An out-of-phase relationship of precipitation anomalies exists between northern

Mexico (adjacent to southwestern US) and Central America (Méndez and Magaña 2010; see Fig. S1) regions the multi-year scale. For example, during the 1950s, relatively dry conditions occurred in northern Mexico that contrasted with the anomalously wet conditions in Central America. Using a 500-year record of reconstructed tree-ring Palmer Drought Severe Index (PDSI) Cook et al. (2004) also showed that persistent droughts in northern Mexico correspond with wet conditions in Central America.

The physical causes of western US climate variability at the seasonal timescale are fairly well understood, in terms of relationships to coupled modes of ocean–atmosphere variability (e.g., ENSO, Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation; Wallace and Gutzler 1981; Gershunov and Barnett 1988; Carleton et al. 1990; Castro et al. 2001, 2007b; Ciancarelli et al. 2013). Persistent multiyear to multidecadal climate variability, including long-term drought, is comparatively less well understood (Woodhouse and Overpeck 1998; Ault et al. 2014). Two principal mechanisms have been recently proposed to physically explain multiyear droughts within the modern instrumental era: oceanic forcing and internal atmospheric variability (Seager and Hoerling 2014). For example, the 1930s drought in North America has been linked to cool tropical SST and warm North Atlantic SST (Schubert et al. 2004), which confirms that the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) and the Atlantic Multidecadal Oscillation (AMO; Enfield et al. 2001) are the likely orchestrators of long-term drought. Drought in Central America is similarly related to an out-of-phase configuration between positive PDO and negative AMO (Méndez and Magaña 2010).

The aforementioned occurrence of dual season drought found in tree ring records in the southwestern US by Griffin et al. (2013) is quite relevant to explain the nature of persistent drought during the last five centuries, notwithstanding the methodological caveats of their precipitation reconstruction process that may adversely bear on the ability of tree ring data to reliably capture true low-frequency climate variability. These caveats include tree physiology related to root and crow mass (Fritts 2001) and standardization of the ring-width time series (Cook et al. 1995).

Carrillo et al. (2016) provide additional evidence to support the existence of a dual-season drought signal. They statistically isolated the low-frequency, dual-season drought signal from a network of tree-ring sites within the southwestern US and showed it to be significant and spatially coherent.. This study also confirmed the spatiotemporal patterns of cool and warm season precipitation variability in the western and central US that are known to exist within the period of the modern instrumental era. However, Carrillo et al. (2016) was not able to ascertain the true nature of the continental-scale spatial pattern of the low-frequency

drought signal, because of the geographic constraints of the tree-ring network.

To better understand low-frequency climate variability, as revealed by the network of tree-ring data in the southwestern US by Carrillo et al. (2016), an alternative source of long-term, historical climate data is needed (on the order of at least a century) that encompasses the spatial scale of the North American continent. Specifically, we seek to obtain a statistically significant mode of long-term climate variability that would explain the dual-season wet and dry periods related to multiyear droughts. For this purpose we utilize the newly created twentieth Century Reanalysis (Compo et al. 2011) for its entire period of record (1871-present). Dynamical downscaling of this reanalysis product with a regional climate model (RCM) is performed to more reasonably represent precipitation in the southwestern US in the cool and warm season. We hypothesize that low-frequency climate variability exists within the RCM simulation in a manner that is consistent with the prior studies with tree-ring data, then we may use RCM data to reveal (1) the continental-scale pattern of precipitation variability associated with multiyear droughts in the southwestern US and (2) the relationship of the low-frequency climate to coupled ocean–atmosphere variability.

2 Data

2.1 The twentieth-century reanalysis

We use the NCEP-NCAR twentieth century reanalysis version 2 project dataset (henceforth 20CR, Compo et al. 2011). The 20CR is a coordinated, international effort to produce a retrospective atmospheric reanalysis from 1871 to the present, the longest period to date of an atmospheric reanalysis. Data are available every 6 h with 2° resolution at 24 standard pressure vertical levels. The 20CR assimilates available observational data by using an Ensemble Kalman Filter (Whitaker and Hamill 2002). Ingested observations include surface pressure from the International Surface Pressure Databank and monthly sea surface temperature and sea-ice concentration from the Hadley Centre Sea Ice and SST dataset (Rayner et al. 2003). In terms of prior investigation of long-term climate variability, the 20CR Version 1 has been used to study the US Dust Bowl of the 1930s by Cook et al. (2010). This same study notes that though the 20CR is limited to approximately 140 years length it may be sufficient to capture several cycles of long-term drought. The major limitation in 20CR, similar to other global atmospheric reanalysis products of shorter duration, is its poor representation of the precipitation features at regional and local scale. Therefore, in lieu of the direct use of 20CR precipitation, for analyses in this study

we use moisture flux convergence, similar to prior work by the authors with the NCEP-NCAR reanalysis that investigated long-term variability of the North American monsoon (Castro et al. 2001).

2.2 The sea surface temperature and the geopotential height data

Sea surface temperature (SST) from the Hadley Centre Sea Ice SST dataset (Rayner et al. 2003), is used to: (1) to specify the surface boundary condition in regional climate model simulations and (2) to link large-scale SST variability and modes of climate variability with RCM-simulated precipitation. SST is averaged for the warm and cool season, respectively defined as July–August (JA) and November to April (NA), during the entire period of record of the 20CR (1871 to 2010). The present study investigates large-scale modes of precipitation variability in North America related to sea surface temperatures, similar to previous work by the authors (Castro et al. 2001, 2007a, b; Ciancarelli et al. 2013). The atmospheric response to SST forcing is analyzed using geopotential height anomalies (GPHA) at 500 hPa from the 20CR. In addition, we compute transport of moisture into North America using meridional wind velocity at 850 hPa as an index for the Great Plains low-level jet following a similar approach in Weaver and Nigam (2011). Alternatively, for Central America large-scale circulation of moisture is inferred from vertical velocity computed in mandatory pressure levels of the 20CR. The vertical velocity is inferred from the omega equation following the quasi-geostrophic approximation in Holton (2004).

2.3 Dynamical downscaling of 20CR with WRF

The 20CR is dynamically downscaled with the Weather Research and Forecasting (WRF) model (henceforth DD-20CR). The utility of dynamical downscaling of atmospheric reanalyses to represent North American climate, specifically in the southwestern US, in the cool and warm season has been firmly established in numerous studies (Gutzler et al. 2005, 2009; Castro et al. 2007a, 2012; Wi et al. 2012; Dominguez et al. 2012; Bukovsky et al. 2013). This would include a reasonable representation of climate variability due to coupled-ocean atmosphere interactions, as we showed for North American Regional Climate Change Assessment Program (NARCCAP, Mearns et al. 2012) regional climate models in Carrillo et al. (2015).

However, RCM simulations have documented limitations that could affect the outcome of this experiment. For example, loss of synoptic variability (Rockel et al. 2008) in the initialization of the boundary conditions

that here was reduced by the use of spectral nudging. In the southwest, previous dynamically downscaling simulations have shown a deficit of moisture transport from the Gulf of Mexico (Cerezo-Mota et al. 2011) that can be affect the intensity of the drought and pluvial inter-annual variability in two important regions the northern Great Plains and the Southwest. Also, proper timing of propagating organized convection from elevated to low regions is also miss-represented and potentially a major cause or dry bias in the nearest locations of the Gulf of California (Castro et al. 2012). A better way to address this limitation is probable through the use of convective-permitting modeling (Luong et al. 2016). In our experiment, a continuous simulation is performed over a domain that extends the contiguous US and Mexico with 35 km grid spacing. Boundary conditions are updated every 6 h. The WRF model is used with similar parameterizations to the operational forecasting configuration of the Department of Hydrology and Atmospheric Sciences at the University of Arizona, as previously described in Castro et al. (2012). Our WRF simulation use fixed Greenhouse Gas (GHG) emissions which is reasonable given this is a historical simulation and not climate change projections. Although several studies suggest that global climate change may result in more frequent and intense droughts (Ault et al. 2016). However, this numerical experiment is restricted to historical droughts. Nevertheless this issue needs to be urgently addressed in the context of pseudo global warming simulations. The DR-20CR uses the NOAH land surface model (LSM), which uses fixed land cover and vegetation type. Thus the model can potentially capture land surface feedback processes associated with changes in soil moisture, but not the feedbacks from dynamic vegetation. Our current research effort will incorporate the impact of dynamic vegetation within the context of the NOAH-Multiparameterization LSM (Niu et al. 2011). Sea surface temperatures are bias corrected to the observed satellite record at the Gulf of California (GoC). The original cooler than normal 20CR sea surface temperature at the GoC is found to suppress convective precipitation during the warm season over the Southwest, consistent with Mitchell et al. (2002). Spectral nudging is imposed on the interior of the RCM domain to conserve large-scale (synoptic) variability from the driving 20CR, including the quasi-stationary Rossby wave train atmospheric teleconnections that are ultimately the likely drivers of low-frequency climate variability in western North America, similar to the seasonal timescale. Prior studies have generally found better representation of the climate variability in North America when implementing the spectral nudging approach (e.g., Castro et al. 2012;

Mearns et al. 2012; Bukovsky et al. 2013; Carrillo et al. 2015).

2.4 Observed precipitation data

Observed precipitation data is from a new 0.5° gridded National Oceanic and Atmospheric Administration (NOAA) product (P-NOAA), provided by Drs. Russ Vose and Richard Heim (Vose et al. 2014). P-NOAA covers the entire area of study (the US and Mexico) and incorporates a terrain correction interpolation function, similar to the Parameter-elevation Regressions on Independent Slopes Model (PRISM Climate Group 2004), beneficial for the complex terrain of the Southwest. The P-NOAA product has been previously used by the authors in evaluation of a dynamically downscaled global seasonal forecast model for the warm season period in North America (Castro et al. 2012).

3 Statistical analysis methodologies

3.1 Moisture flux convergence and water vapor budget analysis

In lieu of precipitation from the 20CR, as in Castro et al. (2001) and Castro et al. (2007b), we use moisture flux convergence (MFC) because of its stronger tie to the underlying atmospheric dynamics and less dependence on model parameterized processes. Evaporation, precipitation, and MFC are directly related to the water vapor budget equation (Schmitz and Mullen 1996; Higgins et al. 1997).

$$\frac{\partial W}{\partial t} + \nabla \cdot \vec{Q} = E - P \tag{1}$$

Where, E is evaporation, P is precipitation, $\vec{Q} = \frac{1}{g} \int_0^{P_s} \vec{V} dp$, is water vapor flux, q is specific humidity, p is pressure, g is gravity, $\vec{V}$ is velocity, and $W = \frac{1}{g} \int_0^{P_s} q dp$ is precipitable water. MFC from 20CR is used to identify the regions that are associated with spatial variability in precipitation on continental and larger scales.

3.2 Standardized Precipitation Index (SPI)

The standardized precipitation index (SPI) is used to specify cool and warm season precipitation anomalies during the period 1871 to 2010. SPI is computed using a gamma-normalization procedure applied to total precipitation at various timescales, typically ranging from a month to multiple years (McKee et al. 1993), and was developed in large measure to spatially characterize and monitor short and long-term drought in the United States (e.g., Heim 2002).

Cool season SPI is defined for the period November to April (NA) and warm season SPI is defined from July to August (JA). With respect to the objectives of this study, main advantage of using SPI is its ability to clearly reveal spatial patterns of precipitation variability at regional and continental scales (e.g. Castro et al. 2009; Ciancarelli et al. 2013; Carrillo et al. 2016). We used the same methodology to compute SPI as in these studies applied to P-NOAA and the DD-20CR.

3.3 MTM-SVD analysis

Multi-Taper-Method Singular Value Decomposition (MTM-SVD) (Mann and Park 1994, 1996; Mann and Lees 1996; Rajagopalan et al. 1998) is used to determine the dominant spatiotemporal variability of MFC, observed SPI, and DD-20CR SPI. The MTM-SVD technique and implementation is explained in detail in Rajagopalan et al. (1998), and has been previously used by the authors in Castro et al. (2009) and Carrillo et al. (2016). The resultant analysis produces a Local Fractional Variance (LFV) spectrum, reconstructed spatial patterns, and reconstructed temporal time series (Mann and Park 1996). The LFV is an alternative form of a power spectrum where the temporal and spatial variation is accounted for simultaneously. Statistically significant spectral peaks in the LFV spectrum are identified by statistical significance intervals determined by bootstrap re-sampling (Rajagopalan et al. 1998). The reconstructed spatial pattern represents the spatial variability associated with a specific spectral band, or specific frequency. The reconstructed spatial patterns presented are reconstructed for spectral bands that are statistically significant at the 90% level or above. The reconstructed spatial patterns are plotted as correlation maps, where the correlation fields were computed by Pearson correlation between the original variable and the reconstructed temporal time series. The reconstructed temporal time series are obtained at point in the domain specified at reference point within the analysis domain. The reference point for both datasets analyzed is located at the center of the North American Monsoon Experiment region 2 (NAME 2; 32.75°N, 110.25°W; Gochis et al. 2009), coincident to the approximate geographic location of Tucson, Arizona. The same methodology was used to compute MTM-SVD as in Castro et al. (2009) and the codes were obtained from the website of Professor Michael Mann at the Pennsylvania State University.

3.4 Correlation, local significance, and field significance

Spatial correlation patterns for MFC, observed SPI, DD-20CR SPI, SSTA, and GPHA are computed using the Pearson correlation coefficient. Local significance is assessed by a Student's t test and field significance is assessed by a Monte Carlo method originally described in Livezey and Chen (1983). The threshold for local significance is the 90% confidence level ($p < 0.10$) and the Monte Carlo method for determining field significance uses 1000 iterations. These statistical methodologies are quite consistent with the previous work by the authors in Castro et al. (2007b) and Ciancarelli et al. (2013).

4 Results and discussion

The main purposes of this work are to (1) demonstrate whether 20CR and DD-20CR are able to reasonably represent the low-frequency, dual-season droughts in the southwestern US that would lead to accumulative annual precipitation deficits over multiple years and (2) establish a clear connection of these droughts to continental to global scale patterns of climate variability and possible forcing mechanisms. We first analyze the low-frequency variability of moisture flux convergence for the 20CR with focus on the large-scale circulation over Central America. For reasons previously mentioned in the last section, we use MFC in lieu of precipitation to consider moisture variability within the 20CR. The same analysis is then applied to precipitation from the DD-20CR applied over a high resolution domain that covers North America. The first step establishes that low-frequency climate variability exists within the 20CR and it can be thus transferred in the boundary forcing to DD-20CR. The second step improves regional features of precipitation in space and time in the western US, due to better representation of orographically-forced precipitation during the cool season and monsoon thunderstorms during the warm season.

4.1 Evidence of the dominant low-frequency climate variability in Central America as diagnosed by moisture flux convergence

As previously mentioned in the Introduction, persistent long-term droughts in the Southwest and northern Mexico are inversely related to anomalously wet conditions in Central America (Méndez and Magaña 2010; Cook et al. 2004). If the low-frequency variability of precipitation in these two geographic regions is related, then it must be due to coherent variability in atmospheric circulation patterns at continental to global scales and forcing mechanisms. At least climatologically, these two regions are connected during the warm season by the evolution of the North American monsoon system and its relation to the changing position of the Inter-tropical Convergence Zone (ITCZ). Central America has a bimodal summer precipitation, with one peak during June-July and the other in September (Magaña

et al. 1999; Karnauskas and Busalacchi 2009), and slight decrease in between corresponding to the period of the midsummer drought as the ITCZ moves north, or locally referred to in Spanish as the *canícula* (Mosiño and Garcia 1966; Hastenrath 1967). In contrast, the southwestern US presents a mono-modal summer precipitation peak in July and August, coincident with the timing of the *canícula* in Central America, with an abrupt increase in precipitation in late June and early July with onset of the North American monsoon (Adams and Comrie 1997).

Global patterns of MFC variance are shown for the warm and cool season in Fig. 1 for the entire globe. At the global scale, the variability in MFC is mostly associated with changes in tropical convection in the central tropical Pacific tied to El Niño Southern Oscillation (ENSO). There is a local maximum in variability of MFC located over Central America during the warm season. This region is highlighted by a red box, labeled as CA in Fig. 1, and will be a target of further analysis. The combined Pacific SST variability (P-SST) index was calculated, as defined in Castro et al. (2001), for the 20CR cool and warm season. The P-SST index basically reflects the combination of ENSO and PDO through a SST-based metric. Then P-SST index is correlated with cool and warm season MFC to analyze patterns of convergence and divergence associated to Pacific SST forcing at the global scale (Fig. S2). Irrespective of the season, there is a clear out-of-phase pattern in the MFC and P-SST correlation field between the central Pacific and both the western Pacific and equatorial Atlantic, that generally reflects the known influences of ENSO on precipitation in the tropics and the mid-latitudes (Ropelewski and Halpert

1986, 1987). Therefore, 20CR MFC is capable to capture the global scale distribution of MFC associated with ENSO, so it probably also contains information on low-frequency climate variability.

The aforementioned region of local maximum MFC variability in Central America (CA) during the warm and cool seasons is used to explore the low-frequency climate variability within the 20CR. The 10-year running mean filtered and the original time series of JA and NA MFC spatially averaged over CA are shown in Figs. 2 and 3 (bottom). The 10-year running mean reveals low-frequency climate variability. Periods with a sustained positive (negative) sign of MFC are associated with pluvials (droughts) in CA. The MFC time series in both seasons identify three distinct pluvial and drought-related periods related to low-frequency climate variability: the 1892–1899 pluvial, the 1912–1937 drought, and the 1942–1951 pluvial. These periods are defined by the range of consecutive year exciding ±75% of the standard deviation of the 10-year running mean time series (Fig. 2; bottom). We have selected periods for the summer season only and use their ranges for the winter composite for comparison purposes. The spatial patterns for these three periods for JA and NA MFC are shown as composite in Figs. 2 and 3 (top). Positive (negative) values represent convergence (divergence), which are emphasized with vectors. The spatial and temporal patterns of these results suggest an in-phase relationship between the winter and summer composite at least for Central America. Fig. S3 is similar to Fig. 2 but for precipitation instead of MFC to validate the sign of the convergence in MFC. In general, wet (dry) periods in Central America are associated with

Fig. 1 Variance of moisture flux convergence (MFC) for the twentieth-century reanalysis (20CR) Version 2 for the period 1871–2012. The summer season (*top*) is defined during July–August (JA) and winter (*bottom*) during November–April (NA). The *box* located in Central America (CA) is defined as reference for further analysis
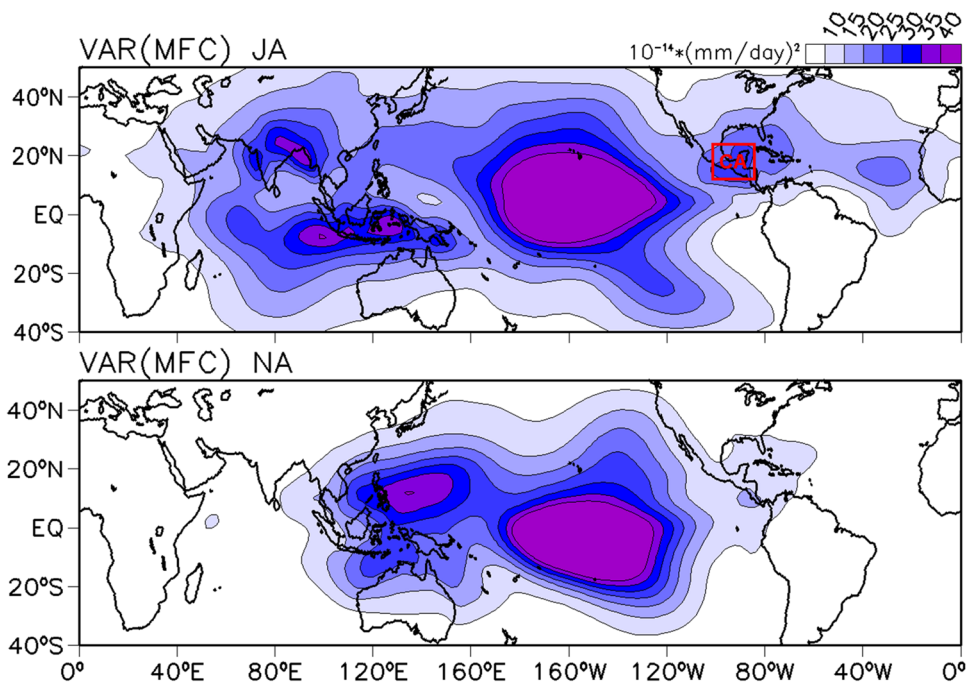
Fig. 2 JA Moisture Flux Convergence (MFC) composite anomaly for the periods: 1892–1898, 1912–1937, and 1942–1951 (*upper*). These periods are defined using the positive and negative anomalies in the JA MFC anomaly time series (*bottom*), as highlighted by the *red boxes*. Vectors in the map show the convergence/divergence of the flux. The JA MFC time series is calculated over the Central America (CA) region in Fig. 1 (10–25°N; 100°–80°W). *Big arrows* highlight the intensity of these peaks associated with pluvial and drought regimes. The *vertical bars* are the interannual variation and the *solid line* is the 10-year running mean
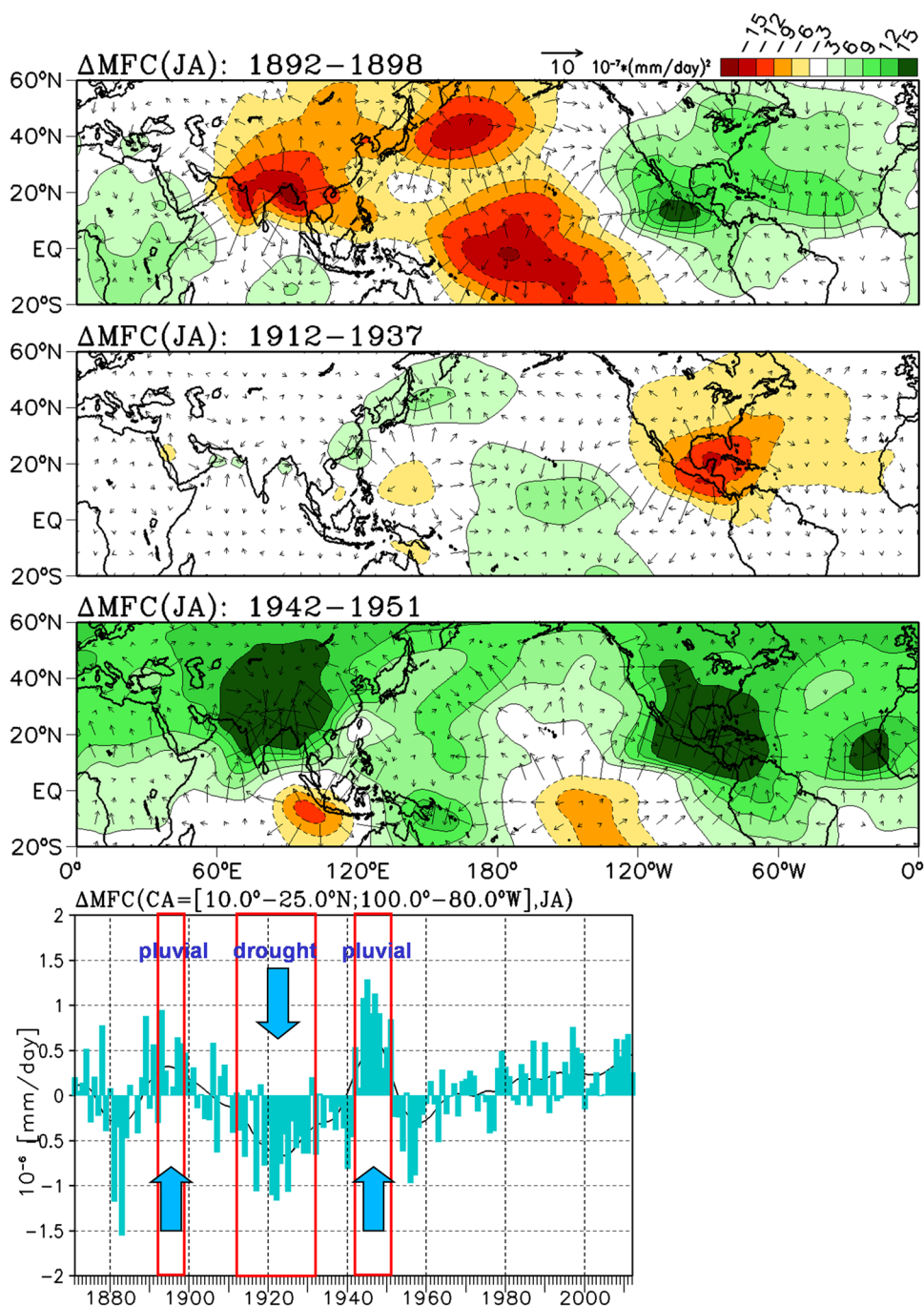
moisture flux divergence (convergence) in the central equatorial Pacific, which would be consistent with La Niña-like (El Niño-like) conditions. We use the MFC to show that the large-scale low-frequency climate variability is presented in the coarse 20CR. Therefore, anomaly vertical velocity as defined in Holton (2004) is calculated for two periods 1892–1898 (wet) and 1912–1937 (dry) for Central America using 20CR. These not only shows a clear subsidence during the major drought in CA but also the counterpart lifting during the pluvial years that exemplify and active

Hadley-like circulation at a low-scale (Fig. 4). This manuscript does not explore the large-scale dynamical mechanisms of Central American drought. One of the main goals of the paper is to confirm an in-phase relationship between the summer and winter season low-frequency precipitation variability of the Southwestern US and Central America exists in the 20-CR, that has already been described by other authors (Méndez and Magaña 2010). This analysis demonstrates that low-frequency droughts and pluvials in both regions are part of a much larger pattern of continental

**Fig. 3** Similar to Fig. 2 but for the cold season, November through April (NA)
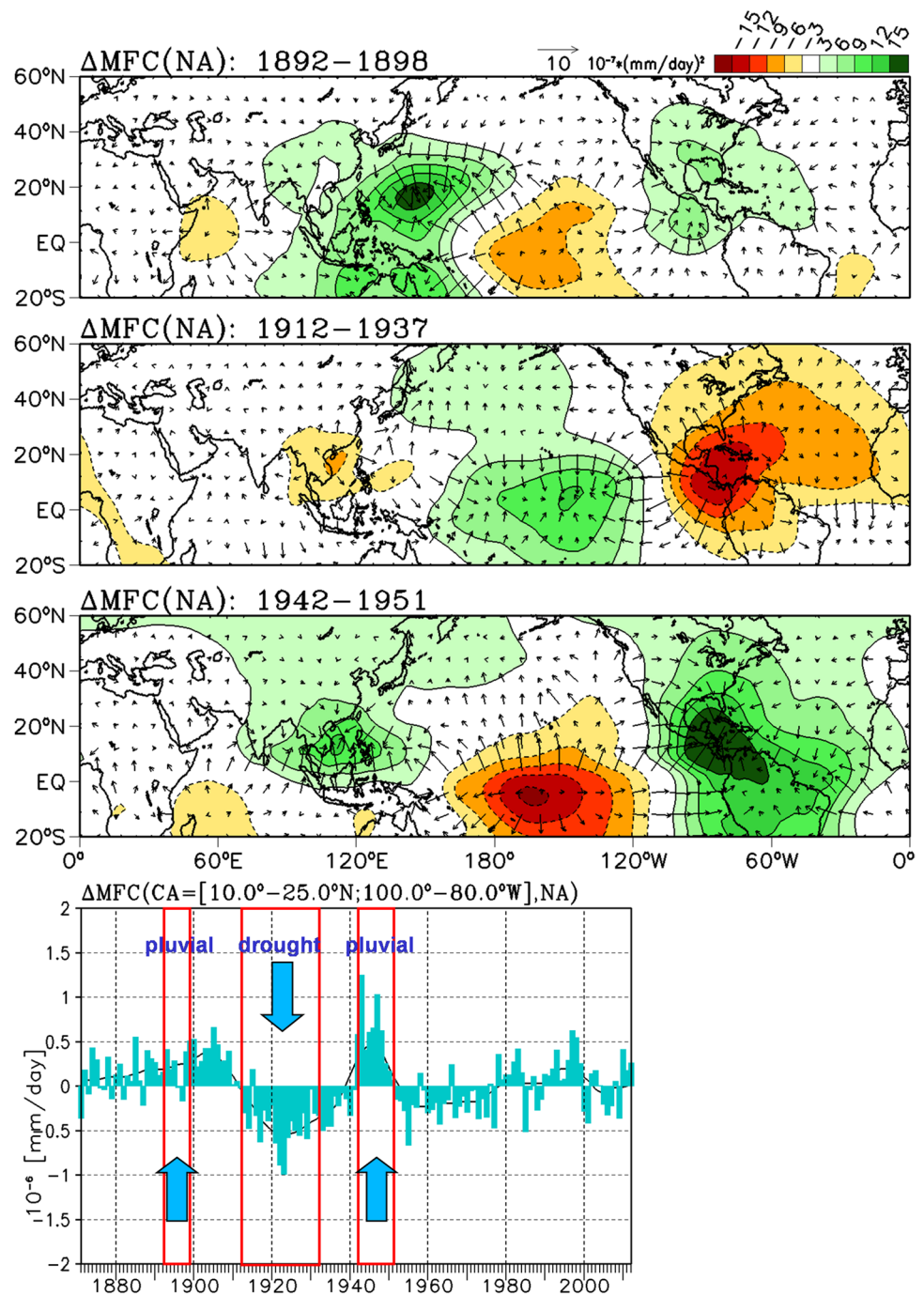
to global scale circulation variability. The subsidence and lifting circulation over Central America (Fig. 4) during the selected periods for the drought and pluvial shows the ability of 20CR to represent the large-scale circulation (with limitations) over Central America and later how this is potentially linked with North America. Therefore, 20CR seems to have adequate information to be applied prior to 1950 in the study of droughts. The in-phase summer and winter patterns of the multiyear droughts and pluvials in Central America suggest a similar concept to dual season

drought in the southwestern US (Griffin et al. 2013). The warm season precipitation anomalies (Fig. S3) during the identified droughts and pluvials in Central America show that enhanced (suppressed) precipitation occurs with a more northward displacement of the Intertropical Convergence Zone (ITCZ; Karnauskas and Busalacchi 2009), that would again tend to occur with more La Niña-like (El Niño-like) conditions (Giannini et al. 2000).

Previous investigations of cool and warm season precipitation variability in the southwestern US (Griffin et al.

Fig. 4 Zonally averaged circulation anomaly for two periods: 1892–1898 (*top*) and 1912–1927 (*bottom*). The circulation is zonally averaged between 100 and 90 W during the July–August (JA) season. U_D is the zonal stream function component and ω (omega) is the rising and sinking motion (omega equation approximation, Holton 2004)
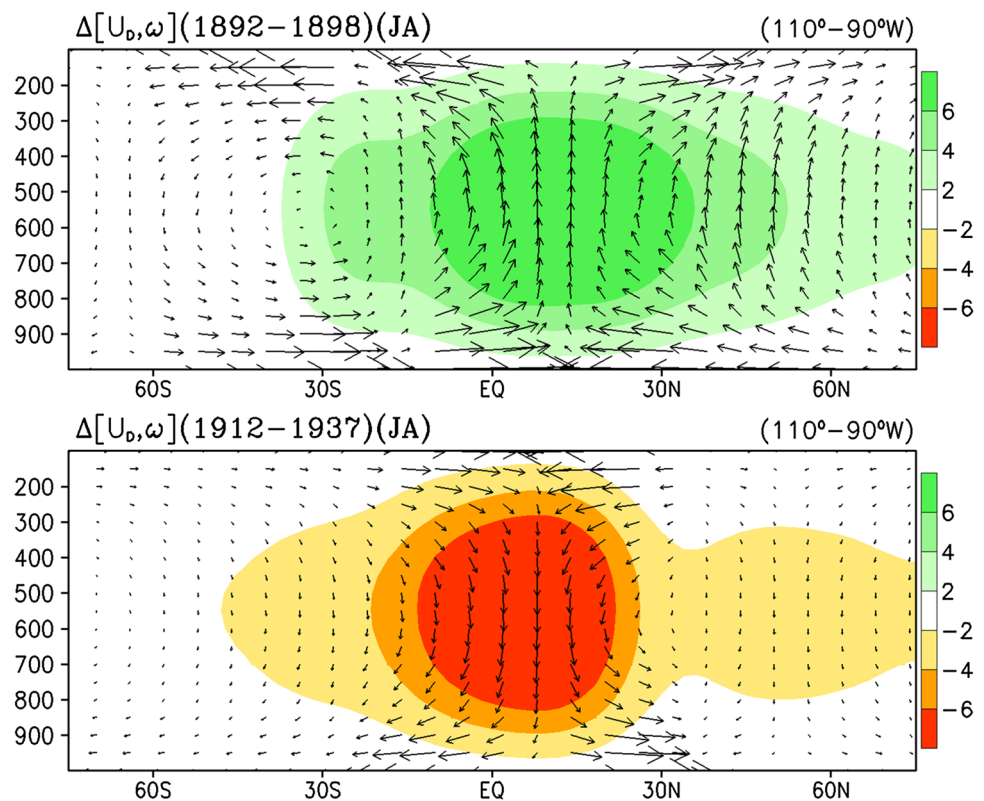
2013; Carrillo et al. 2016) considered EW and LW_{adj} tree-ring indices, for a 400-year record, to describe statistically significant in-phase low-frequency variability, as shown in Carrillo et al. (2016; their Fig. 14). By comparing these results, we assert that major droughts and pluvials in the Southwest are inversely related to precipitation changes in Central America as portrayed here within the 20CR record and also suggested by Méndez and Magaña (2010). Long-term droughts in the Southwest would be associated with persistent La Niña-like conditions in the Pacific, as in Herweijer et al. (2007). Though the 20CR precipitation signal in Central America is quite evident in Fig. S3, there is not a comparably inverse relationship in 20CR precipitation over southwestern North America, which could be due to erroneous representation of regional scale precipitation patterns.

4.2 Assessment of statistically significant low-frequency variability in 20CR MFC using MTM-SVD

The composite analyses of MFC in Central America during major droughts and pluvials in this region suggest an existing coherent pattern of low-frequency climate variability. To reiterate, at least from the composite analyses presented in the previous section, a physically coherent anti-phase relationship exists between MFC in Central America and MFC in the central tropical Pacific, tied to ENSO. Is this spatiotemporal variability in MFC statistically significant at the decadal timescale and longer? To address this question, the MTM-SVD was applied to the JA MFC field for the entire record of the 20CR. Three main results are shown in Fig. 5: the LFV spectrum, the reconstructed time series for low-frequencies (decadal and longer), and the pattern correlation map of the reconstructed time series with MFC. The MTM-SVD reference point is selected at the center of the NAME2 region. The LFV spectrum reveals a statistically significant low-frequency band, in the range of 25–50 years. The reconstructed MFC time-series of this low-frequency (25–50 years) reveals a similar spatial pattern as shown with the 10-year running mean time series (Fig. 2). The spatial correlation map in Fig. 5b also basically shows a similar anti-phase relationship in MFC between Central America and the central tropical Pacific, but the negative center of action is located more in the southern hemisphere, maximized at 30°S. Therefore we conclude that low-frequency climate variability exists and it is a statistically significant dominant feature in the 20CR dataset that drives the droughts and pluvials in Central America, similar to Méndez and Magaña (2010).

The same analysis on 25–50 year band-pass filtered MFC yields a consistent same result, but with a stronger spatial loading pattern in the MFC correlation map (Fig. S4a). To verify that this global-scale pattern of MFC is associated with southwestern US drought during the warm season, the

Fig. 5 Local Fractional Variance (LFV) spectrum of the leading Multi Taper Method-Singular Value Decomposition (MTM-SVD) mode for the Moisture Flux Convergence anomaly (ΔMFC) (**a**), for the warm (July–August; JA) season of the Twenty-Century Reanalysis (20CR). Spatial correlation pattern of MFC anomaly obtained between the JA 20CR ΔMFC and its reconstructed MTM-SVD temporal pattern for frequencies greater than 10 years (**b**). Local significance is shown with *oblique lines* and field significance in percentage. The reconstructed temporal pattern of JA 20CR ΔMFC for frequencies greater than 10 years (**c**). *Same boxes* and *big arrows* defined in Fig. 3 are superimposed
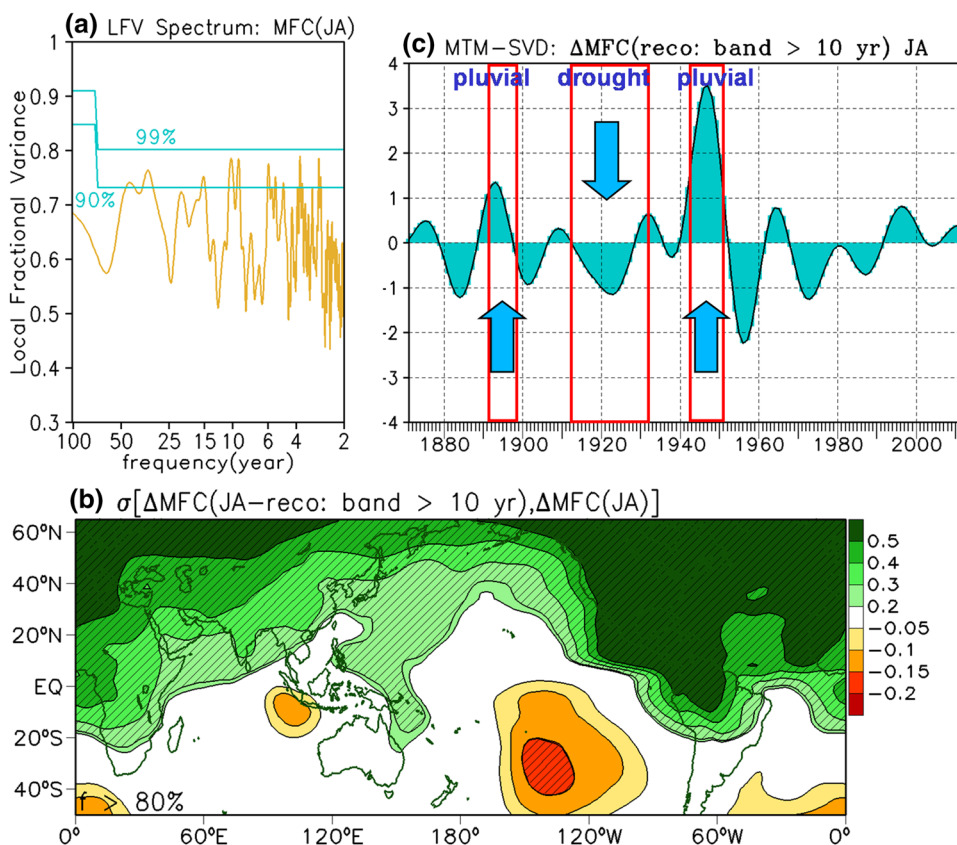

MFC reconstructed time series (Fig. S4b) is correlated with JA SPI (Fig. S4c). A statistically significant negative correlation with JA SPI exists throughout much of the southwestern US, corresponding to those geographic areas with the US that are influenced by the North American monsoon (e.g. Adams and Comrie 1997). When MTM-SVD analysis is performed for the cool season, the results are similar to the warm season, in terms of the pattern of MFC. However, the statistically significant spatiotemporal variability at low frequencies is only apparent in a 10–15 year band. Cool season variability in NA SPI is considered later when analyzing the DD-20CR. Similar to other studies that investigate the role of transport of moisture in the continental US (Weaver and Nigam 2011), we calculated the transport of moisture into North America using the statistical dominant mode of the Empirical Orthogonal Function of meridional wind velocity at 850 hPa from 20CR (Fig. 6). Our result not only reproduce the spatial variability of the Great Plains low level jet (GPLLJ), but also the temporal variability with the minimums during the 1930s and 1950s droughts. The GPLLJ index portrays the link with precipitation anomalies at a continental scale (Weaver and Ruiz-Barradas 2009). As previously described in Cook et al. (2010), variability of the Great Plains low-level jet seems to synchronize well the 1930s and 1950s droughts. This GPLLJ index shows that the lack of moisture transport into

the US interior as an important characteristic of the large scale impact of the drought represented by the 20CR.

4.3 Precipitation patterns in the DD-20CR using WRF

Though the 20CR can resolve statistically significant global-scale low-frequency climate variability at decadal and longer timescales as demonstrated by the prior analyses of MFC, MFC in the 20CR is probably not sufficient to characterize climate variability in the southwestern US, owing to its better fit for large-scale and course resolution circulation patterns (e.g. Castro et al. 2007b, 2012). A necessary requirement of a robust physical modeling system for the southwestern US is a reasonable representation of the monthly precipitation climatology, prior to any consideration of year-to-year variability. To illustrate the point, Fig. 7 shows the variance and climatology of monthly precipitation for the periods of 1895–2010 for P-NOAA, and 1871–2010 for both DD-20CR and 20CR. The 20CR tends to underestimate precipitation in the southwestern US but this is improved upon in the DD-20CR. In general, DD-20CR shows enhanced precipitation variability, with a clear terrain influence throughout the western US and northern Mexico. The annual cycle of monthly precipitation for the Southwest was analyzed also (Fig. S5) for P-NOAA, DD-20CR, and 20CR. In Arizona, the DD-20CR does a better
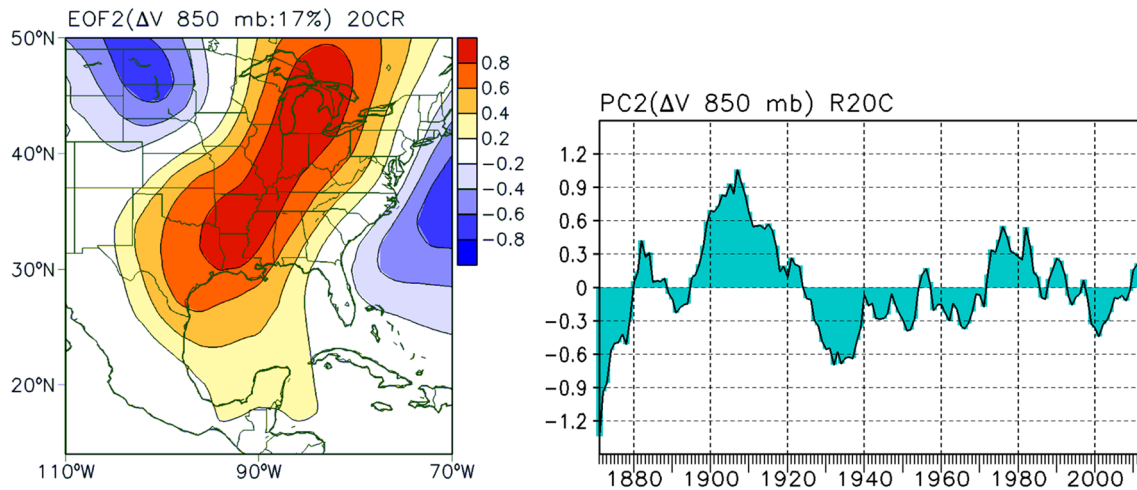
Fig. 6 *Left* Spatial Empirical Orthogonal Function (EOF2) pattern of 850-mb meridional wind anomalies (ΔV) from the Twenty Century Reanalysis (20CR) obtained for the July–August summer season (1871–2010), with explained variance of 18%. *Right* The 10-year running mean average of the associated temporal PC2 mode of the meridional wind at 900-mb (Great Plains Low-Level Jet index)

job than 20CR of reproducing the annual cycle of precipitation. In comparison to the 20CR, the DD-20CR reduces the positive precipitation bias in winter, more importantly, simulates a distinct North American monsoon where none exists in the 20CR. The valued-added of dynamical downscaling in the representation of precipitation is thus principally realized during the warm season, consistent with prior work that has specifically considered the southwestern US in regional climate model simulations that have used other atmospheric reanalyses to specify the boundary forcing (e.g. Gutzler et al. 2009; Castro et al. 2007a, 2012).
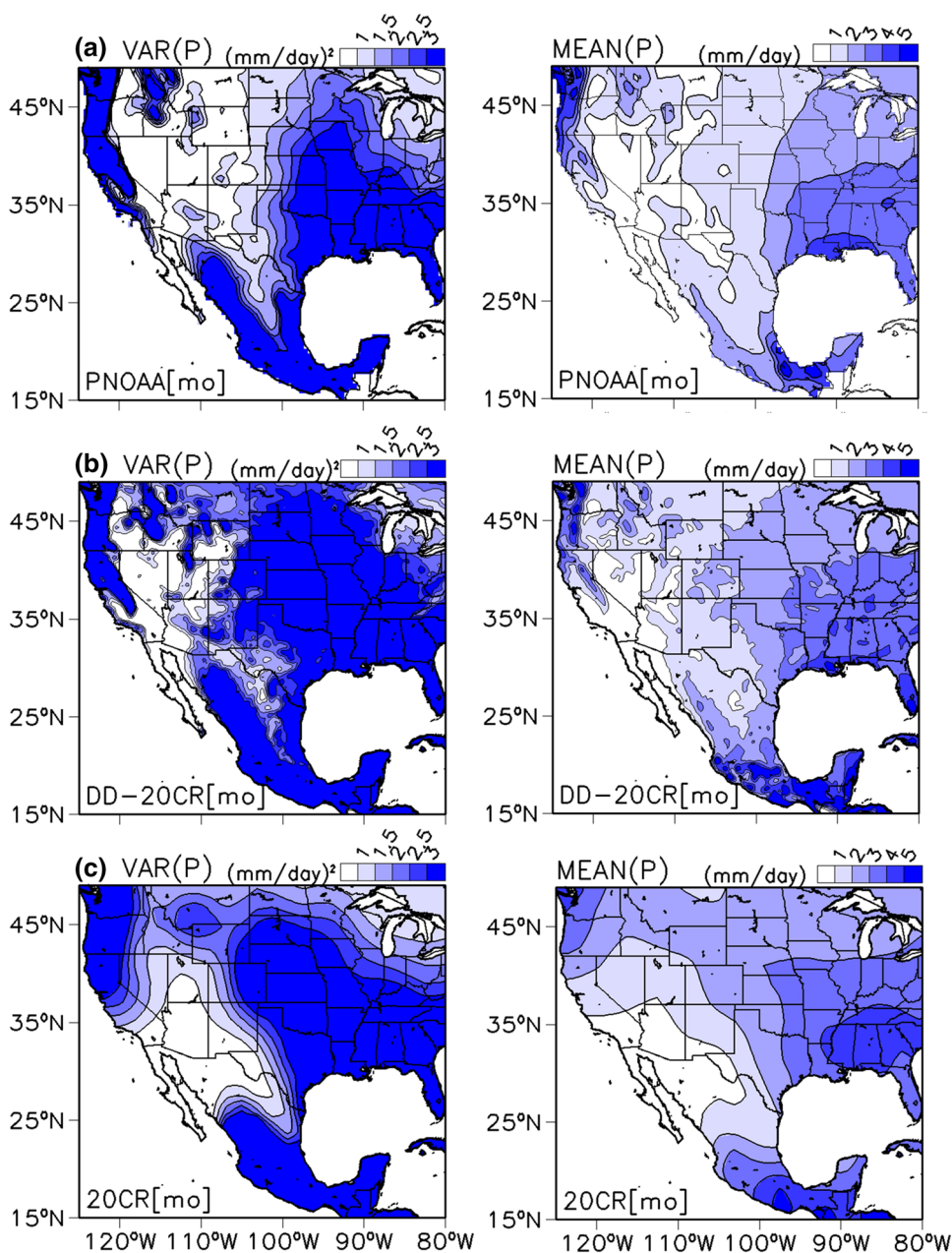
4.4 Low-frequency precipitation variability in the dynamically downscaled regional climate data

It seems reasonable to expect that the statistically significant low-frequency spatiotemporal variability in precipitation would be nearly identical between P-NOAA and DD-20CR precipitation. After all, 20CR just has an additional 30 years of data prior to 1900, as compared to P-NOAA. The MTM-SVD analysis of observed P-NOAA JA SPI shows only statistically significant low-frequency variability in the range of 15 years (Fig. S6). The correlated pattern of JA SPI shows a classic anti-phase relationship between precipitation in the southwestern US and central US/Pacific Northwest that is driven in great part by ENSO and Pacific Decadal Variability (e.g. Castro et al. 2001, 2007b, 2009). However, the abrupt discontinuity in the low-frequency scale along the Southwest precipitation pattern in the US/Mexico border is suspicious and may reflect discrepancies in precipitation data sources between the US and Mexico used in the construction of the P-NOAA product.

Performing the identical analysis on DD-20CR precipitation reveals a different result, with more statistically significant variability at low- frequencies (Fig. 8). The LFV spectrum shows significant temporal variability beyond the 10-year timescale and the corresponding spatial pattern in the SPI correlation map does not have any abrupt discontinuity at the US-Mexico border. More importantly, it shows that climate variability at this timescale is strongly coherent across northern Mexico and the southwestern US Otherwise, the negative sign over the Great Plains is shifted north, but is still consistent with the signal from the equivalent P-NOAA analysis.

The out-of-phase spatial relationship between Central America and the Southwest is explicitly resolved by identical analyses for both seasons (Figs. 8, 9). The reconstructed low-frequency time series also closely matches the known sequencing of droughts and pluvials in southwestern US from the tree-ring record (Carrillo et al. 2016). Why might DD-20CR precipitation yield a result for low-frequency precipitation variability in North America that has better correspondence with the tree-ring record and global MFC, in comparison to the P-NOAA product? It might be the additional time length of 20CR that allows for consideration of the late 1890s drought, so even the seemingly inconsequential addition of 30 years of data captures this important climate event that P-NOAA cannot. Perhaps less obvious is the fact that the dynamically downscaled precipitation is a result of consistent large-scale dynamical forcing mechanisms (i.e. atmospheric teleconnections) as input boundary forcing to the RCM. Though we consider P-NOAA as observational truth, it is subject to data limitations in the station site availability where precipitation data would have been recorded, especially during the

Fig. 7 Variance (*left* panel) and climatology (*right* panel) of monthly precipitation for observed precipitation (P-NOAA) (**a**), the dynamically downscaled Twenty-Century Reanalysis (DD-20CR) precipitation (**b**), and the Twenty-Century Reanalysis (20CR) precipitation (**c**). The two parameters are calculated during the following periods: 1895–2010 for P-NOAA and 1871–2010 for both the DD-20CR and 20CR


early part of its record. In addition, statistically significant low-frequency spatiotemporal variability in cool season precipitation is in phase with that of the warm season, with the peaks of the 1890s drought, 1912–1937 pluvial and 1942–1951 drought present. Important to note is that cool and warm season precipitation anomalies are in-phase which is consistent with the idea of dual-season drought.

This synergistic phasing of precipitation anomalies in the low-frequency regime is statistically assessed by the temporal ($r = 0.58$) and spatial ($\rho = 0.43$) correlations between the winter and summer spatiotemporal patterns. The ability to simulate the spatiotemporal pattern

of low-frequency climate variability in DD-20CR is important because: (1) it provides further evidence that the low-frequency variability in EW and LW_{adj} tree-ring data from the Southwest US network is not an artifact of the biological processes in the trees themselves (Carrillo et al. 2016), (2) it permits consideration of the possible forcing mechanisms for the variability with a consistent physical modeling framework, and (3) it confirms that multi-year droughts and pluvials in the southwestern US is a result of the synergistic phasing of cool and warm season precipitation anomalies, at least in the period of the 20CR.

Fig. 8 Local Fractional Variance (LFV) spectrum of the leading Multi Taper Method-Singular Value Decomposition (MTM-SVD) mode for the Standardized Precipitation Index (SPI) from the dynamically-downscaled Twenty-Century Reanalysis (DD-20CR) (**a**), for the warm (July–August; JA) season. The spatial correlation pattern of SPI obtained between the JA DD-20CR SPI and its reconstructed temporal pattern for frequencies greater than 10 years (**b**). Local significance is shown with oblique lines. The reconstructed temporal pattern of JA DD-20CR SPI for frequencies greater than 10 years (**c**)
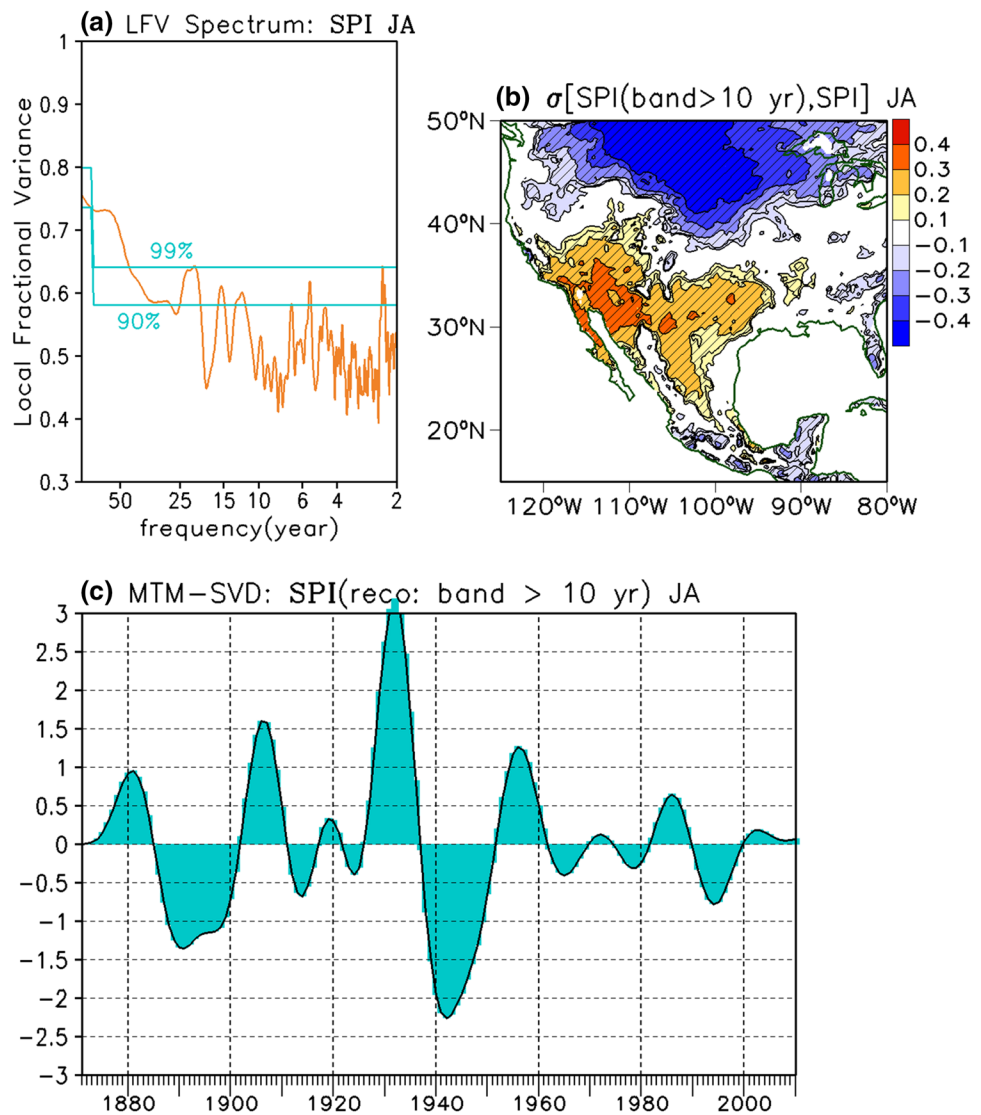

4.5 Associated sea surface temperature anomalies and atmospheric teleconnections

The associated sea surface temperature anomalies (SSTA) during the identified periods of anti-phase droughts and pluvials in Central America and the southwestern US during the early twentieth century are shown in Figs. 10 and 11, respectively for the warm and cool seasons. The SSTA patterns between two periods are quite consistent (1912–1937 and 1942–1951). An ENSO-like signal is present in the central tropical Pacific for the 1912–1937 (El Niño-like) and 1942–1951 (La Niña-like) periods, consistent with the change in ITCZ positioning noted earlier and North American drought variability described by Herweijer et al. (2007). However, there is no ENSO signal apparent for the 1892–1899 drought. As has been pointed out by Seager and Hoerling (2014), the 1892–1899 drought is most related to internal atmospheric variability. There are

not clear and consistent linkages to PDO for these droughts either, at least by the composite analysis. More physically consistent results are revealed by correlated the reconstructed low-frequency DD-20CR SPI time series for the Southwest US for warm and cool season with global SSTA (top of Figs. 12, 13). In the Southwest, low frequency cool season positive precipitation anomaly is associated with El Niño-like conditions in the central equatorial Pacific and warm Pacific Decadal Variability. The corresponding warm season precipitation variability is more associated with just cold Pacific Decadal Variability, but the pattern is not field significant. In contrast to the composite analysis, the SSTA patterns associated with sustained dual season drought in the Southwest US do not appear to be persistent from the cool to warm season, more in agreement with Griffin et al. (2013).

The warm and cool season DD-20C SPI was regressed on the corresponding 500-mb 20CR geopotential height

Fig. 9 Similar to Fig. 8 but for the cold season, November through April (NA)

(a) LFV Spectrum: SPI NA

(b) σ[SPI(band>10 yr),SPI] NA

(c) MTM−SVD: SPI(reco: band > 10 yr) NA
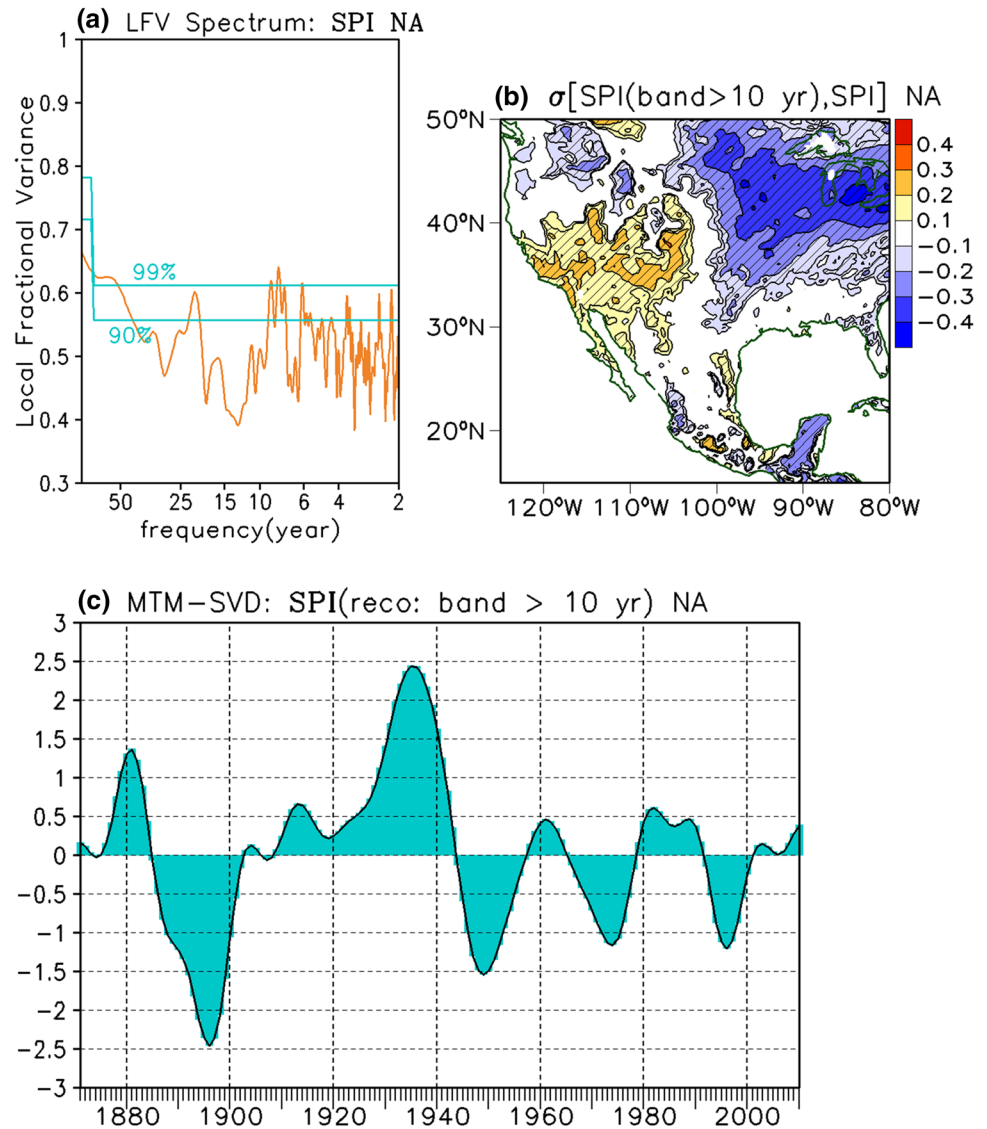
anomalies as shown in Figs. 12 and 13 (lower panels). Coherent stationary wavetrains are present for both seasons, field significant above the 80% level. It is likely that SST anomalies associated with the patterns of low-frequency variability shown by the analysis are responsible to maintain these low-frequency patterns. However, the only way to prove that would be to do an experiment with a GCM with superimposed idealized SST patterns. During the cool season, a PNA-like pattern is observed over western North America, which has connection to ENSO. During the warm season, the atmospheric Western Pacific North America (WPNA) pattern is present, as described in Ding et al. (2011) and Ciancarelli et al. (2013). Somewhat similar to the PNA pattern in winter, WPNA is a quasi-stationary Rossby wavetrain that emanates from the western tropical Pacific and Indian monsoon region and modulates the strength and positioning of the North American monsoon ridge. Castro et al. (2007a, b) and Ciancarelli et al. (2013) suggest this warm season teleconnection response is more connected to ENSO-PDV variability in the early part of summer (JJ). Though the exact physical mechanism(s) of how WPNA is generated during the warm season is still a subject of active research, it clearly bears heavily on low-frequency variability in Southwest US monsoon precipitation. The teleconnection patterns just described considering the DD-20CR also appear in a similar way with respect to the dominant modes of EW and LWadj tree-ring data in the Southwest US network (Carrillo et al. 2016).

5 Concluding points

This investigation evaluates whether there is coherency in warm and cool season precipitation at the low-frequency

Fig. 10 Warm season (July–August; JA) composite sea surface temperature anomalies (ΔSST) for the periods defined in Fig. 2: 1892–1898 (*top*), 1912–1937 (*middle*), and 1942–1951 (*bottom*). The mean climatology is defined for the period 1854–2012
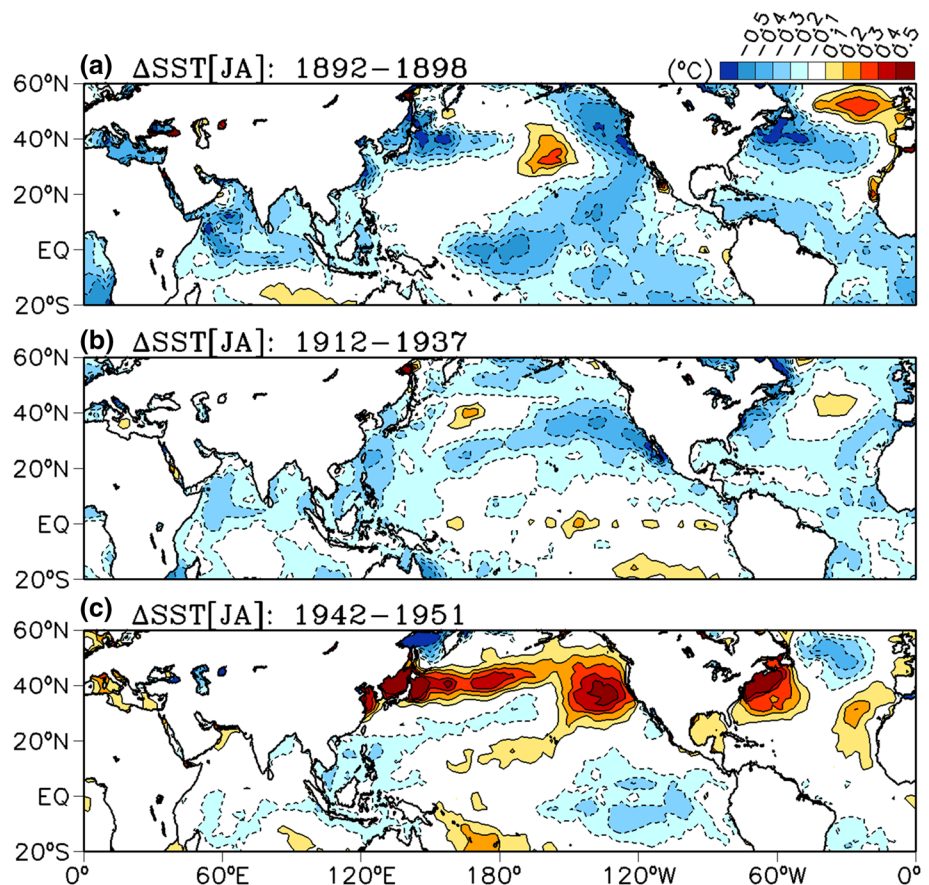

scale that may be responsible for multi-year droughts in the US Southwest. As has already been described in the context of a network of tree-ring chronologies in the southwestern US (Griffin et al. 2013; Carrillo et al. 2016), tree ring reconstructions already support this hypothesis. We complement these prior tree ring-based analyses by using the new Twentieth-Century Reanalysis product (20CR) and a long-term regional climate model simulation that dynamically downscales these data over North America. We utilize the moisture flux convergence (MFC), with focus in the large-scale circulation, in lieu of precipitation because the MFC is not as tied to parameterized precipitation processes. The low-frequency variability in the 20CR is evaluated by exploring global to continental-scale spatiotemporal variability in MFC to the occurrence of multiyear droughts and pluvials in Central America, as Central America has a demonstrated anti-phase relationship in low-frequency climate variability with northern Mexico and the southwestern US (Méndez and Magaña 2010). We have hypothesized that the 20CR is able to well resolve low-frequency, multiyear climate variability. By using the MFC as a proxy precipitation, we show that the 20CR contains similar low-frequency variability climate as previously identified in Carrillo et al. (2016) with tree-ring chronologies.

The dynamically downscaled version of the Twentieth-Century Reanalysis (DD-20CR) is used to investigate the low-frequency climate variability with precipitation in the southwestern US (continental scale). The DD-20CR better climatologically represents terrain-forced warm season monsoon precipitation that occurs more on the mesoscale. Precipitation variability in the southwestern US at this timescale are clearly related and tied to large-scale dynamical processes, for example ENSO and PDO-associated atmospheric teleconnection patterns, consistent with existing prior work. The long-term regional climate model simulation is able to realize the effect of these atmospheric teleconnections through its lateral boundary forcing and imposed interior (spectral) nudging. Given the value added of the regional model to represent precipitation in the southwestern US, as just mentioned, we argue that is quite suitable to use its precipitation data to investigate climate variability prior to the 1950s. In other words, DD-20CR provides robust, gridded model precipitation product to provide information on the continental-scale patterns of low-frequency precipitation variability that only a data record longer than a century is able to reveal.

In the context of the DD-20CR, multiyear droughts and pluvials in the southwestern US (in the early twentieth century) are significantly related to low-frequency climate

Fig. 11 Similar to Fig. 10 but
for the cold season, November
through April (NA)
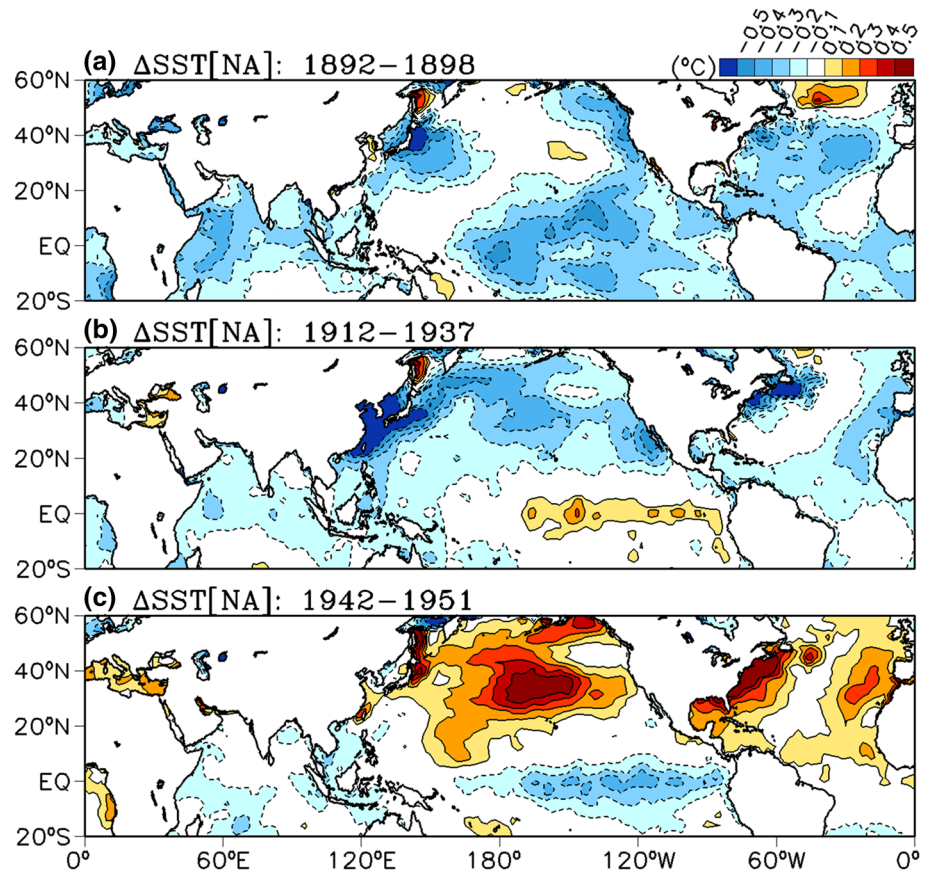
Fig. 12 Warm season (July–
August; JA) sea surface
temperature anomaly (ΔSST)
spatial correlation pattern
(*upper*) obtained from the
reconstructed temporal MTM-
SVD pattern of JA DD-20CR
SPI for frequencies greater
than 10 years (as defined in
Fig. 8c) and the JA sea surface
temperature anomaly (ΔSST);
the correlations are calculated
for the period 1871–2010 using
a 5-year sampling approach.
Similarly, the warm season
500-mb geopotential height
anomaly (ΔGPH) spatial pattern
correlation (*bottom*). Local
significance is shown in oblique
lines and filed significance in
percentage for both cases
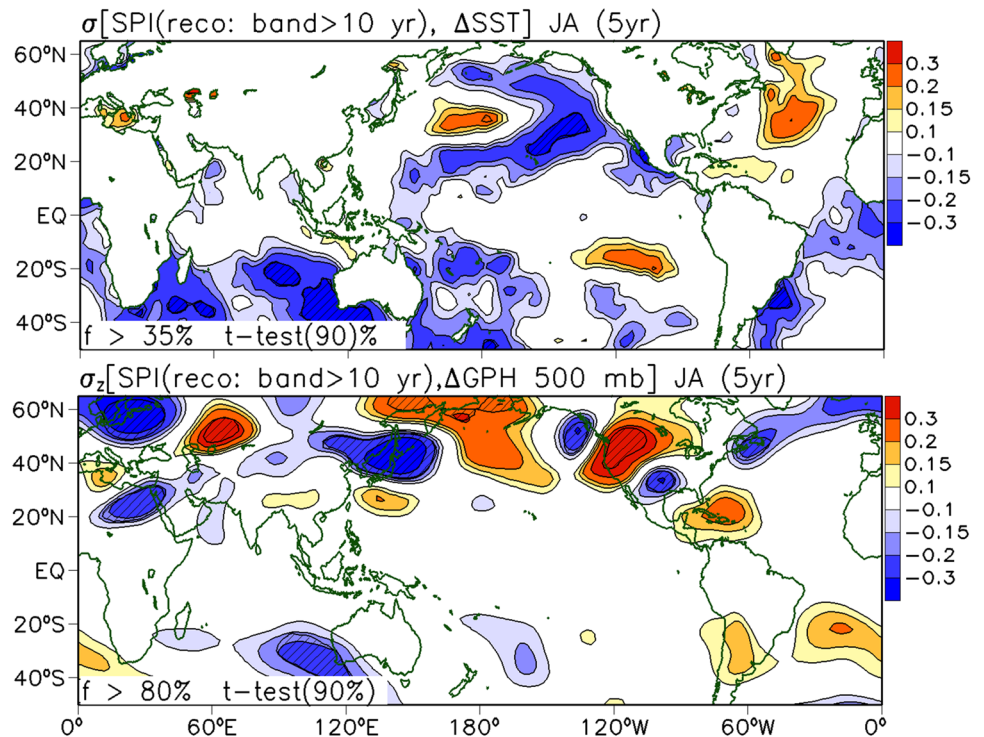
Fig. 13 Similar to Fig. 12 but for the cold season, November through April (NA)
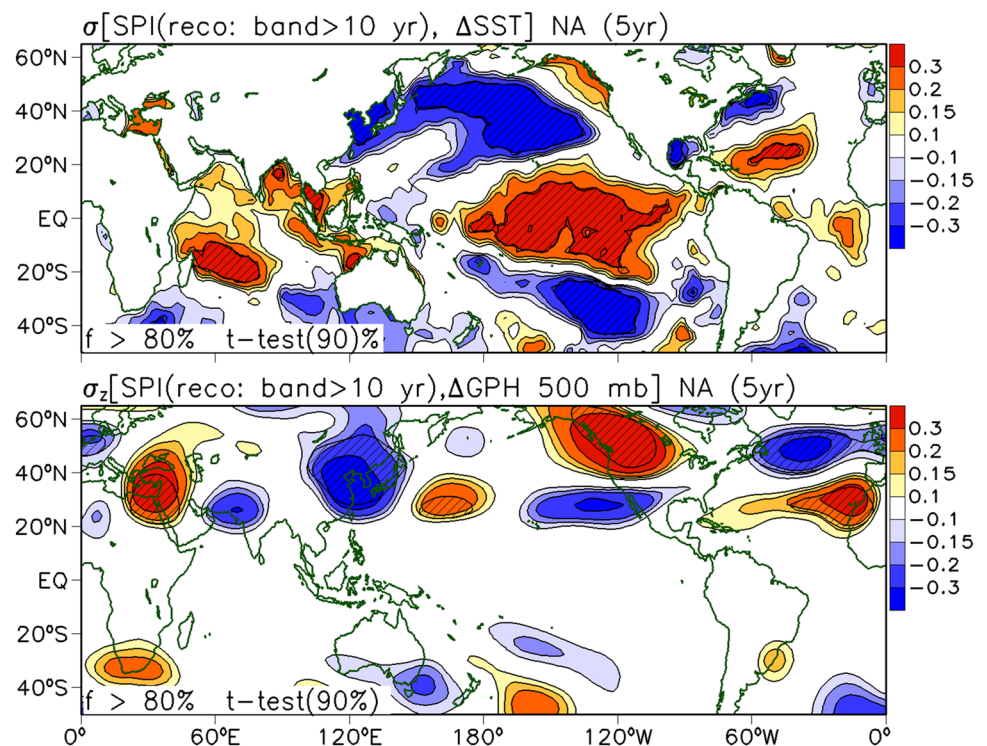
variability at timescales longer than ten years. The precipitation anomalies at these low-frequency timescales are in phase between cool and warm season, entirely consistent with the concept of dual-season drought as has been previously shown in tree ring data. The in-phase, dual-season precipitation variability regime at low-frequencies appears to account for the occurrence of the most persistent droughts in the southwestern US during the period 1871–1950 and is the continental-scale spatial nature of precipitation anomalies with these droughts is effectively revealed by the regional climate model. For this period, we would argue the regional climate model data may actually be a more suitable data source to characterize low-frequency climate variability than the comparable P-NOAA product, as it is not subject to the vagaries of data limitations in observed precipitation that may adversely impact the signal, especially in the quality and quantity of stations in Mexico (Livneh et al. 2015). It is important to note that tree-ring data and the 20CR are only able to effectively statistically characterize climate variability at the multi-year to multi-decadal timescale. The even lower temporal frequencies at the centennial timescale, however, still cannot be resolved. A global climate model (GCM) integrated for period longer than several hundred years would be necessary to capture this type of variability (Coats et al. 2015). Such GCM data could presumably be used to provide boundary forcing to a RCM to resolve precipitation patterns tied to centennial-scale climate variability, provided that the GCM can reasonably represent this type of variability

as best as available paleoclimate data can inform. We suggest this as a possible future research direction, given the strong consistency of our RCM results here with tree-ring data for the period of the 20CR prior to the modern instrumental era since the late 1950s. The forcing mechanism for the cool season low-frequency precipitation variability appears to be related to the El Niño-like variability in central tropical Pacific and a PNA-like pattern. However, for the warm season it seems to be more related to Pacific Decadal Variability. The atmospheric teleconnection for summer is the Western Pacific North America (WPNA) quasi-stationary Rossby wave train, as in Ding et al. (2011) and Ciancarelli et al. (2013).

As the DD-20CR is able to reasonably capture low-frequency climate variability in a quite similar manner to tree-ring chronologies, it could be potentially used to investigate long-term droughts in the warming future climate in the Southwest. By employing a pseudo global warming modeling framework (Kawase et al. 2009) the boundary forcing to the regional model may be adjusted to incorporate long-term trends derived from global climate change projection models. A pseudo-global warming experiment with DD-20CR may actually be quite socially valuable from the standpoint of assessing the impact of climate change with known climate variability in the early twentieth century because it would not subject to the vagaries of the widely different representations of natural climate variability that exists within the Coupled Model Intercomparison Project (CMIP) climate change projection models (Sheffield et al.

2013). This particular time period (1871–1950) is very important for water resource risk assessment, as it corresponds to the construction of major infrastructure (e.g. dams along the Colorado River) and the establishment of the Colorado River compact. Water resource management agencies, for example, Bureau of Reclamation, Central Arizona Project, and Salt River Projects, already account for the major droughts of this period in their operational planning.

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