

The influence of the inter-decadal Pacific oscillation on US precipitation during 1923–2010

Aiguo Dai

Received: 12 April 2012 / Accepted: 4 July 2012 / Published online: 29 July 2012
© Springer-Verlag 2012

Abstract Precipitation over the contiguous United States exhibits large multi-decadal oscillations since the early twentieth century, and they often lead to dry (e.g., 1946–1976 and 1999–present) and wet (e.g., 1977–1998) periods and apparent precipitation trends (e.g., from the 1950s to 1990s) over most of the western and central US. The exact cause of these inter-decadal variations is not fully understood. Using observational and reanalysis data and model simulations, this paper examines the influence of the Inter-decadal Pacific Oscillation (IPO) on US precipitation. The IPO is a leading mode of sea surface temperatures (SSTs) seen mostly in the Pacific Ocean. It is found that decadal precipitation variations over much of the West and Central US, especially the Southwest, closely follow the evolution of the IPO ($r = 0.85$ during 1923–2010 for the Southwest US), and the dry and wet periods are associated, respectively, with the cold and warm phases of the IPO. In particular, the apparent upward trend from the 1950s–1990s and the dry decade thereafter in precipitation over much of the West and Central US are largely caused by the IPO cycles, which switched to a warm phase around 1977 and back to a cold phase around 1999. An atmospheric model forced with observed SSTs reproduces much of this

association of US precipitation with the IPO ($r = 0.95$ between smoothed observed and simulated Southwest US precipitation during 1950–2009 and $r = 0.88$ between the simulated Southwest US precipitation and the IPO). Atmospheric reanalysis and model data both show a strong high (low) pressure center and anti-cyclonic (cyclonic) anomaly circulation over the North Pacific in the lower troposphere during cold (warm) phases of the IPO, which lead to dry and cold northwesterly and northerly winds and below-normal precipitation over much of the West US during IPO cold periods. The IPO induced changes are most pronounced during the boreal cold season. The results reinforce the notion that tropical Pacific SSTs (and the accompanying SST anomalies in the North Pacific) have large impacts on US precipitation and highlight the need to understand and simulate the IPO for decadal prediction of US precipitation.

Keywords Precipitation · United States · IPO · Pacific SST

1 Introduction

Many studies have shown that oceanic conditions, especially sea surface temperatures (SSTs), in the Pacific and Atlantic basins have large influences on precipitation over the contiguous United States (CONUS) through their impacts on atmospheric circulations (Ting and Wang 1997; Schubert et al. 2004a, b, 2009; Seager et al. 2005; Meehl and Hu 2006; Mo et al. 2009; Wang et al. 2006, 2010; Kushnir et al. 2010; Feng et al. 2011; Nigam et al. 2011; Hu et al. 2011; Zhong et al. 2011; Hu and Feng 2012). For example, many of these studies found that persistent La Niña-like cold SST anomalies in the tropical central and eastern Pacific Ocean lead to below-normal precipitation

The National Center for Atmospheric Research is sponsored by the US National Science Foundation.

A. Dai (✉)
National Center for Atmospheric Research, P.O. Box 3000,
Boulder, CO 80307-3000, USA
e-mail: adai@ucar.edu

A. Dai
Department of Atmospheric and Environmental Sciences,
University at Albany, 1400 Washington Avenue,
Albany, New York 12222, USA
e-mail: adai@albany.edu

(mostly in the cold season) and often drought over Southwest North America and the US Great Plains (e.g., Seager et al. 2005; Schubert et al. 2009; Wang et al. 2010); whereas warm Atlantic SSTs reduce summer precipitation over the West and central US (Kushnir et al. 2010; Feng et al. 2011), although some studies (e.g., Mo et al. 2009) suggested that the Atlantic influence is comparatively weak and is mainly through its modulation of the impact of El Niño–Southern Oscillation (ENSO)-like SST forcing from the Pacific.

In a 1500-year control experiment of a coupled ocean–atmospheric general circulation model (CGCM), Meehl and Hu (2006) found large multi-decadal variations in precipitation over Southwest North America, and these multi-decadal variations are linked to multi-decadal SST variations in the Pacific that resemble the observed Inter-decadal Pacific Oscillation (IPO) (Power et al. 1999; Deser et al. 2004). The North Pacific component of the IPO is often referred to as the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997) and the PDO is thought to be caused by a “reddening” of the ENSO combined with stochastic atmospheric forcing (Newman et al. 2003). In their CGCM, Meehl and Hu (2006) found that the transit times of the wind-forced ocean Rossby waves near 20°N and 25°S in the Pacific basin determine the multi-decadal time scales of the IPO, which influences atmospheric circulation over the North Pacific and North America through atmospheric Rossby wave response to tropical SST and latent heating anomalies. Thus, predictions of future IPO evolution have major implications for precipitation and drought conditions over Southwest North America (Meehl et al. 2010).

Precipitation and streamflow over the CONUS experienced an upward trend from 1950–2008, while large drying trends occurred over many other low- and mid-latitude land areas during the same period (Dai 2011a). This recent wetting trend over the CONUS is in sharp contrast to the coupled model-predicted severe drying over most North America under green-house gas (GHG) induced global warming (Seager et al. 2007; Burke and Brown 2008; Sheffield and Wood 2008; Dai 2011a; Dai 2012). Resolving this apparent inconsistency is a necessary step for accepting the model predictions (Dai 2012). Time series of the CONUS precipitation and drought areas (Dai 2011b) show that the upward trend during 1950–2008 resulted mainly from precipitation increases from the 1950s to the late 1990s; thereafter precipitation decreased and drying occurred over much of the CONUS, especially over the western CONUS. It is known that the IPO has changed from a cold to a warm phase around 1977 and vice versa in the late 1990s (Deser et al. 2004). Given the above-mentioned influence of the IPO on CONUS precipitation, these IPO phase changes are likely to have played a significant role for the recent trends in CONUS precipitation and drought.

Although many studies have investigated the influence of tropical Pacific SSTs on CONUS precipitation using atmospheric general circulation models (AGCMs) forced with observed or specified SSTs (e.g., Schubert et al. 2004a, b, 2009; Seager et al. 2005; Wang et al. 2010) or by analyzing historical records (e.g., Ting and Wang 1997; Zhong et al. 2011), these studies have focused mainly on the sensitivity of CONUS precipitation to specified tropical SST anomalies or for specific periods (e.g., the 1930s and 1950s) that are not explicitly stratified by IPO phases, or on the statistical relationship between US precipitation and tropical Pacific SSTs. Thus, the exact role of the IPO since the early twentieth century in determining the observed multi-decadal variations and long-term trends in CONUS precipitation is not fully understood.

In this study, I investigate the effect of the IPO on CONUS precipitation during 1923–2010 using observational, reanalysis and AGCM simulations, with a focus on the multi-decadal variations that often result in apparent trends over 30–60 year periods. Consistent with the previous studies cited above, I found that the SST variations associated with the IPO have large influences over CONUS precipitation, especially over the Southwest US. In particular, the apparent upward precipitation trend in the Southwest US since the 1950s has resulted mainly from the IPO phase change around 1977. The abrupt change to drier conditions since the late 1990s over much of the West and Central US is largely caused by the switch from a warm to cold phase of the IPO around 1999.

2 Data and method

I used the updated HadISST monthly gridded SST data from the UK Met Office Hadley Centre (Rayner et al. 2003), and the gridded monthly precipitation data (based on gauge records) from Dai (2011b), who merged precipitation data from Dai et al. (1997) before 1948 mostly for land, Chen et al. (2002) for 1948–1979 for land, and Huffman et al. (2009) for 1979–2010 for land (based mainly on rain gauge data) and ocean (based on satellite observations). Since SST observations over the tropical Pacific are sparse before around 1920 and the correlation between tropical Pacific SST and CONUS precipitation records is considerably lower before around 1923 than thereafter, this study focuses on the period from 1923–2010.

I also used the Niño3.4 (5°S–5°N, 120°W–170°W) SST index data obtained from <http://www.esrl.noaa.gov/psd/forecasts/sstlim/Globalssst.html> (for 1950–2010) and from http://www.cgd.ucar.edu/cas/catalog/climind/TNI_N34/index.html#Sec5 (for before 1950 years, rescaled to match the 1950–2010 index over the 1950–2007 common data period).

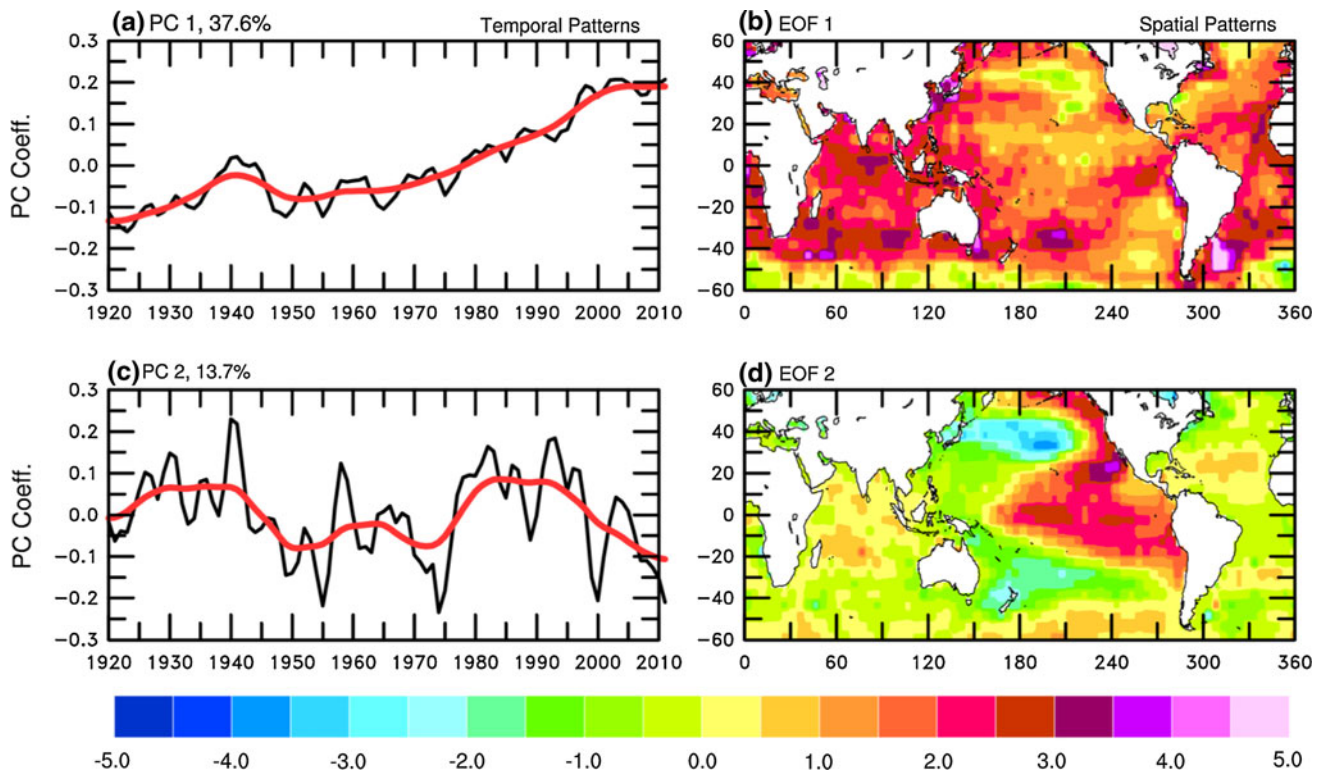


Fig. 1 The first (a, b) and second (c, d) leading empirical orthogonal functions (EOFs) of the 3-year moving averaged sea surface temperatures from 1920–2011 from the HadISST data set. The red curve in the left panels is a smoothed line derived by applying the 9-year moving averaging twice to the (3-year smoothed) annual series

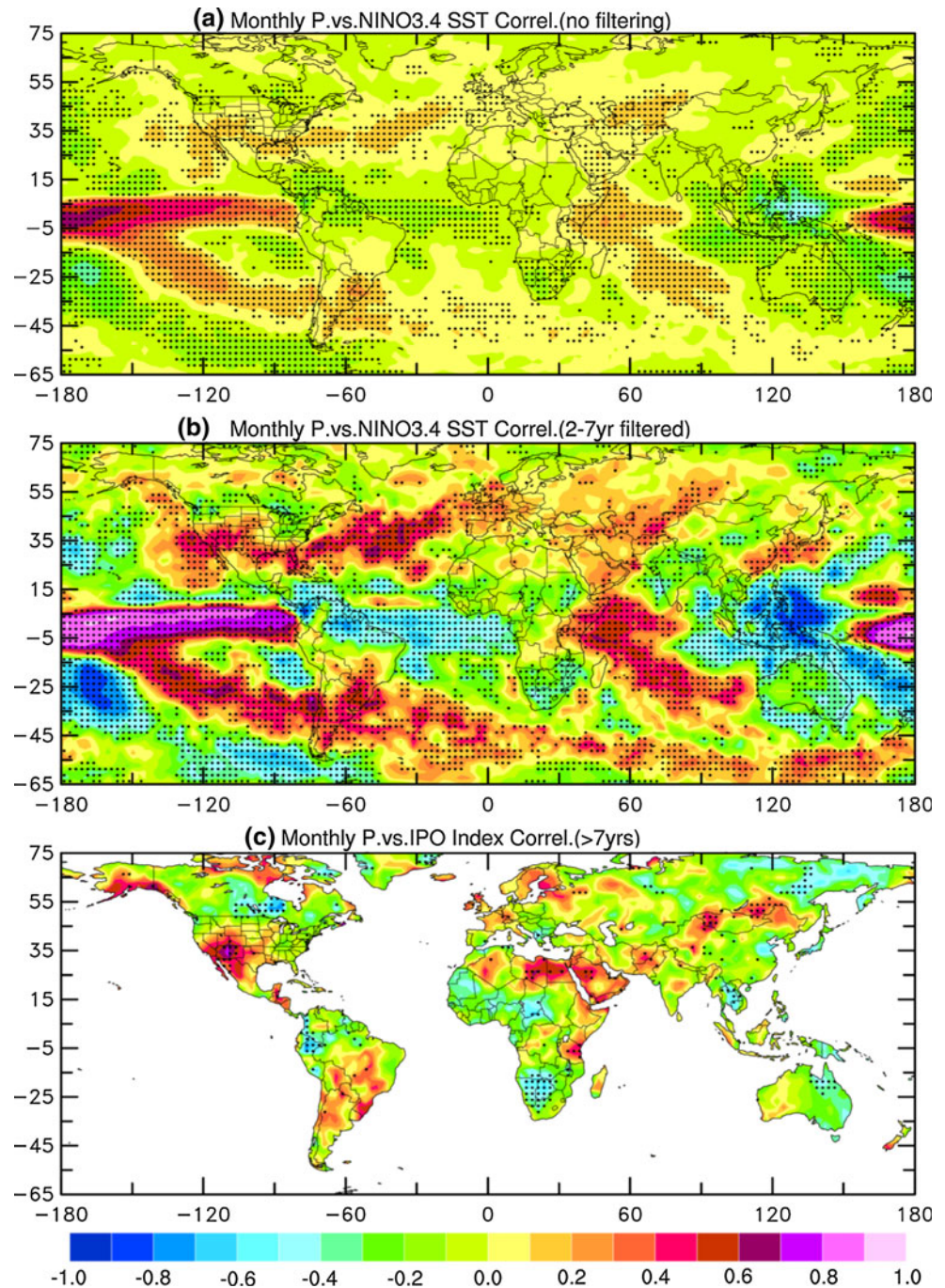
The NCEP/NCAR atmospheric reanalysis monthly data (obtained from <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>) for circulation and other fields from 1948–2010 were used, as other similar products have much shorter records. For the recent period from 1979–2010, the ERA-Interim data (<http://data.ecmwf.int/data/>) were also examined and the results are mentioned when appropriate.

To examine how CONUS precipitation responds to observed SST forcing alone, I analyzed the CMIP5 AMIP simulations (see <http://cmip-pcmdi.llnl.gov/>), for which most models only have data from 1979 to around 2008. Here I used the CanAM4 model simulations (on T42 or $\sim 2.8^\circ$ grid) from the Canadian Centre for Climate Modelling and Analysis (<http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=8A6F8F67-1>), which contain four AMIP ensemble runs forced by observed SSTs from 1950–2009. These CanAM4 ensemble runs were averaged to obtain an ensemble mean, which was then analyzed in this study. For the period since 1979, I also examined the AMIP runs by the HadGEM2-A model from the UK Met Office Hadley Centre, which shows change patterns of precipitation and atmospheric circulation similar to those of the CanAM4.

(black line). The EOF1 represents the global warming mode while the EOF2 depicts the SST variability mainly in the Pacific associated with the ENSO and the inter-decadal Pacific Oscillation (IPO, red curve in panel c). The percentage variance explained by each EOF is shown on top of panel (a) and (c)

An empirical orthogonal function (EOF) analysis of the global SST fields from 1920–2011 was performed to separate the IPO mode from other modes of variability. This allows a better definition of the IPO than using the tropical SST-based indices, since the latter includes many other variations such as the global warming signal. Digital filtering and moving averaging were also used to separate and remove short-term variations from decadal to multi-decadal changes associated with the IPO. To extend the IPO time series as back and as present as possible, moving averaging with mirrored end points (i.e., anomaly data points are symmetric around the two ends) was used to create the IPO index and the smoothed precipitation series. This approach seems to work reasonably well based on visual comparison with un-smoothed series, although the (smoothed) IPO index near 2010 is likely to be negatively biased due to recent La Niña events. Spatial anomaly patterns are depicted using epoch composites averaged over the different IPO phase periods, and epoch composites of atmospheric 850 hPa wind and geopotential height anomalies are examined for atmospheric circulation response to tropical SST forcing in atmospheric reanalyses and AMIP model runs.

Fig. 2 Maps of the correlation coefficient between observed monthly precipitation anomalies and Nino3.4 (5°S–5°N, 120°W–170°W) SST index during 1920–2010 (1979–2010 over oceans) for (a) all variations and (b) variations on 2–7 year time scales, and (d) between the IPO index (red line in Fig. 1c) and precipitation anomalies on >7 year time scales. The stippling indicates the correlation is statistically significant at the 5 % level in (a, b) and at the 10 % level in (c), with autocorrelation being accounted for using the effective degree of freedom



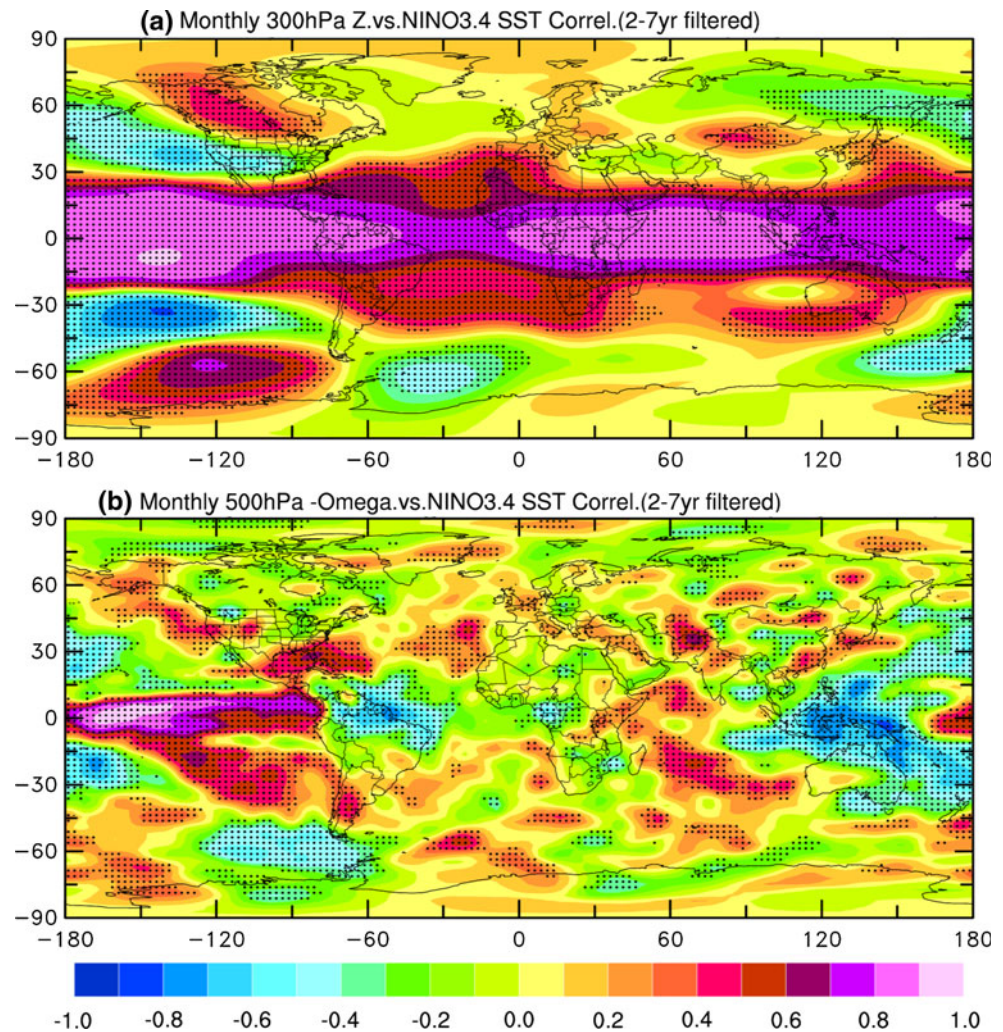
3 Results

3.1 Definition of an IPO index

Figure 1 shows the two leading EOF modes of global (60°S–60°N) SSTs from the HadISST data set during 1920–2011. Inter-annual variations were removed using 3-year moving averaging at each grid box prior to the EOF analysis. EOF 1 clearly represents global warming with the temporal coefficient resembling the global-mean temperature series (IPCC

2007) and nearly ubiquitous warming over the oceans. The focus here is on EOF 2, which shows typical ENSO-like SST patterns (Alexander et al. 2002) in the tropical Pacific with substantial contributions from the North and South Pacific and relatively small anomalies in the Indian and Atlantic Ocean, and an out-of-phase SST patterns between the western and eastern Pacific (Fig. 1d). The temporal coefficient (Fig. 1c) exhibits large multi-decadal variations in addition to the ENSO-related multi-year variations. Both the spatial and (smoothed) temporal coefficients for EOF 2 resemble

Fig. 3 Same as Fig. 2b but for correlation between observed Niño 3.4 SST index and NCEP/NCAR reanalysis (a) 300 hPa geopotential height and (b) 500 hPa pressure velocity (omega, multiplied by -1) during 1948–2011 on 2–7 year time scales



those of the Inter-decadal Pacific Oscillation (IPO) discussed in many previous studies (e.g., Power et al. 1999; Deser et al. 2004; Meehl and Hu 2006). Because of the similarity in the SST spatial patterns for typical ENSO events and the IPO, one may consider the IPO as the multi-decadal variations of ENSO, or ENSO-like inter-decadal variability (Zhang et al. 1997).

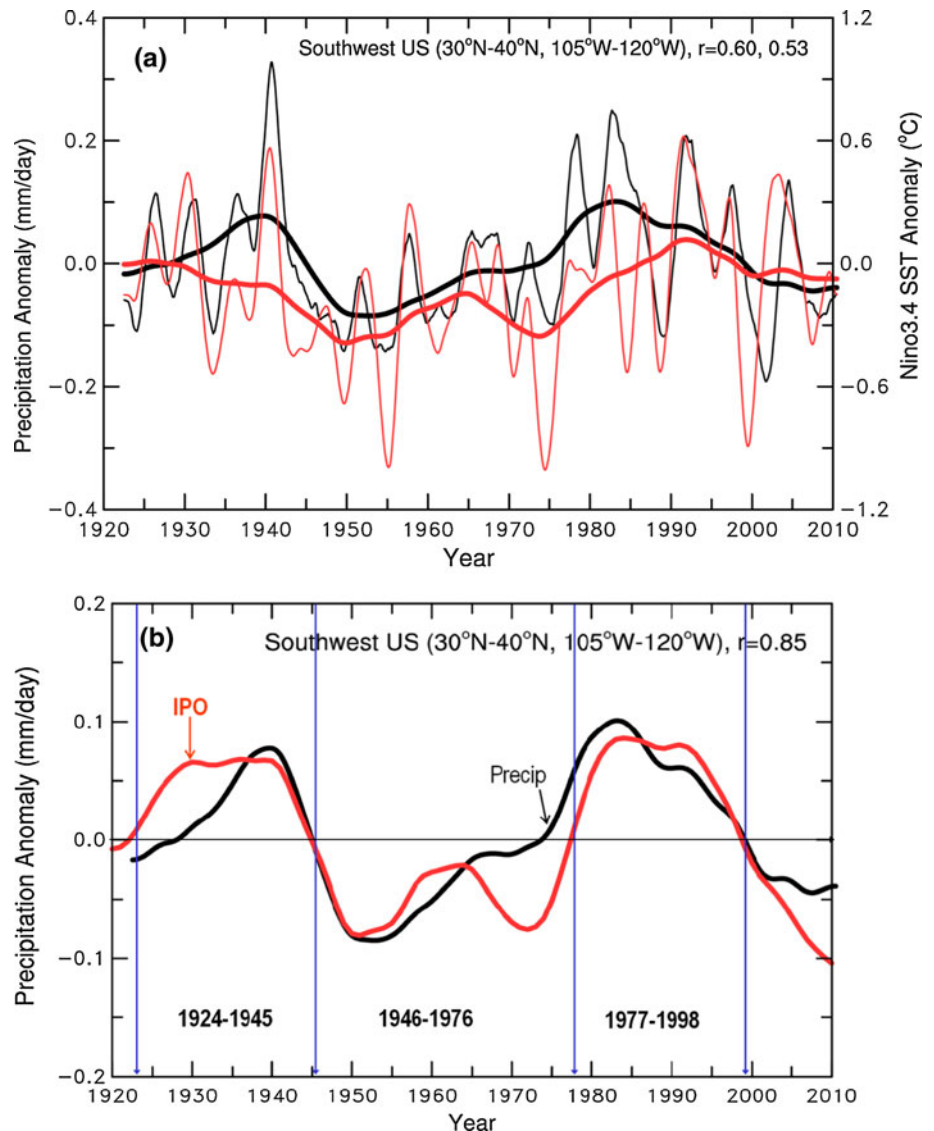
Another aspect of the IPO is that it has large cold SST anomalies in the western-to-central midlatitude Pacific when the central and eastern tropical Pacific is warm (referred to as the IPO warm phase). As shown by Deser et al. (2004), the Pacific Decadal Oscillation (PDO) is linked to and likely originates from the tropical Pacific Ocean. The SST patterns associated with the PDO (Mantua et al. 1997) are very similar to those over the tropical and North Pacific shown in Fig. 1d. Figure 1d suggests that the PDO is part of the IPO that extends to the whole Pacific basin. The smoothed red line in Fig. 1c matches the IPO indices discussed by Deser et al. (2004), such as the phase switch around 1924, 1946, and 1977. Note that the exact

location of these phase changes may vary slightly depending on which variable and what smoothing one uses. In this study, the smoothed red line in Fig. 1c is used as the IPO index for quantifying the IPO evolution from 1920–2011, which can be characterized by warm periods (for the central and eastern Pacific) from 1924–1945 and 1977–1998 and cold periods from 1946–1976 and 1999–present.

3.2 Global correlation patterns between precipitation and tropical Pacific SSTs

To provide a global perspective of the relationship between CONUS precipitation and tropical Pacific SSTs, I calculated the Niño 3.4 SST and the IPO index versus precipitation correlation on different time scales over the globe. Figure 2 shows that precipitation over many parts of the tropical and mid-latitude oceans in the Pacific, Indian and Atlantic basins is significantly correlated with Niño 3.4 SST, especially on 2–7 year ENSO time scales. Many of

Fig. 4 a Time series of smoothed monthly precipitation anomalies from observations (black lines) from 1923–2010 averaged over the Southwest US (30°–40°N, 105°–120°W, land only). The thin black line was derived by applying 25-month moving averaging twice to the monthly anomalies and the thick black line was derived by applying 109-month moving averaging (with mirrored end points) twice to the thin black line. The red lines (on the right-side ordinate) are the similarly averaged Nino 3.4 SST anomalies (see Fig. 1 for data sources). The r values are the correlation coefficient, from left to right, between the thin black and thin red lines, and the thick black and thick red lines. **(b)** The smoothed Southwest US precipitation (black) and IPO (red, from Fig. 1c) time series, with $r = 0.85$. The phase transition of the IPO is indicated by the thin vertical lines. The x-axis label indicates the middle point of the nominal year in both (a) and (b)



the large-scale correlation patterns extend from the tropical Pacific to higher latitudes and cover many land areas. For example, the negative correlations over the tropical western Pacific and eastern Indian Ocean extend to cover most Australia and South Asian land masses, and the positive correlation band from the south-central Pacific to the southern circumpolar oceans also passes through southern South America (Fig. 2a, b). In the Northern Hemisphere, there is a similar band of positive correlation extending from the eastern low-latitude Pacific all the way to central Asia, with the West and South US being part of this band (Fig. 2a, b). Accompanying these two bands of positive correlation, there are bands of negative correlation on the equator- and pole-ward sides of the two bands. At the low-latitudes, centers of positive correlation over the central and eastern Pacific Ocean and the western and central India Ocean are separated by the regions of negative correlation

over the western Pacific and eastern Indian Ocean and the Atlantic Ocean (Fig. 2a, b).

We notice that the correlation is stronger at the 2–7 year ENSO time scales (Fig. 2b) as ENSO events dominate tropical SST variability and the associated precipitation variations. For the precipitation correlation with the IPO on longer than 7 year time scales (Fig. 2c), for which the ocean precipitation records are too short, the overall correlation patterns are less significant statistically than and differ considerably from those on ENSO time scales (Fig. 2b). For example, the correlation with the IPO is slightly negative over the Southeast US, in contrast to the positive correlations shown in Fig. 2a, b over the same region. The correlation with the IPO is strongest over Southwest North America, southern Africa, and northeastern Australia.

The large-scale correlation patterns shown in Fig. 2 are comparable to ENSO-induced precipitation anomaly

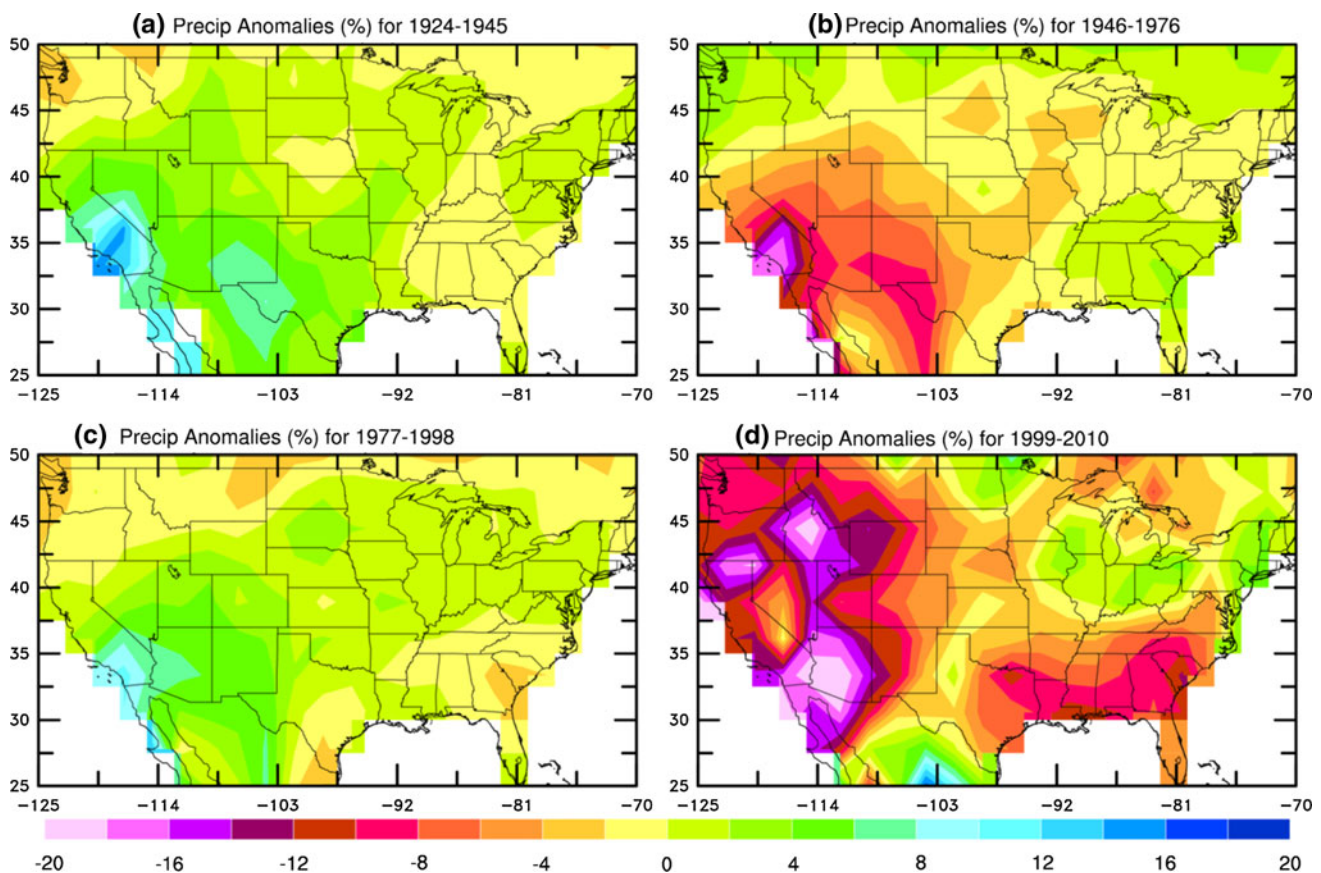


Fig. 5 Annual precipitation anomalies (relative to and in % of the 1924–1998 mean) for the IPO period (a) 1924–1945, (b) 1946–1976, (c) 1977–1998, and (d) 1999–2010. The data were detrended using the linear trend estimated for the 1924–1998 period before computing

the epoch anomalies. Note the 1999–2010 anomalies in (d) are likely affected by individual ENSO events and other inter-annual variations as data records are insufficient to remove these short-term variations

patterns shown in previous studies (e.g., Dai and Wigley 2000). They are coupled to atmospheric circulation response to ENSO-like tropical SST forcing, especially the response of the Hadley circulation in the meridional direction and of the Walker circulation in the tropics (Fig. 3). In particular, the response of the 500 hPa vertical velocity in the NCEP/NCAR reanalysis to Niño 3.4 SST anomalies (Fig. 3b) broadly captures the observed precipitation vs. Niño 3.4 SST correlation patterns (Fig. 2b). Figures 2, 3 show that the correlation of US precipitation with tropical Pacific SSTs is part of the planetary-scale response of the atmosphere (mostly the Hadley circulation) to tropical SST forcing. Thus, the relationship examined below is not a local, random correlation between the CONUS precipitation and the IPO.

3.3 Observed CONUS precipitation changes associated with the IPO

To explore the relationship between the IPO and precipitation over the Southwest US, where the correlation is strongest (Fig. 2c), we averaged the monthly precipitation

anomalies over the land areas within 30°N–40°N and 105°W–120°W and compared them with the Niño 3.4 SST in Fig. 4a and with the IPO index in Fig. 4b after smoothing. It can be seen that the Southwest US precipitation (Psw) correlates significantly with Niño 3.4 SST on both multi-year ($r = 0.60$) and multi-decadal ($r = 0.53$) time scales. The multi-decadal variations of the Psw correlates much stronger ($r = 0.85$) with the IPO index (Fig. 4b) than with the Niño 3.4 SST, as the latter includes global warming and other variations whose relationship with the Psw differs from that of the IPO. For example, models predict decreasing Psw due to enhanced drying by the subsidence of the Hadley circulation over the Southwest US under greenhouse gas (GHG)-induced global warming (Seager et al. 2007; Chou et al. 2009), and the SST change patterns associated with global warming and the IPO are very different (Fig. 1).

Figure 4b shows that during the warm IPO periods from 1924–1945 and 1977–1998, the Southwest US received above-normal precipitation, while during cold phases from 1946–1976 and 1999–present precipitation over the Southwest US was below-normal (note the positive Psw for

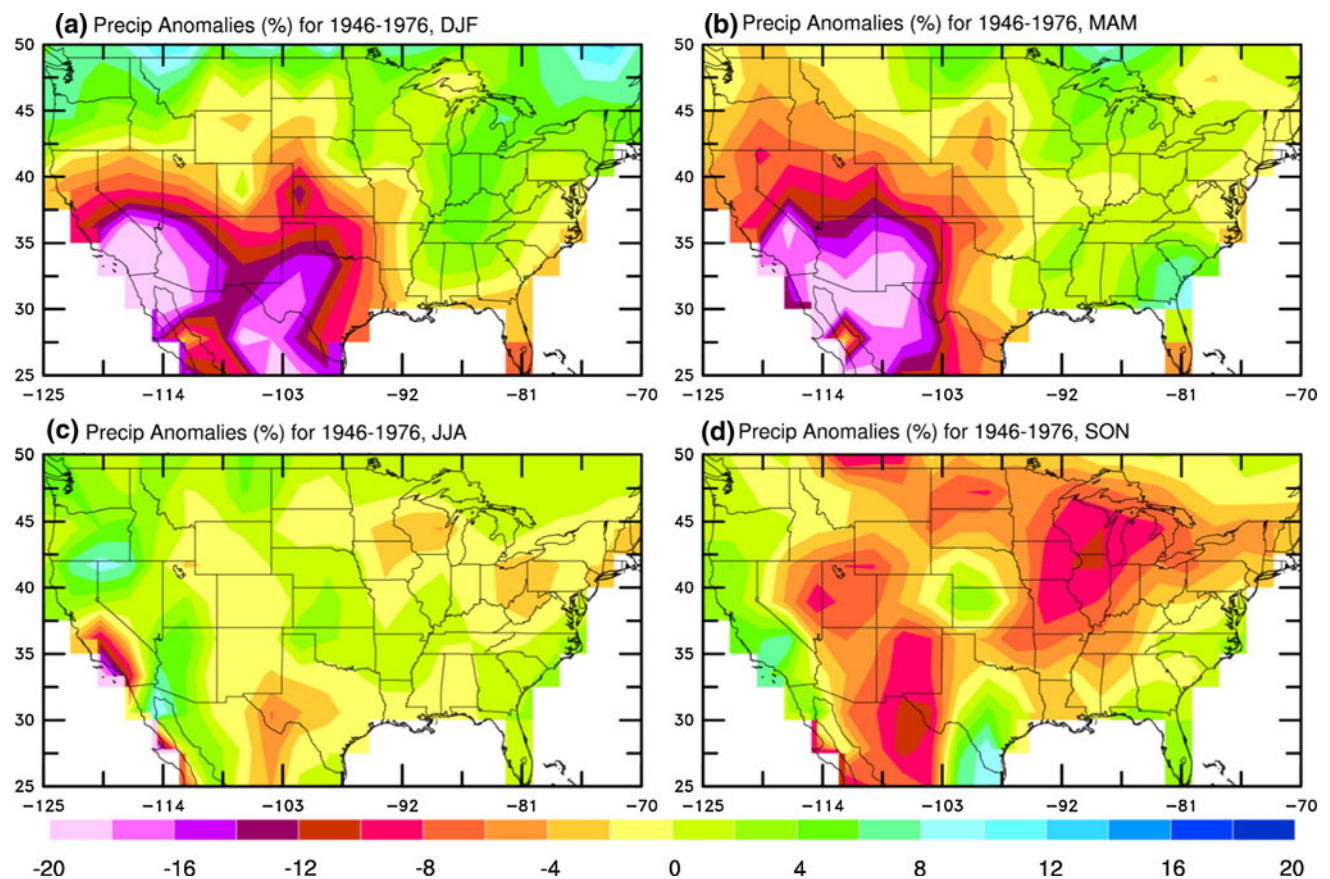


Fig. 6 Same as Fig. 5 but for the seasonal precipitation anomalies of the 1946–1976 period. The seasonality is similar for other IPO periods

1976 resulted from smoothing in Fig. 4). Because of these multi-decadal variations, there is an apparent upward trend from around 1950–1983 and a downward trend thereafter in the Psw, and estimates of linear Psw trends since the early 1950s are positive. These apparent trends result from multi-decadal variations associated with the IPO, which is mostly a natural oscillation and not related to global warming (Fig. 1). These results highlight the risk of comparing the apparent precipitation trends estimated from short records (<60 year) to model-simulated trends under GHG forcing.

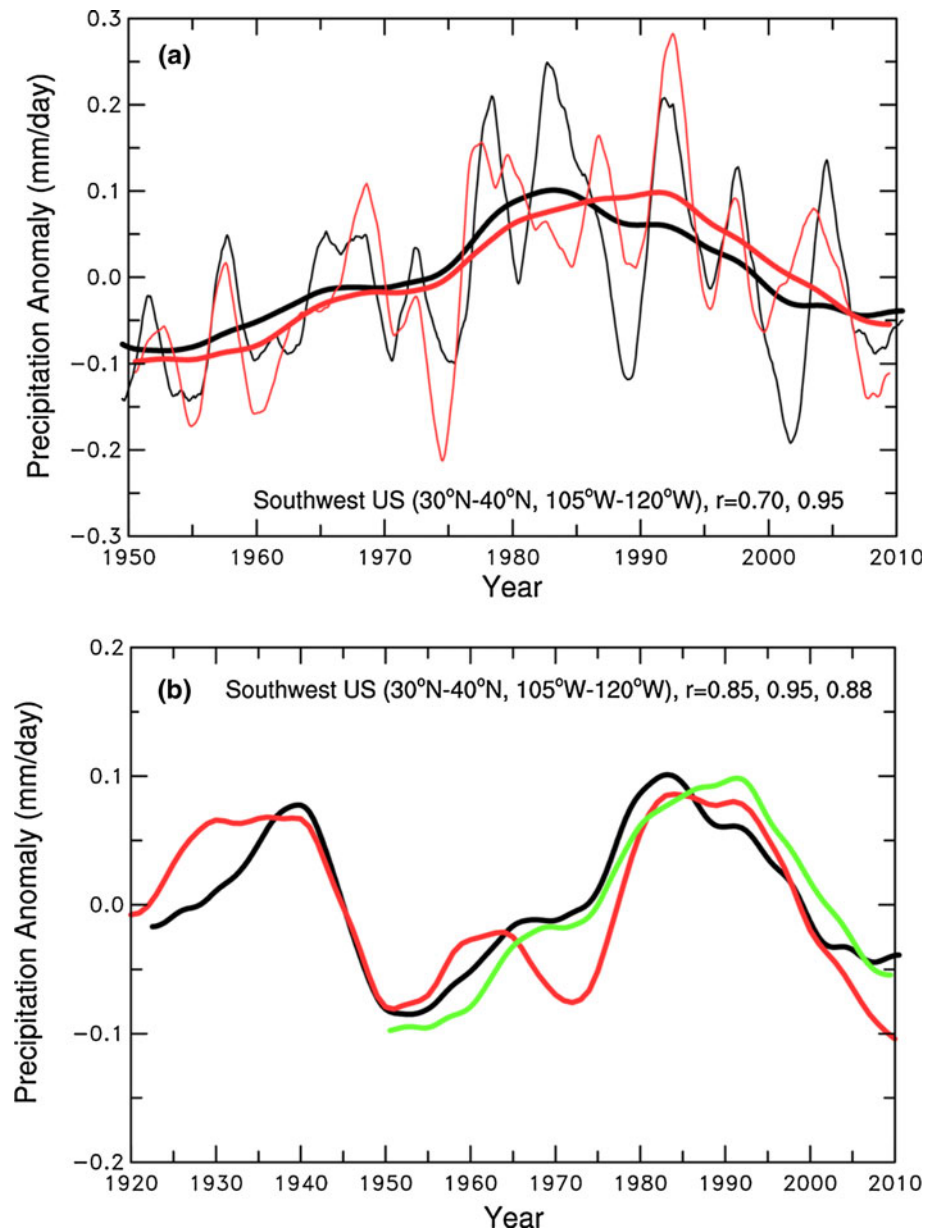
The current cold phase of the IPO started around 1999, and it may continue for another 18 years or so based on the length of its previous cold phase from 1946–1976. The Southwest US may continue to receive below-normal precipitation for the next 1–2 decades due to the IPO. This is in addition to the drying induced by GHG-induced global warming (Seager et al. 2007; Dai 2011a). Thus, the outlook for this region is not good for the next 1–2 decades.

Despite the close correlation shown in Fig. 4b, there are some short periods (e.g., 1925–1935 and 1966–1975) when Southwest US precipitation diverges from the IPO index. The drop in the smoothed IPO index around the early 1970s results mainly from the large negative SST

anomalies around 1974 (Fig. 4a). Precipitation over the Southwest US responded to this cold ENSO event, but with comparatively small amplitude (Fig. 4a). It is expected that other processes (e.g., local land surface conditions and other atmospheric and ocean conditions) can also affect Southwest US precipitation and modulate IPO and ENSO's influences in the region. Furthermore, the smoothing used in Fig. 4b may also have contributed to the apparent divergence, especially near the start and end of the data period.

The spatial patterns of the IPO-induced precipitation anomalies are shown in Fig. 5 for the annual mean and in Fig. 6 for seasonal precipitation. Consistent with the correlation patterns shown in Fig. 2c, the Southwest US receives 5–15 % more precipitation during the warm IPO periods from 1924–1945 and 1977–1998, while the changes over the East, Northwest and Midwest US are generally small (within a few % of the long-term mean, but appear to be stable patterns) during the warm periods (Fig. 5a, c). During the cold IPO period from 1946–1976 (Fig. 5b), the change patterns are roughly reversed from those of the warm periods, with 5–15 % less than normal precipitation over the Southwest US. For the most recent cold period from 1999–2010 (Fig. 5d), large decreases of precipitation

Fig. 7 a Precipitation anomalies from 1950–2010 averaged over the Southwest US (30°N – 40°N , 105°W – 120°W) from observations (black lines) and atmospheric model (CanAM4) simulations (red lines) forced by observed SSTs. The thin lines are 25-month moving averages while the thick lines are 109-month moving averages of the thin lines. The ensemble average of four CanAM4 runs was used. The correlation coefficient is 0.70 (0.95) between the thin (thick) black and red lines. **(b)** Same as panel (a) except for smoothed precipitation from observations (black) and the CanAM4 model runs (green), compared with the IPO index (red, from Fig. 1c). The correlation between the black and red, black and green, and red and green lines is, respectively, 0.85, 0.95, and 0.88 in (b)



(8–16 %) are also seen over the Northwest and Southeast US. These abnormal features may result from insufficient data to remove ENSO and other short-term variations during the most recent decade.

Over the US Central Great Plains (Oklahoma, Kansas, Missouri, etc.), precipitation response to IPO-induced tropical forcing is similar to the Southwest, but with reduced magnitude in percentage terms (Fig. 5). This result is consistent with Schubert et al. (2004a, b) who found that cold SSTs in tropical Pacific contributed to the Dust-Bowl and other droughts over the US Central Great Plains.

The IPO-induced precipitation changes are most pronounced in boreal winter and spring, with small changes in summer (Fig. 6). In autumn, precipitation decreases during

IPO cold periods over most CONUS except for the West Coast, Florida and southern Texas where precipitation increases. The seasonal maps for the warm period from 1977–1998 (not shown) are roughly the opposite of Fig. 6.

3.4 Model-simulated CONUS precipitation changes associated with the IPO

Current coupled models still have difficulties in simulating many unforced natural variations such as observed tropical SST change patterns and they cannot reproduce many observed regional precipitation changes (Hoerling et al. 2010). A common approach to study the influence of tropical SSTs on land precipitation over the US and other

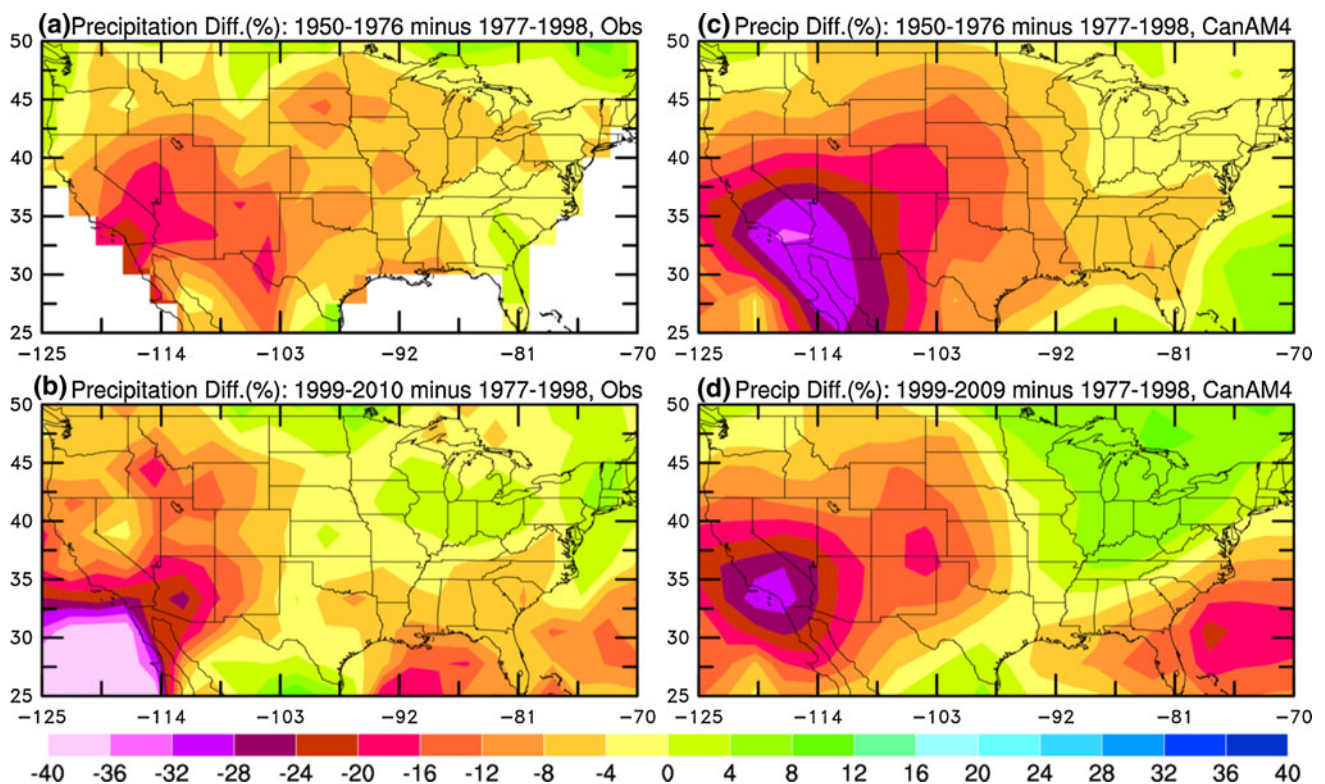


Fig. 8 Epoch difference (in % of the 1977–1998 mean, IPO cold minus warm phase) of annual precipitation over the US from observations (*left column*) and CanAM4 model simulations forced by observed SSTs (*right column*). Seasonal maps show more spatial

variations but still overall similarity between the observation and model cases. The cold seasons (December–May) contribute most to the annual change patterns

regions is to run AGCMs forced with specified or historical SSTs (e.g., Schubert et al. 2004a, b, 2009; Seager et al. 2005; Wang et al. 2010; Hoerling et al. 2010). Figure 7 compares the precipitation series averaged over the Southwest US from observations and simulations by the CanAM4 model forced with observed SSTs from 1950–2009, which allows the model to simulate the precipitation response to observed tropical SSTs. The model reproduces the observed Psw variations remarkably well on both multi-year ($r = 0.70$) to decadal ($r = 0.95$) time scales. The model-simulated Psw correlates with the IPO index even stronger than the observed Psw ($r = 0.88$ vs. $r = 0.85$), although both cases underestimate the Psw response to tropical cold SST anomalies during the 1974/75 La Niña event (Fig. 4a), which results in a large dip in the IPO index around the early 1970s that is not well matched by the smoothed Psw (but the Psw decline is evident in less-smoothed series, see Fig. 7).

Figure 8 compares spatial patterns of the IPO epoch difference (for 1950–1976 minus 1977–1998 and 1999–2009/10 minus 1977–1998) of annual precipitation from observations and the CanAM4 runs. The model captures the large precipitation decreases over the Southwest US (overestimated for 1950–1976) and the drier conditions

over most of the CONUS during 1950–1976 compared with the warm period from 1977–1998. For the most recent cold period from 1999–2009, the model shows increased precipitation over the Midwest and Northeast US, while the observations show relative small changes over these regions. Given the relatively coarse resolution of the CanAM4 ($\sim 2.8^\circ$), the overall agreement between the observed and simulated precipitation change patterns and temporal evolution (Figs. 7, 8) is remarkable.

3.5 Atmospheric circulation changes associated with the IPO

The IPO affects US precipitation through atmospheric circulation response to IPO-associated tropical SST anomalies (cf. Fig. 1d). Figure 9 compares the IPO epoch differences (1950–1976 minus 1976–1998) of 850 hPa geopotential height (Z), precipitation, and horizontal winds for December–February (DJF) from the NCEP/NCAR reanalysis and the CanAM4 model simulations. The overall patterns over the Pacific and North America are similar between the reanalysis and CanAM4 runs. Both show a strong anomalous high pressure center and anti-cyclonic circulation in the lower troposphere over the North Pacific

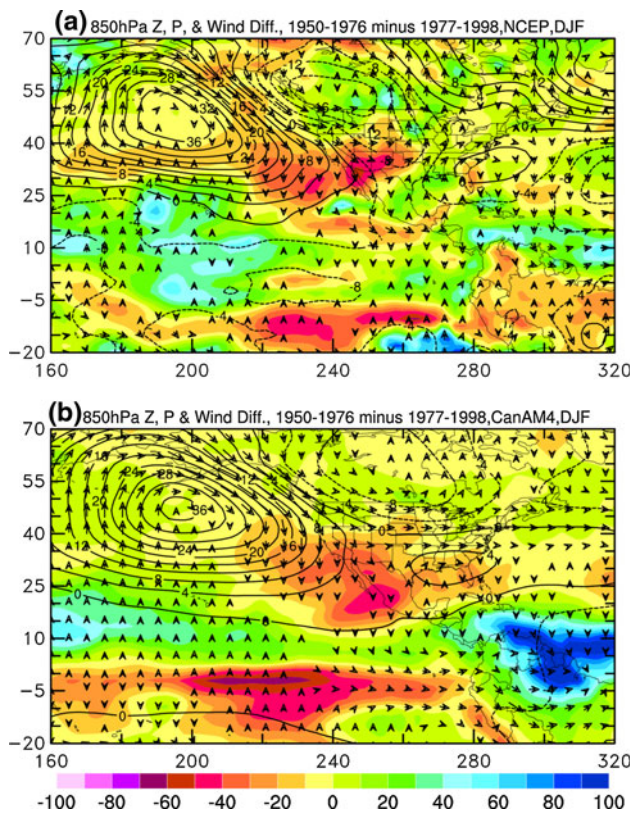


Fig. 9 **a** The 1950–2009 minus 1977–1998 difference of DJF 850 hPa geopotential height (m, contours, dashed lines for negative values, interval = 4 m), DJF 850 hPa winds (vectors, maximum length = 3.0 m/s), and DJF precipitation (colors, in % of the 1977–1998 mean) from the NCEP/NCAR reanalysis. **b** Same as (a) but for the CanAM4 model simulations (maximum vector length = 2.4 m/s). Results are similar to (b) for model HadGEM2-A. Annual maps are similar

(centered around 47°N and 195°W) during the cold period (1950–1976) compared with the warm period (1977–1998). To the east of this high pressure center, there is a weak low pressure center over Canada in both the reanalysis and CanAM4. The geopotential height anomaly patterns shown Fig. 9 is similar to the 500 hPa height patterns associated with the PDO shown by Mantua et al. (1997) and Zhang et al. (1997). The cold and dry northwesterly and northerly winds around the western coast of North America between these two pressure centers result in reduced precipitation (by 10–50 %) over a large region extending from the subtropical eastern North Pacific to Southwest North America in both the reanalysis and CanAM4, although this dry zone extends farther south to Mexico in the CanAM4 (Fig. 9). Thus, the reduction of precipitation over much of the West US (except the Northwest) during cold IPO periods is part of the large-scale precipitation changes associated with the pressure and wind changes over the North Pacific and Canada. Around the Florida Peninsula, there is a weak anomalous high pressure center and

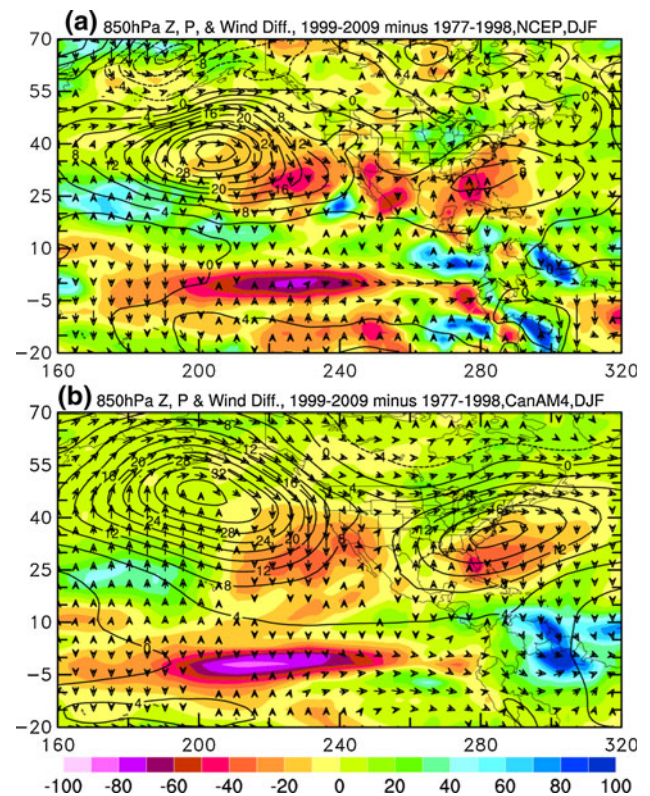


Fig. 10 Same as Fig. 9, but for the 1999–2009 minus 1977–1998 difference. The maximum vector represents 2.7 m/s in (a) and 2.0 m/s in (b). Results for the ERA-Interim are similar to (a)

anti-cyclonic circulation in both the reanalysis and CanAM4, although the exact location differ slightly between them. As a result, precipitation over Florida is reduced in both cases. Over most of the Midwest and Northeast US, the circulation and precipitation changes are relatively small in both the reanalysis and CanAM4 (Fig. 9).

For the most recent cold period (1999–present), the broad change patterns (Fig. 10) of atmospheric circulation and precipitation are comparable to the 1950–1976 period. The main differences include a southeast-ward shift of the high pressure center over the North Pacific in the reanalysis, and the disappearance of the low pressure center over Canada, and a stronger high pressure center and anti-cyclonic anomalous circulation along the US Southeast coast. The latter leads to anomalous southwesterly winds into the Midwest US and above-normal precipitation there in both the reanalysis and CanAM4 (Fig. 10).

The DJF circulation change patterns last into the spring, but they largely disappear in the summer and fall in the reanalysis (Fig. 11) and become weaker in the CanAM4 in the warm seasons (Fig. 12). Nevertheless, precipitation over much of the West US decreases in all the other seasons during the recent cold period compared with the warm period from 1977–1999 in both the reanalysis and CanAM4. The NCEP/NCAR reanalysis (but not the CanAM4)

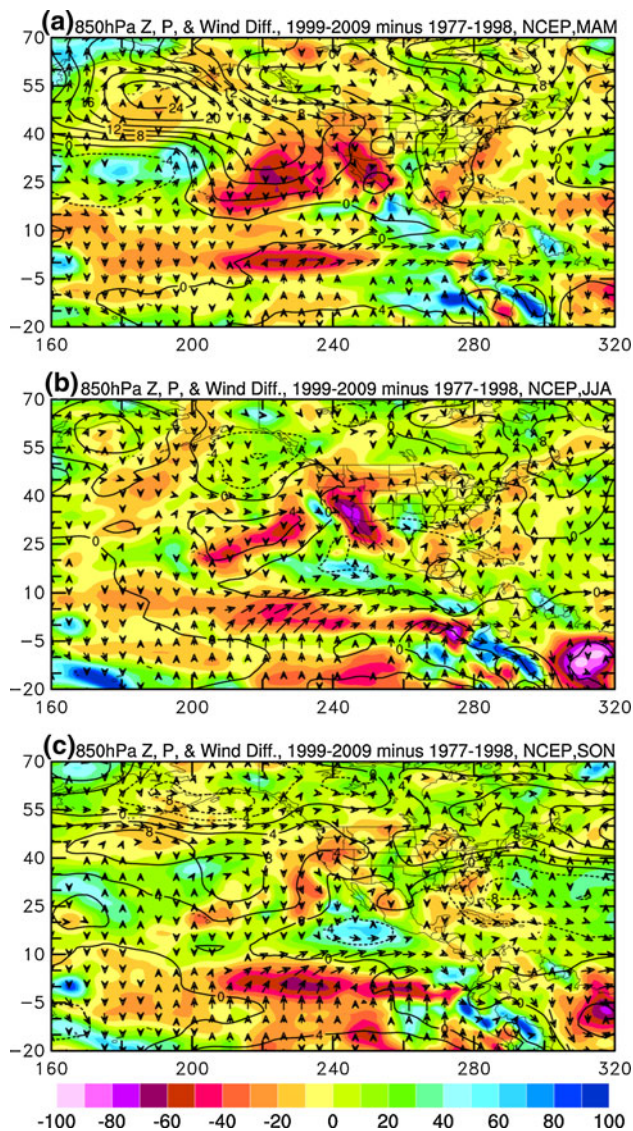


Fig. 11 Same as Fig. 9 but for **a** March–May (MAM), **b** June–August (JJA), and **c** September–November (SON) from the NCEP/NCAR reanalysis

shows increased precipitation over Texas and the US Southern Plains from spring to fall (Fig. 11), but this is not evident in observed precipitation (Fig. 8b). The CanAM4 shows fairly consistent reduction of precipitation over the West US from spring to fall due to anomalous northerly winds (Fig. 12), which also appear to be a major factor for decreased precipitation over most of the West US in the reanalysis (Fig. 11).

4 Summary and concluding remarks

To investigate why the contiguous US has become wetter since the 1950s when models predict severe drying under GHG-induced global warming, I have examined the

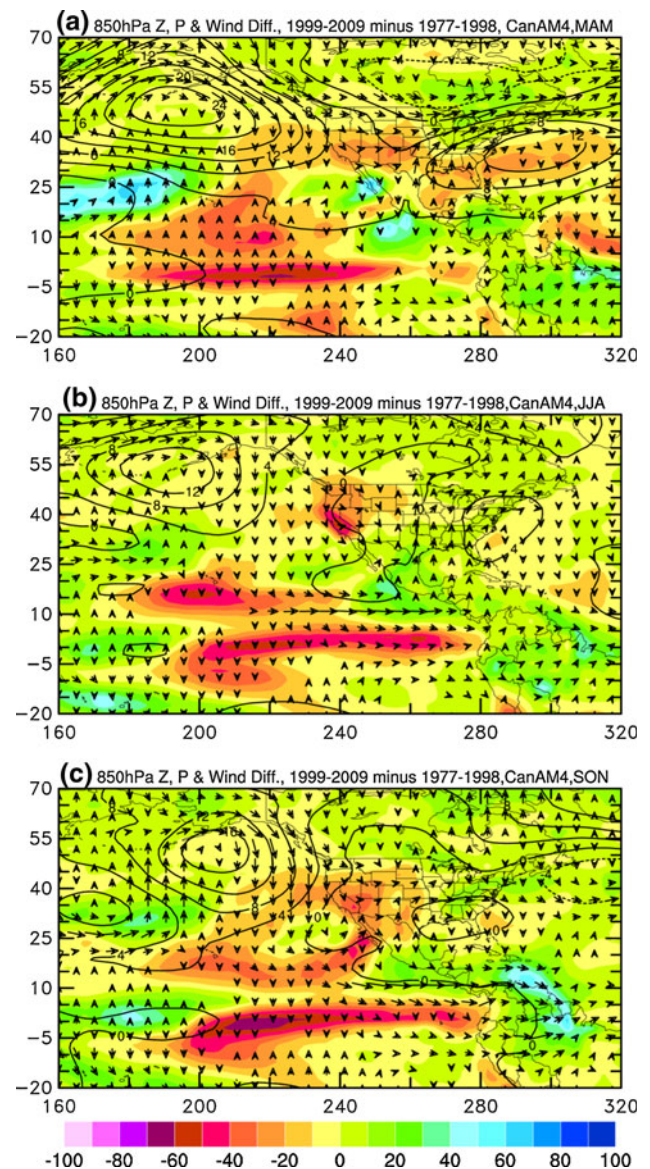


Fig. 12 Same as Fig. 9 but for **a** March–May (MAM), **b** June–August (JJA), and **c** September–August (SON) from the CanAM4 simulations

influence of the Inter-decadal Pacific Oscillation on US precipitation, especially over the Southwest US using historical data from 1923–2010, atmospheric reanalyses from 1948–2010, and CanAM4 model simulations forced with observed global SSTs from 1950–2009. Consistent with previous studies, I found that precipitation over Southwest North America is highly correlated with SSTs in the tropical Pacific Ocean on ENSO and longer time scales. Cold SST anomalies in the tropical central and eastern Pacific associated with the IPO induce a strong high pressure anomaly center and anti-cyclonic winds in the lower troposphere over the North Pacific during the cold season. This results in cold and dry northwesterly and northerly winds around the

western coast of North America, leading to 5–20 % reduction in annual precipitation over much of the West US (except the Northwest US) and the US Central Great Plains during the cold phases of the IPO, such as the periods from 1946–1976 and 1999–present. During the warm phases of the IPO (e.g., 1924–1945 and 1977–1998), the circulation and precipitation changes are roughly reversed, with higher precipitation over much of the West US and the Central Great Plains. The IPO's influence on precipitation over the Midwest, Northeast, and Southeast US is relatively weak, especially for annual mean.

Precipitation averaged over the Southwest US follows closely with the IPO index ($r = 0.85$) from 1923–2010 on decadal to multi-decadal time scales. The IPO experienced warm periods from 1924–1945 and 1977–1998 and cold periods from 1946–1976 and 1999–present, and annual precipitation over the Southwest US is about 5–15 % above normal during the warm periods and 5–20 % below normal during the cold periods. The IPO cycles, especially the phase change around 1976/77, induce an apparent upward trend in precipitation over much of the West US and the Central Great Plains for the periods since the 1950s. Since around 1999, however, precipitation has decreased over these regions as the IPO switched into another cold phase that is likely to last for another 1–2 decades.

The CanAM4 model forced with observed global SSTs from 1950–2009 reproduces much of the precipitation and circulation changes seen in observations and atmospheric reanalyses, including the close correlation between the IPO index and Southwest US precipitation ($r = 0.88$), and the strong anomalous pressure high over the North Pacific during IPO cold periods. The model simulates the observed variations in Southwest US precipitation remarkably well on both multi-year ($r = 0.70$) and decadal ($r = 0.95$) time scales. This further reinforces the notion that tropical SSTs (and the associated SST anomalies in the North Pacific, Fig. 1d) have large influences on precipitation over the Southwest US and the Central Great Plains on both ENSO and decadal to multi-decadal time scales.

The results presented here are consistent with many previous studies, such as those based on AGCM experiments (Schubert et al. 2004a, b, 2009; Seager et al. 2005; Wang et al. 2010) that showed strong sensitivity of precipitation over the US Great Plains and Southwest to tropical Pacific SST forcing and the large role of the tropical SSTs in producing historical droughts and pluvial periods over North America. The tight coupling with the IPO cycles revealed here suggests potential decadal predictability of precipitation over these regions. It also highlights the need to better understand the physical processes behind the IPO, so that coupled models can simulate these processes and predict the IPO and the associated precipitation changes decades ahead (Meehl et al. 2010). Such predictions have

major implications for agriculture and water resources over the Southwest US and other regions affected by the IPO (cf. Fig. 2). The fact that apparent trends can result from the IPO-induced cycles in precipitation in the Southwest US over periods of 30–60 years underscores the difficulties in estimating externally-forced long-term trends from noisy records with relatively short length (<60 years), as natural SST variations have also contributed to apparent trends in precipitation during recent decades over many other regions (Hoerling et al. 2010).

Acknowledgments The author is grateful to the Canadian Centre for Climate Modelling and Analysis, the UK Met Office Hadley Centre and the PCMDI for making the model and SST datasets available to the public, and Ben Sanderson and John Fasullo for providing some of the model and ERA-Interim data files.

References

- Alexander MA, Bladé I, Newman M, Lanzante JR, Lau N-C, Scott JD (2002) The atmospheric bridge: the influence of ENSO teleconnections on air–sea interaction over the global oceans. *J Climate* 15:2205–2231
- Burke EJ, Brown SJ (2008) Evaluating uncertainties in the projection of future drought. *J Hydrometeorol* 9:292–299
- Chen M, Xie P, Janowiak JE, Arkin PA (2002) Global land precipitation: a 50-year monthly analysis based on gauge observations. *J Hydrometeorol* 3:249–266
- Chou C, Neelin JD, Chen CA, Tu JY (2009) Evaluating the “rich-get-richer” mechanism in tropical precipitation change under global warming. *J Climate* 22:1982–2005
- Dai A (2011a) Drought under global warming: a review. *WIREs Clim Change* 2:45–65
- Dai A (2011b) Characteristics and trends in various forms of the Palmer Drought Severity Index (PDSI) during 1900–2008. *J Geophys Res* 116:D12115. doi:10.1029/2010JD015541
- Dai A, Wigley TML (2000) Global patterns of ENSO-induced precipitation. *Geophys Res Lett* 27:1283–1286
- Dai A, Fung IY, Del Genio AD (1997) Surface observed global land precipitation variations during 1900–88. *J Climate* 10:2943–2962
- Dai A (2012) Increasing drought under global warming in observations and models. *Nat Clim Change* (in press)
- Deser C, Phillips AS, Hurrell JW (2004) Pacific interdecadal climate variability: linkages between the tropics and the North Pacific during boreal winter since 1900. *J Climate* 17:3109–3124
- Feng S, Hu Q, Oglesby RJ (2011) Influence of Atlantic sea surface temperatures on persistent drought in North America. *Clim Dynam* 37:569–586
- Hoerling M, Eischeid J, Perlwitz J (2010) Regional precipitation trends: distinguishing natural variability from anthropogenic forcing. *J Climate* 23:2131–2145
- Hu Q, Feng S (2012) AMO- and ENSO-driven summertime circulation and precipitation variations in North America. *J Clim*. doi:10.1175/JCLI-D-11-00520.1
- Hu Q, Feng S, Oglesby RJ (2011) Variations in North American summer precipitation driven by the Atlantic Multidecadal Oscillation. *J Climate* 24:5555–5570
- Huffman GJ, Adler RF, Bolvin DT, Gu GJ (2009) Improving the global precipitation record: GPCP version 2.1. *Geophys Res Lett* 36:L17808. doi:10.1029/2009GL040000

- IPCC (2007) Climate change 2007: the physical science basis. Cambridge University Press, Cambridge 996 pp
- Kushnir Y, Seager R, Ting MF, Naik N, Nakamura J (2010) Mechanisms of tropical Atlantic SST influence on North American precipitation variability. *J Climate* 23:5610–5628
- Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull Am Meteorol Soc* 78:1069–1079
- Meehl GA, Hu AX (2006) Megadroughts in the Indian monsoon region and southwest North America and a mechanism for associated multidecadal Pacific sea surface temperature anomalies. *J Climate* 19:1605–1623
- Meehl GA, Hu AX, Tebaldi C (2010) Decadal prediction in the Pacific region. *J Climate* 23:2959–2973
- Mo KC, Schemm JKE, Yoo SH (2009) Influence of ENSO and the Atlantic Multidecadal Oscillation on drought over the United States. *J Climate* 22:5962–5982
- Newman M, Compo GP, Alexander MA (2003) ENSO-forced variability of the Pacific Decadal Oscillation. *J Climate* 16:3853–3857
- Nigam S, Guan B, Ruiz-Barradas A (2011) Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the great plains. *Geophys Res Lett* 38:L16713. doi:[10.1029/2011GL048650](https://doi.org/10.1029/2011GL048650)
- Power S, Casey T, Folland C, Colman A, Mehta V (1999) Interdecadal modulation of the impact of ENSO on Australia. *Clim Dynam* 15:319–324
- Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J Geophys Res* 108:4407. doi:[10.1029/2002JD002670](https://doi.org/10.1029/2002JD002670)
- Schubert SD, Suarez MJ, Pegion PJ, Koster RD, Bacmeister JT (2004a) On the cause of the 1930s Dust Bowl. *Science* 303:1855–1859
- Schubert SD, Suarez MJ, Pegion PJ, Koster RD, Bacmeister JT (2004b) Causes of long-term drought in the US Great Plains. *J Climate* 17:485–503
- Schubert S et al (2009) A US CLIVAR project to assess and compare the responses of global climate models to drought-related SST forcing patterns: overview and results. *J Climate* 22:5251–5272
- Seager R, Kushnir Y, Herweijer C, Naik N, Velez J (2005) Modeling of tropical forcing of persistent droughts and pluvial over western North America: 1856–2000. *J Climate* 18:4065–4088
- Seager R et al (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–1184
- Sheffield J, Wood EF (2008) Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Clim Dynam* 31:79–105
- Ting M, Wang H (1997) Summertime US precipitation variability and its relation to Pacific sea surface temperature. *J Climate* 10:1853–1873
- Wang CZ, Enfield DB, Lee SK, Landsea CW (2006) Influences of the Atlantic warm pool on western hemisphere summer rainfall and Atlantic hurricanes. *J Climate* 19:3011–3028
- Wang H, Schubert S, Suarez M, Koster R (2010) The physical mechanisms by which the leading patterns of SST variability impact US precipitation. *J Climate* 23:1815–1836
- Zhang Y, Wallace JM, Battisti DS (1997) ENSO-like interdecadal variability: 1900–93. *J Climate* 10:1004–1020
- Zhong YF, Liu ZY, Notaro M (2011) A GEFA assessment of observed global ocean influence on US precipitation variability: attribution to regional SST variability modes. *J Climate* 24:693–707