



Decadal Drought Variability Over North America: Mechanisms and Predictability

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Abstract The physical mechanisms and potential predictability of North American drought on decadal timescales are reviewed in a simple and straightforward manner amenable to a wide audience. During decadal droughts, the tropical oceans, most notably cold states of the Pacific but also warm states of the Atlantic, provide forcing that continually nudges the atmosphere toward circulation anomalies that favor high pressure over southern North America and dry conditions. However, even in these regions, and even more so in the northwest and northeast, the oceans exert less than dominant control and actual drought onset, evolution and termination can deviate due, presumably, to potent internal atmosphere variability. The ocean influence, however, justifies efforts to determine if the driving sea surface temperature anomalies in the tropical Pacific and Atlantic are predictable beyond the seasonal to interannual timescale. Evidence to date, based on initialized predictions with coupled models, is tantalizingly suggestive that useful predictability on these timescales may exist within the atmosphere-ocean system although relevance to North American decadal drought has not yet been demonstrated. These recent advances in drought science and prediction warrant continued research aimed at developing useful long term predictions of drought that can guide adaptation and minimize the associated widespread social and economic disruptions.

Keywords Drought · Decadal · Predictability · North America

Introduction

For our purposes here, we take decadal drought variability to be something that is obvious to the perceptions of a long lived person rather than something that fancy statistical techniques are required to make evident. For the case of North America, decadal drought and hydroclimate variability are abundantly evident to the observer. A long-term resident of New York City, especially one who watches the *New York Times*' daily recordings of the levels of the City's Catskill Mountains reservoirs, will be very aware that the northeast is much wetter than it was before the 1970s and that it enjoys an apparent robust water security without threat of sustained drought. By contrast, a much younger resident of the southwest will be keenly aware that for over a decade now the water supply has been a worry in a way that it was not in the 1980s and 1990s. Anyone who has lived or vacationed in the Rockies and Sierras at the end of the twentieth century and again in the past decade will have been struck by the common lack of spring snow, the parched forests struck by bark beetles, the expanse of fire damage and the half empty reservoirs. Looking further back in time, the Dust Bowl drought of the 1930s, a decade of low precipitation within an overall drier mid-century, remains one of the worst environmental catastrophes to befall the country whose consequences we still live with today, including a permanent change in farm economy and drop in land prices [22]. These are the decadal variations in drought that are of concern and they have tremendous social impact. What causes them and can we predict them? Are sustained droughts becoming more intense or more frequent?

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The causes of decadal drought over North America have become much clearer in the past decade or so. But it is worthwhile noting that as recently as 2002, the National Research Council, in considering the causes of the Dust Bowl drought, did not think there was a role for ocean-forced circulation change [31]. That perception was upended by two game changing papers [37, 38] that demonstrated, using a sea surface temperature (SST)-forced atmosphere model, that the Dust Bowl drought was caused primarily by an extended cold state of the tropical Pacific Ocean and, to a lesser extent, by a warm tropical North Atlantic Ocean. Follow up work by Herweijer et al. [19] and Seager et al. [47] made clear that this same driving of North American decadal drought variability by the tropical Pacific and Atlantic Oceans extended back to the beginning of SST measurements in 1856 (and no doubt before).

Our purpose here is to briefly review, with some new analyses, the state of our understanding of decadal drought variability across North America, consider the case of the ongoing decadal drought across the West, and then to see if drought science has been able to advance from understanding to prediction and, if not, whether the limiting factors are intrinsic to the chaotic nature of the atmosphere-ocean system or inadequacies of our model prediction systems.

Mechanisms of North American Decadal Drought Variability

In the spirit of decadal drought variability being a phenomenon that is plain to see, Fig. 1 shows time series of unfiltered, annual mean precipitation totals in four cities across the U.S. Southwest from 1900 to now (using the co-located grid point from a gridding of Global Historical Climatology Network station data from Menne et al. [29]): Phoenix, AZ, Oklahoma City, OK, Albuquerque, NM, Austin, TX. The variability year to year, as a proportion of the long term mean, is truly striking reflecting the fickle nature of precipitation in a region where the climatological precipitation sustains a semi-arid climate but individual years can vary from bone-dry to flood. Just as noticeable is the variation between decades, emphasized by the 6-year low pass filter of the raw data shown as the thin red line. The 1980s and 1990s stand out as wet in these cities and, in each, the drier early twenty-first century is clear. Earlier, the 1930s Dust Bowl drought is clear in Oklahoma City and the 1950s Southwest drought in Austin.

To move toward a broader assessment, we next average the annual mean precipitation (from the University of East Anglia Climatic Research Unit CRU TS v.3.24 Harris et al. [18]) across two regions: southwest North America (25°–40° N, 120°–110° W) and the southern Plains (30°–40° N, 110°–90° W) and also perform a low pass filter of the time

series to emphasize variability on timescales of 6 years or more. Time series are shown for both the observations and the mean of a 16 member ensemble of simulations with the NCAR CCM3 atmosphere model¹ forced by observed SSTs [36] over the ocean with the plus and minus two standard deviation spread of the ensemble shown as shading. In a general sense, the decadal drought variability is reproduced by the model as a response to SST forcing. This includes the wet decades in the 1980s and 1990s followed by the shift to drought since in both the Plains and southwest, the Dust Bowl drought in the Plains and, to some extent, the 1950s drought. The 1940s and early 1970s stand out as times in the Southern Plains when the SST conditions favored dry conditions but the real world was wet. Indeed, the model-observations agreement is only general leaving internal atmosphere variability as explaining up to three quarters of the low frequency variability. The oceans' role should be understood as nudging the atmosphere toward drought-inducing conditions but not so strongly as being able to always overrule the atmosphere's own intrinsic variability.

Global SST anomalies [36] and observed (CRU TS v.3.24) or modeled precipitation were then regressed onto the time series of observed and modeled low pass filtered precipitation time series for the Southwest and southern Plains regions. The results are also shown in Fig. 1 with SST anomalies only plotted where significant at the 5% level. These show for model and observations and for both regions a strong connection between wet (dry) and warm (cold) tropical Pacific SST anomalies. That is, the longer than interannual timescale variability of ENSO that gives rise to either extended La Niña or cold states and/or the absence of El Niños, is the prime ocean driver of decadal drought over southwest North America and the southern Plains. Then, 200 mb height anomalies were also regressed onto the low pass precipitation time series. Since this is a linear analysis, Fig. 1 (lower panels) show that the cool tropical Pacific waters force a teleconnection with a North Pacific subtropical cyclone and a high over the extratropical North Pacific that favors a weaker jet stream flow into southwestern North America that in turn would generate a northward displaced storm track [17, 48]. The physics of decadal drought generation by tropical Pacific SST anomalies is essentially the same as that during individual La Niña

¹Sixteen member ensembles with later versions of the NCAR model up to the current CAM5.3 have been generated at Lamont. These models show similar behavior to CCM3 but the older model is chosen here due to a modestly better agreement between observations and model for precipitation history of the southwest. The observed precipitation values occasionally lie outside the two standard deviation spread of the model ensemble which could be because the 16 members are insufficient to capture the full range of model internal variability.

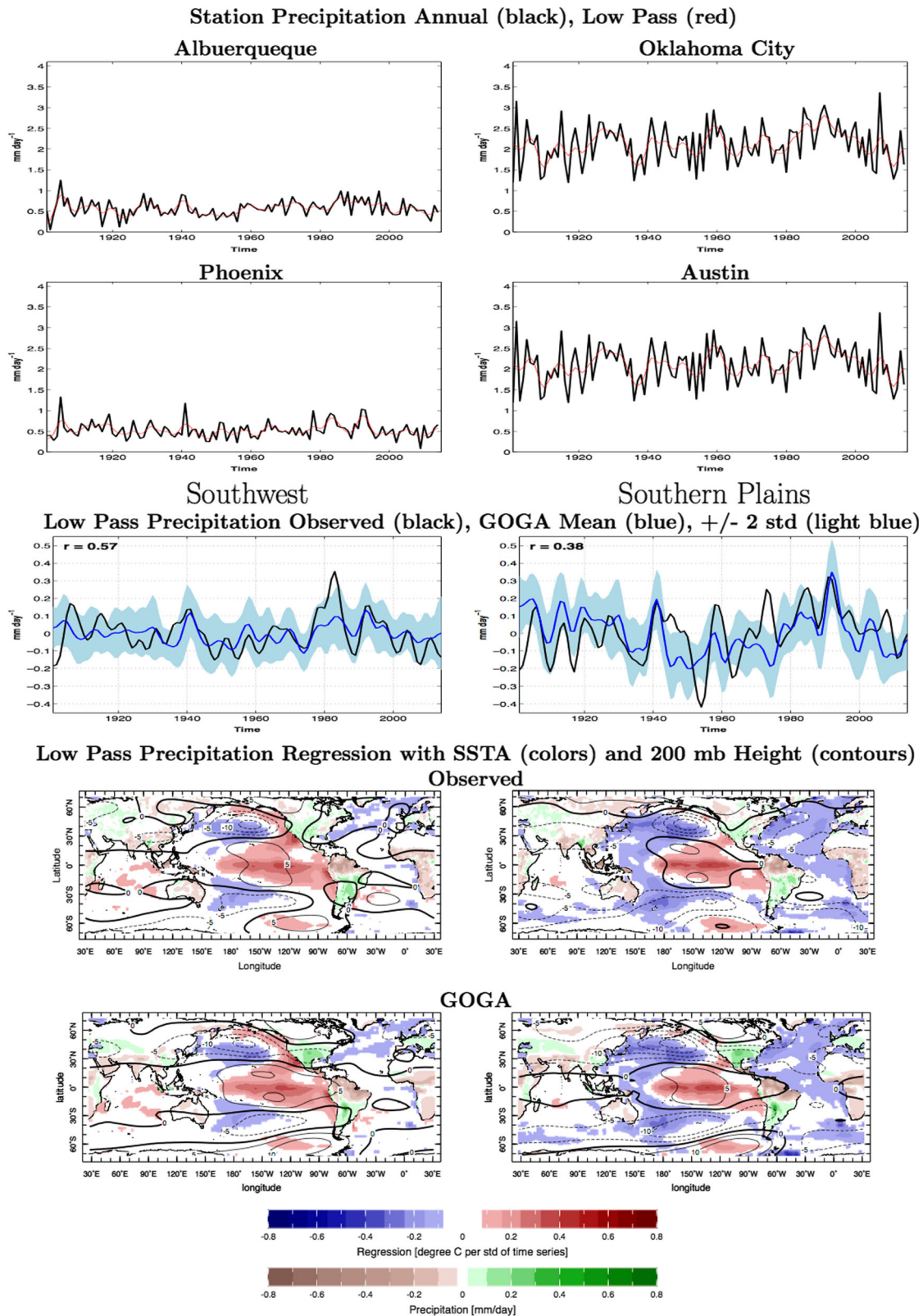


Fig. 1 Time series of annual mean (black), and 6-year low pass-filtered (red), precipitation at Albuquerque, Oklahoma City, Phoenix and Austin (top), the observed and modeled (with global SST forcing, ensemble mean blue and shading indicating plus and minus two standard deviations of the ensemble spread), annual mean precipitation

averaged over the southwest (middle left) and southern Plains (middle right) and the regression of SST (colors only where significant at the 5% level) and 200 mb heights (contours) on the southwest (left) and Plains (right) time series for observations (above) and the SST-forced model (below)

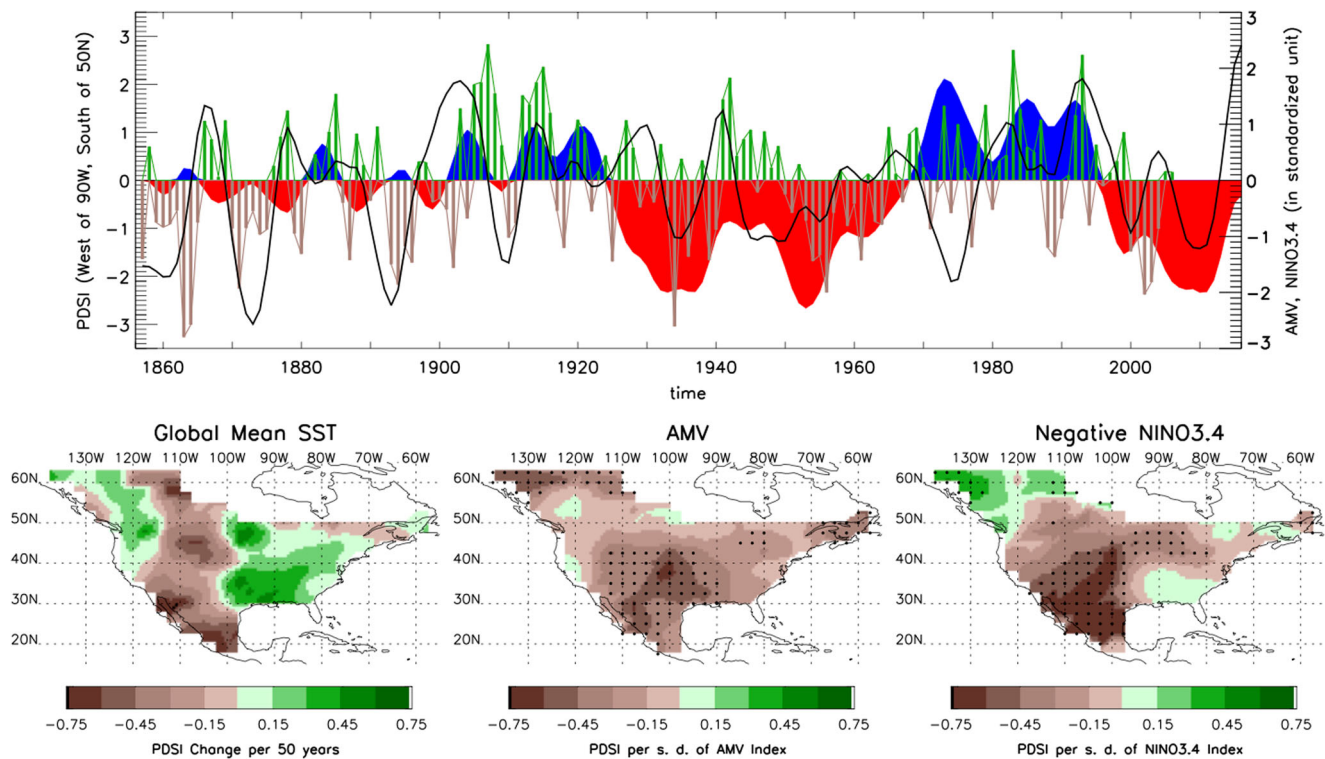


Fig. 2 Time series of the NADA PDSI for west of 90° W and south of 50° N (bars) and standardized, low pass filtered, negative of the AMO (red warm/blue cold) and NINO3.4 (black line) indices (top) and results of a multiple regression of NADA PDSI on time series of global mean SST (bottom left), the AMO (bottom middle) and NINO3.4

(bottom right). Regression maps are in unit of PDSI change over the period for global mean SST and PDSI per standard deviation of the index for the AMO and NINO3.4. Stippling is added where the regression is significant at the 5% level

winters that are dry in southern North America [5, 42]. For the southern Plains, but not so much the southwest, wet (dry) conditions are also associated to a statistically significant degree with cool (warm) North Atlantic SST anomalies in a pattern akin to Atlantic Multidecadal Variability (AMV) in both observations [58] and coupled models [59] with a horse-shoe structure extending from the subpolar North Atlantic to the tropical Atlantic along the eastern part of the Atlantic basin. Kushnir et al. [26] have examined the physical mechanisms for how tropical Atlantic SST anomalies can influence North America precipitation. Warm tropical North Atlantic SST anomalies, in summer, force a subtropical Rossby wave that places northerly, descending flow over the southwest and southern Plains but, in winter, first suppress precipitation over the tropical Pacific that drives a La Niña-like Rossby wave teleconnection and dry conditions over the southwest.

Figure 2 further illustrates these relations by showing the time series of the spatial average of the Palmer Drought Severity Index (PDSI) for south of 50° N and west of 90° W based on the North American Drought Atlas (NADA) tree-ring reconstructions from Cook et al. [10]. Tree ring reconstructions are used to allow the analysis to extend back into the nineteenth century, when there are few rain gauge

records, and cover the whole period of SST observations.² PDSI is a proxy for soil moisture and is therefore influenced by both water supply in the form of precipitation and demand in the form of evapotranspiration. High temperatures tend to cause reduced soil moisture (negative PDSI) due to an increase in atmospheric evaporative demand. The figure also shows the AMV index after removal of a regression on the global mean SST [58] and the results of a multiple regression of the NADA PDSI on the 10 year low pass filtered indices of (1) global mean SST, (2) the AMV (as above), and (3) the NINO3.4 index. On these timescales, the variations of tropical Pacific SST arise from Pacific decadal variability and are akin in three dimensional atmosphere-ocean structure to the higher frequency ENSO behavior [5]. The Atlantic SST variations will contain components due to the basin scale Atlantic Multidecadal Oscillation [25] and tropical North Atlantic variability (e.g., Servain et al. [53]). The Pacific and Atlantic sources of SST variations induce similar magnitude PDSI variations with the response to the tropical Pacific centered in the southwest

²Cook et al. [10] show calibration and verification statistics for the NADA revealing quite uniform skill across North America despite variations in density of tree ring records.

and the response to the Atlantic centered in the southern Plains. Notably, similar analyses done on precipitation alone [26, 52] show the response to the tropical Pacific to be dominant (but also with the Pacific doing its work in winter and the Atlantic in summer) so the similar amplitude here suggests the temperature influence of the AMO on PDSI. The AMO is associated with widespread warming across the continent perhaps as a direct response to the warm Atlantic SST anomalies rather than purely as an indirect response to precipitation reduction.

For the annual mean PDSI, neither the Pacific nor Atlantic have strong influences in the northwest, northeast, or southeast of North America [9]. The long-term change in PDSI derived by regression on global mean SST (Fig. 2 bottom left) most notably has drying in the southwest and wetting in the southern Plains and is of the same amplitude as the natural variability but is not statistically significant and, hence, its amplitude and pattern should be viewed with caution. To the extent it is discernible, it is likely because of the temperature influence on PDSI as opposed to the long-term change in precipitation which is small [44].

Regardless, the long-term change due to rising greenhouse gases, which is better estimated by using the CMIP5 historical simulations and projections, will strengthen and be the most predictable component of PDSI variation offering some short term predictability [15, 20, 42].

The Early Twenty-First Century Decadal North American Drought

Much of southwestern North America has been in drought, with little respite, since the 1997/98 El Niño and this too has been linked to variations in tropical SSTs [4, 12, 44, 50, 60]. In Fig. 3, we show the observed atmosphere-ocean state and modeled atmosphere state for the period from 1999 to 2014 relative to a 1901 to 2014 climatology. To take a long-term perspective, we use geopotential height anomalies from the NOAA Twentieth Century Reanalysis [8]. Amidst the overall warming of SSTs, tropical Pacific SSTs during this period have been broadly La Niña-like in a pattern reminiscent of Pacific decadal variability [5, 63]

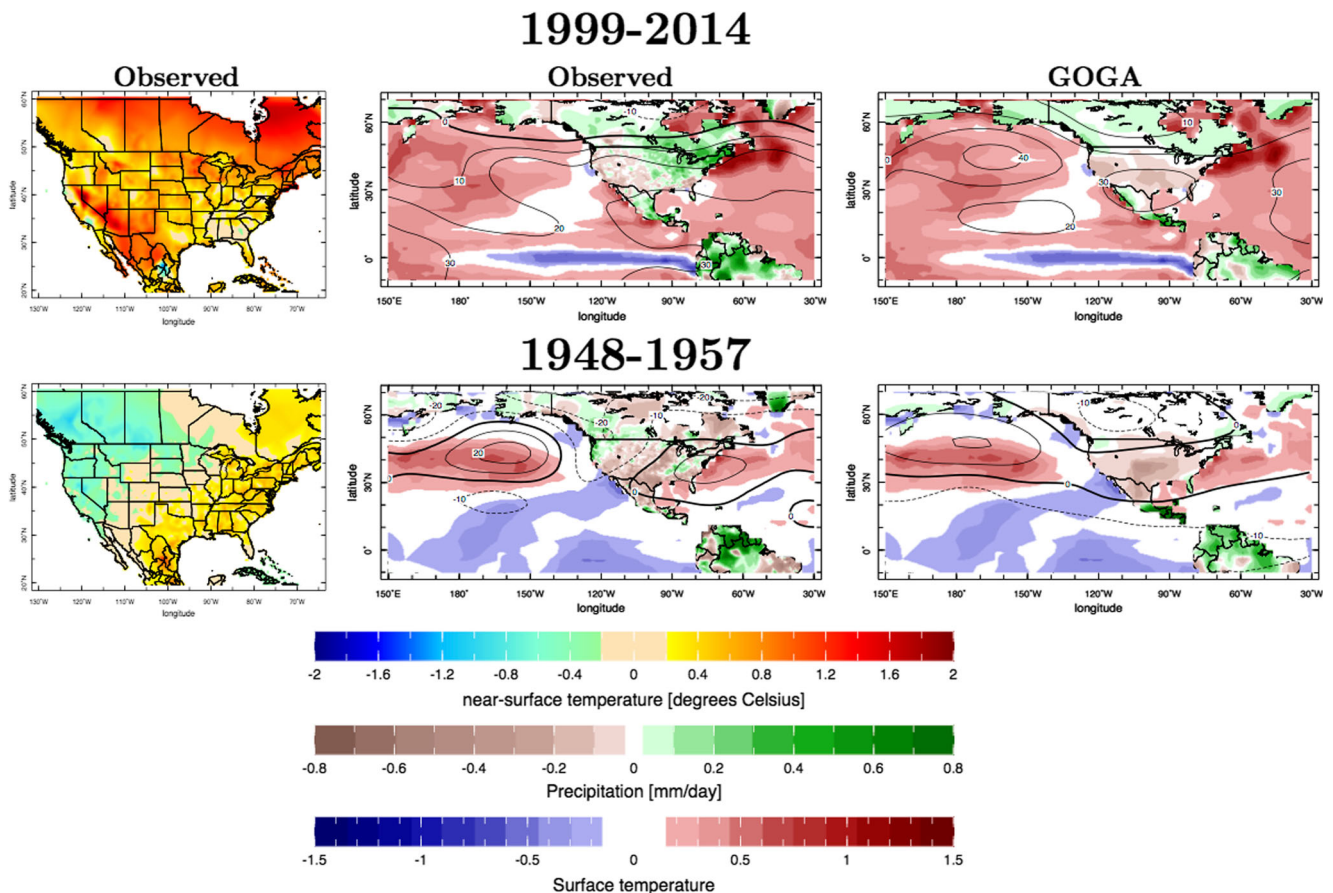


Fig. 3 Anomalies of the observed surface air temperature (*left*), observed SST over ocean, precipitation over land and 200 mb heights (*middle*) and observed SST over ocean, modeled ensemble mean precipitation

over land and 200 mb height (*right*) for the current drought (1999–2014, *top*) and 1950s drought (1948–1957, *bottom*). Units are K for temperature, meters for heights and mm/day for precipitation

and, together with this, there have been higher than normal heights over North America and negative precipitation anomalies in many northern subtropical areas that includes southwestern North America. Also shown are the same anomalies from the global SST-forced atmosphere model ensemble mean. Averaging across the ensemble removes the weather that is uncorrelated between ensemble members and isolates the common SST-forced signal. Hence, in the model ensemble mean, the North Pacific to southern North America ridge is clearly seen and consistent with the La Niña-like SST forcing. The southwest U.S. drought is quite well simulated as an SST-forced response but the model misses the drought in northwest Mexico.

For comparison, we also show in Fig. 3 the same maps for the case of the 1950s drought. The global oceans were much cooler then but the especially cold tropical Pacific is clear. The model once again produces a clear North Pacific-southern North America ridge. The observed height anomalies have highs over the North Pacific and southeast U.S. but an interrupting low over the west coast. The model simulates the extensive dry anomalies across much of southern and central North America, once again emphasizing the ocean driving of decadal drought. The left panels of Fig. 3 show the surface air temperature anomalies over just North America. Although spatial patterns of SST, height and precipitation anomalies for these two decadal droughts bear some limited similarity, the 1950s drought has warm anomalies restricted to regions of precipitation reduction and are probably caused by surface energy budget adjustment to reduced evapotranspiration (e.g., Hoerling et al. [21]; Seager et al. [43]), while the ongoing decadal drought has occurred within the context of overwhelmingly much warmer conditions across the continent that no doubt arise from global warming. The warming increases atmospheric evaporative demand as saturation vapor pressure increases by more than actual vapor pressure [45]. Consequently, from the soil moisture and streamflow perspective, we expect greater impacts of SST-forced decadal droughts now than in the past because the droughts are being imposed within a warmer climate [60]. Increased water use efficiency by plants due to rising CO₂ might be able to offset this somewhat [56].

Predictability of North American Decadal Drought Variability

The results so far (and other published results) make clear that the oceans play an important role in decadal drought variability over southwest North America and the Plains. However, they also make clear that this role is limited and variability that is not ocean-controlled has to be invoked to fully explain the observed history of drought on decadal

timescales. It is not thought that this conclusion is seriously compromised by choice of model. We have performed the same analyses with all NCAR models from CCM3 to CAM5.3 and found similar results and much the same conclusions have been reached based on other non-NCAR models (e.g., Schubert et al. [39]). Hence, while skillful prediction of SSTs would lead to some drought predictability, the skill will be limited due to the influence on drought of other factors, most notably internal atmospheric variability. For example, referring back to Fig. 1, the ocean favored drought in the southern Plains in the mid 1940s and mid 1970s but this influence was apparently overwhelmed by atmospheric internal variability [44]. In the oceans, all indications from modeling experiments are that the SST anomalies that need to be predicted are in the tropical Pacific (e.g., Seager et al. [47]) and tropical North Atlantic [38, 55]. Furthermore, soil moisture appears to not be able to offer predictability beyond the seasonal timescale (e.g., Nicolai-Shaw et al. [32]). So now, we consider how well tropical Pacific and North Atlantic SSTs can be predicted on timescales beyond one year.

Interannual to Decadal Predictability of Tropical Pacific SSTs

Skillful prediction of tropical Pacific SSTs on seasonal to interannual (S/I) timescales dates back to Cane et al. [3] and is now the main source of what global S/I climate predictability exists [24]. Operational S/I prediction typically extends to one year. However, there is reasonable evidence that useful predictability may extend to the multiyear timescale. Encouraged by the hindcast decadal predictability skill within the Zebiak and Cane [62] (ZC) model [23], Seager et al. [46] used an initialized operational version of the same model to forecast the 2003 to 2013 period and, based on persistent overall cool conditions, concluded “the 1997/8 El Niño marked the end of the post-1976 warm period.” After that, apparently successful, effort, considerable attention has been devoted to extended ocean prediction aided by the inclusion of decadal hindcasts in the Coupled Model Intercomparison Project Five (CMIP5). Of relevance to drought is the transition into a cold tropical state of Pacific decadal variability after the 1997/98 El Niño which forced the onset and persistence of the turn-of-the-century drought across the West [41]. Studies with single state-of-the-art coupled global climate models have found that the shift toward a state with cool waters in the central and eastern tropical Pacific was predictable when initialized in 1996 [27] or 1998 [13]. Meehl and Teng [28] showed that continuation of the overall cool state for 2007–2011 was predictable within the CMIP5 ensemble initialized in 2005. In all these cases, it should be noted that we use the term “predictable” loosely since actual predicted

amplitudes, trajectories and patterns differ considerably between observations and models (see, for example, Figure 3 in Meehl et al. [27]). However, even the fact that the models get the right sign of SST anomaly for multiyear averages is quite remarkable and encouraging. In a case of further agreement across models, data assimilation and initialization schemes, models agree that we are now entering a period when the post 1997/98 cold state of the tropical Pacific is transitioning back to a normal or warm state [27, 28]. Returning to the ZC model, after confirming the basics of the decadal predictability results in Karspeck et al. [23], Ramesh et al. [35] predict a warm shift in the tropical Pacific over the coming years to essentially neutral conditions. If these predictions are correct then, on the basis of all the atmosphere modeling done, we can expect that natural variability of the Pacific atmosphere-ocean system will introduce a tendency to wetter conditions across southwest North America in the coming years to decades.

Interannual to Decadal Predictability of North Atlantic SSTs

As noted, within the AMV, it is the tropical North Atlantic that forces the precipitation response over North America. Tropical Atlantic SST on seasonal to decadal time scales is influenced by many processes including the remote influence of ENSO but predictability studies have focused on variations of northward ocean heat transport associated with the Atlantic meridional overturning circulation (AMOC, Delworth et al. [11]; Timmermann et al. [57], among many others). Coupled model potential predictability experiments show a predictability of the AMOC on the order of 10 years and of the related subsurface and surface signatures, including SST, to varying degrees, depending on model formulation and experimental set up (e.g., Griffies and Bryan [16]; Boer [1]; Pohlmann et al. [34]; Collins et al. [7]; Msadek et al. [30]; Dunstone and Smith [14]). In the real world, ocean initial conditions, particularly the state of the AMOC, are poorly observed, thus the true predictability on interannual to decadal time scale in the Atlantic basin may not be fully realized. However, Yang et al. [61] examined decadal hindcasts with the GFDL CM2.1 model initialized by an ocean reanalysis and found significant hindcast skill for the internally generated component of the SST and 2m temperatures for forecast lead-times up to 10 years. Although not emphasized in the paper, Yang et al. [61] indicated a decreasing trend for the subpolar North Atlantic SST in the years following the 2011 forecast that seems to match well the recent trend (Fig. 2 and compare to their Fig. 1b). Models, however, do not always have the same strength of connection between subpolar and tropical Atlantic SSTs as observed so it is not clear as of now how well skill in

predicting subpolar ocean and SST variations translates into predicting the tropical Atlantic SSTs of relevance to North American precipitation.

Conclusions

Decadal drought variability is a fact of life in the American West, most recently in the form of the second decade of an ongoing drought that has strained water resources across at least seven states plus Mexico. The tropical oceans, and in particular, the tropical Pacific Ocean play an influential, though not paramount, role in generating decadal droughts over western North America from the Pacific Coast eastward across the Plains. Persistent cool states of the tropical Pacific lead by well-established atmospheric teleconnections to anomalous high pressure across the North Pacific and southern North America and a diversion of the Pacific storm track away from the southwest. However, the ocean-driving acts as a pacemaker that nudges the atmosphere to create drier or wetter conditions while internal atmospheric variability occurs at all time and space scales so that actual drought onset, evolution, and termination is only influenced by, and rarely completely controlled, by the oceans. Nonetheless, the ocean influence that does exist provides potential predictability if the responsible SST anomalies in the tropical Pacific and Atlantic Oceans can be predicted. Work to date does indeed provide some indication that tropical Pacific SST anomalies, including the cool states that nudge the southwest toward drought, can be predicted at lead times of one or more years. The predictability arises from the slow adjustment of the tropical Pacific upper ocean heat content to wind forcing. In the Atlantic subpolar SST predictability may arise from slow variations in the ocean overturning circulation (though a driving role for ocean dynamics has been challenged Clement et al. [6]; Cane et al. [2]) but the connection of this to the essential tropical North Atlantic SST variations is unclear.

On the basis of the associations identified, the current trends in tropical Pacific and Atlantic Ocean states and the predictions that have been performed, it is expected that the cool Pacific-warm Atlantic state that has persisted for over a decade now and which is ideal for generating western drought [40] is coming to an end and natural variability will be favoring a move to wetter conditions in the west. This will have to compete against a regional drying trend due to rising greenhouse gases that originates in wintertime shifts to more northerly flow and low level divergence [49, 51, 54]. Which will win will depend on the amplitude of the natural variations and of the radiatively forced response and we note that claims have been made that the forced drying might be stronger than most climate models project [50, 54].

Future work on decadal drought predictability should:

- i. Adopt a multimodel perspective to determine the predictability of tropical Pacific SSTs on annual to decadal timescales, which aspects of the SST anomalies need to be predicted in order to predict the drought response, and whether realizing predictability is compromised by coupled model biases.
- ii. Focus on the mechanisms of variability and predictability of the tropical North Atlantic SST anomalies that drive a precipitation response over North America, how these are connected to basin-scale Atlantic Multidecadal Variability, and how well these processes are represented in operational prediction models.
- iii. Assess whether any precipitation and temperature predictability that can be operationally realized has sufficient amplitude that, amidst internal atmospheric variability, it can translate into useful predictions of decadal drought onset, evolution, and termination.
- iv. Determine what the ocean processes are that lead to SST predictability on annual to decadal timescales and how well these are represented in climate models.

Decadal drought prediction will be limited to where the oceans exert a notable influence on precipitation and temperature over North America. We have focused on southwest North America and the Plains where this is true. It is worth examining if useful predictability could extend to the southeast US [33], but further north, even if there is an ocean influence, internal atmospheric variability plays a more dominant role and potentially negates useful prediction [44]. However, it is the southern, drier and/or warmer, regions of North America where water resources are more stressed and, hence, the potential predictability is usefully located. We suspect that in the next decade, research will have advanced to the point where either operational decadal drought prediction will be in place, improvements in coupled models to realize predictability are being made or it will have been decided that predictability is too limited to be of any practical use. Either way, the science of decadal drought variability has made dramatic progress over the last decade and the situation is well poised to build on recent progress and make the next advance from understanding to prediction.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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