Did a skillful prediction of sea surface temperatures help or hinder forecasting of the 2012 Midwestern US drought?

Jonghun Kam, Justin Sheffield, Xing Yuan and Eric F Wood

Department of Civil and Environmental Engineering, Princeton University, NJ, USA

E-mail: jkam@princeton.edu

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Abstract

The latest drought to hit the Midwestern (MW) US region, in 2012, was driven by the least summer precipitation for the last three decades with $20 billion in agriculture losses. For 2012, the summer forecast skill for Pacific and Atlantic sea surface temperature (SST) anomalies and low MW precipitation is remarkably good for some National Multi-Model Ensemble (NMME) models, but this is not generally repeated for other drought years, with some models predicting extreme wet anomalies, despite skill in predicting Pacific and Atlantic SST anomalies. In order to diagnose the origins of the limited skill of the NMME models, we use singular value decomposition (SVD) for global SSTs and continental US (CONUS) precipitation from observational data and NMME hindcasts (1982–2012). Observational data indicate that there is an insignificant coupling between global SSTs and MW precipitation during summer over the last 30 years. However, the NMME climate forecast models show strong coupling and therefore predicted the 2012 drought fortuitously for the wrong reason (a strong pan-Pacific El Niño–Southern Oscillation (ENSO)-like pattern). The observational data indicate that the strength of ENSO teleconnections with CONUS precipitation has weakened and the precipitation footprint has shifted over the past decades, suggesting that the transient nature of teleconnections may play a role in poor model skill.

Keywords: pacific SST teleconnections, midwest US drought, NMME, singular value decomposition

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1. Introduction

With improved understanding of ocean–atmosphere–land interactions and representation of such interactions or teleconnections in climate models, seasonal forecasting of drought using coupled climate models has shown potential for forecasting severe drought several months in advance (Luo and Wood 2007, Yuan et al 2013). The rationale for this is that the oceans can serve as a source of seasonal predictability because of its long memory, and the fact that drought onset usually takes several months to emerge. For example, the El Niño–Southern Oscillation (ENSO), which is the major driver of climate variations globally, is now predictable at seasonal and perhaps longer time scales depending on the initial month (e.g. after the spring predictability barrier; Webster and Yang 1992). Observations and climate models suggest that variability in the Pacific and Atlantic ocean conditions are associated with drought in the Midwestern US (MW, 100–85°W and 37–46°N) at interannual (Ting and Wang 1997, Wang et al 2007, Hu and Feng 2012) and decadal scales (Hoerling and Kumar 2003, McCabe et al 2004).
The MW region of the US is susceptible to severe drought due to its highly variable climate than spans semi-arid to continental humid climate zones. Persistent and/or spatially extensive droughts over the MW have plagued the region during the 1930s, 1950s, and 1988, each with different characteristics. The long-term Dust Bowl drought of the 1930s is thought to have been forced by cold SSTs over the tropical Pacific and warm SSTs over the North Atlantic, which induced anomalous large-scale circulation patterns, e.g., strong positive height anomalies in the upper troposphere in extra-tropical regions and upper-level anticyclone anomalies, respectively (Schubert et al. 2004a, Brönnimann et al. 2009) and thus hindered moisture supply from the Gulf of Mexico. The Dust Bowl drought was exacerbated by high surface temperatures and increased evaporative demand, as well as poor agricultural practices that resulted in soil erosion and large dust storms (Cook et al. 2007).

During the 1950s, another major drought persisted over much of the southern and central US for several years, with Texas the worse hit and declared a federal drought disaster area (Sheffield and Wood 2011). Based on the Palmer Drought Severity Index, moderate to extreme drought extended up to about 58% of the continental US (CONUS) in December 1956 (NOAA 2012). This drought was associated with low-tropospheric anti-cyclonic anomalies over the mid-Pacific and a cold phase over the northeastern Pacific (Namias 1982).

The 1938 MW summer drought was relatively short-term but was comparable to the 1930s drought in terms of severity and spatial extent (Schubert et al. 2004b), with the worst agriculture losses on record in the US of US$39 billion, mainly because its location and timing coincided with the major crop growing region and season of the US (Sheffield and Wood 2011). Below average precipitation initiated drought over the MW during the early summer of 1988, and an anomalous high pressure system maintained the drought through the summer, contributing to high surface temperature and high evaporative demand (Sheffield and Wood 2011). The La Niña phase of ENSO, the cold phase of the Pacific Decadal Oscillation (PDO) and the warm phase of the Atlantic Multi-decadal Oscillation (AMO), conspired to form a favorable environment for the drought (McCabe et al. 2004).

The latest drought to hit the MW region, in 2012, was driven by the least summer precipitation for the last three decades, with over 70% of the CONUS experiencing below-normal summer precipitation (figure 1), which is more severe than the 1988 drought (not shown). Total agricultural losses were over US$20 billion based on crop insurance losses (Bootton 2012). In the summer of 2012, the north Pacific and north Atlantic were in a cold and warm phase, respectively, which was also observed in the 1930s and 1988 droughts. The tropical Pacific was, however, in a weak warm phase, differing from the strong cool phase in the 1930s and 1988. The role of these anomalous SST conditions was therefore ambiguous in weakening of CONUS precipitation since ENSO was out of phase with the PDO (Hu and Huang 2009) and AMO (Hu and Feng 2012) during 2012. Two recent studies suggest that the 2012 drought was driven by atmospheric noise. A modeling study (Kumar et al. 2013) found that atmospheric variability alone can reproduce the 2012 MW drought, and Hoerling et al. (2013) found that the drought was caused by a reduction in atmospheric moisture transported from the Gulf of Mexico due to mid-troposphere anti-cyclonic patterns over the Atlantic.

Recently, the National Multi-Model Ensemble (NMME) project (Kirtman et al. 2013), a multi-institutional collaborative seasonal forecasting system, was developed with the goal of improving seasonal prediction of extreme events over the CONUS and globally. Phase I of the project includes seven seasonal forecast models (Kirtman et al. 2013). Here we examine forecasts from six of the models: NCEP-CFSv2 (CFSv2), COLA-RSMAS-CCSM3 (COLA), GFDL-CM2.1 (GFDL), IRI-ECHAM4.5-AnomalyCoupled (IRI-AC), IRI-ECHAM4.5-DirectedCoupled (IRI-DC), and NASA-GMAO (NASA). In 2012, all the NMME models predicted negative precipitation anomalies over the MW. They also predicted a cold phase of the eastern Pacific and a warm phase of the North Atlantic, which are associated with more frequent drought occurrence over the CONUS (McCabe et al. 2004), and a cold phase of ENSO during the antecedent winter, which is also a favorable condition for meteorological drought in the central US during the summer (Wang et al. 2007). However, the magnitude and spatial distribution of the predicted anomalies over the CONUS varied widely (figure 1). The most skillful model was the Geophysical Fluid Dynamics Laboratory (GFDL) model, which forecasted the drought with comparable magnitude to the observational data, and showed the most skillful prediction for SSTs. This raises the following questions: (1) Does the apparent skill for SSTs translate to other historical drought events? In other words, what is the level of potential predictability? (2) How well do the forecast models represent the observed association of conditions in the north Pacific and Atlantic with MW precipitation (actual predictability)? (3) Are the role of the Pacific and Atlantic in driving MW summer drought robust over time?

To answer these questions, we conduct a singular value decomposition (SVD) analysis of the cross-covariance matrices between northern hemisphere summertime global SSTs and CONUS precipitation for 1982–2012. We do this using observational data and the six NMME climate forecast models to assess and compare Pacific and Atlantic SSTs teleconnections with CONUS precipitation. We focus on meteorological drought, which is a precursor to agricultural drought and is defined as a precipitation deficit over a given time period. We also carry out an SVD analysis for earlier periods (1922–1951, and 1952–1981) to examine whether the observed teleconnections are stationary. This is because the influence of the Pacific and Atlantic oceans on CONUS precipitation has been documented to have changed in early 1950s (McCabe and Dettinger 1999, McCabe et al. 2004) and there is evidence that the characteristics of ENSO have changed since the 1970s with less frequent but stronger events (An and Jin 2000), which could have modulated teleconnections with CONUS hydroclimate.
2. Data and methods

Observed precipitation and SST data are taken from the Climate Prediction Center (CPC) Unified Gauge-Based Analysis (0.5° resolution, 1948–present; Chen et al. 2008) and the Extended Reconstructed Sea Surface Temperature v3b (ERSST v3b; Smith et al. 2008) (2.0°, 1854–present), respectively. We focus on northern hemisphere summer averages (JJA) since
this is coincident with the growing season and high water resources demand, and focus on 1982–2012. Furthermore, the summertime is characterized by poor predictive skill (Wang et al. 2007). The ensemble means of the first three month (JJA) precipitation forecast initialized on different dates depending on the model (5th day of every June: CFSv2 and NASA-GMAO; 1st day of June: COLA, GFDL, IRI-AC, and IRI-DC) are used because the zero month lead time forecast has the best seasonal skill (Zhang et al. 2011).

We perform an SVD analysis (Wallace et al. 1992), (Bretherton et al. 1992) of the cross-covariance matrix between the CPC precipitation and ERSST SSTs at the 4369 (CONUS) and 10855 (global oceans) grid points for the period 1982–2012. The number of grid points for the six NMME forecast models are 1456 for the CONUS precipitation but vary for the SSTs from 33891 (COLA) to 65341 (IRI-AC and IRI-DC) due to different spatial coverage. Before the SVD analysis, linear trends, reflecting global warming, in the SST and precipitation data are removed. From the SVD analysis, we compute the loadings and the scores for each mode for the left and right fields (sea surface temperature and precipitation, respectively). The loadings of the SVD modes from the SST (SVD SST) and the precipitation (SVD PREC) fields are computed from the left and right eigenvectors, respectively, and represent spatial patterns for the corresponding mode. The scores of the SVD modes are computed by projecting the data on to the loadings of the corresponding field and often are used to define a climate index (e.g. PDO index). One of the benefits from the SVD is that the order of the SVD modes is based on the strength of their covariability, that is, the first mode is the strongest and the last mode, the weakest. Here, we produce the scores of the SVD modes from SSTs (SVD SST modes) and precipitation (SVD PREC modes). We also construct homogeneous and heterogeneous correlation maps (Wallace et al. 1992) for the SVD SST mode, which are maps of the temporal correlation between the scores of the SVD SST mode and gridded global SSTs (homogeneous correlation) and between the scores of the SVD SST mode and gridded CONUS precipitation (heterogeneous correlation). The statistical significance of the correlation is calculated at a significance level of 0.1. These maps are useful to examine the association of global SSTs with CONUS precipitation.

We explore the multi-decadal variations in the strength of coupling of global SSTs with CONUS summer precipitation using another observational dataset: the University of Washington Extended (UW-Extended) dataset (0.5°, 1915–2008; Andreadis and Lettenmaier 2006), because the CPC dataset starts in 1979. It should be noted that the ERSSTv3b SST data in the first half of the 20th century have larger uncertainties due to inhomogeneities and sparse sampling, which may affect the results. This dataset has been shown to be consistent with other similar SST datasets (Tasunaka and Hanawa 2011) for ENSO after 1880 and but only after 1950 for the PDO. Over the MW region, the UW-Extended dataset is consistent with the CPC dataset for their overlap period (1982–2008) with temporal correlation coefficient >0.9. The SVD analysis is carried out separately for three different periods: 1922–1951, 1952–1981, and 1982–2008.

### 3. Results

#### 3.1. Covariability between global SSTs and JJA CONUS precipitation in observations and NMME models

The covariability explained by the three leading SVD modes between the observed global SSTs and CONUS precipitation for 1982–2012 as represented by the squared covariance fraction (SCF) values are 12%, 11.6%, and 7%, respectively (table 1). For the models, the first SVD mode, S1, explains 20–32% of the covariability (SCF), which is twice to three times as high as for the observational data.

|       | OBS CPC | OBS CFSv2 | OBS COLA | OBS GFDL | OBS IRI-AC | OBS IRI-DC | OBS NASA |
|-------|---------|-----------|----------|----------|------------|------------|----------|
| SCFs (%) | 11.9 | 20.4 | 25.9 | 32.1 | 30.4 | 32.7 | 26.8 |
| Temporal correlation | 0.79 | 0.85 | 0.79 | 0.76 | 0.81 | 0.88 | 0.83 |

For the models, the first SVD mode, S1, explains 20–32% of the covariability (SCF), which is twice to three times as high as for the observational data.

The observational data indicate that the first SVD SST mode homogeneous correlation map shows a positive correlation with tropical Pacific SSTs and a negative correlation with north central Pacific SSTs, which is well-known as the pan-Pacific ENSO-like pattern (figure 2). This pattern is related to interannual (e.g., ENSO) and decadal (e.g. PDO) variability (Schubert et al. 2009). The pan-Pacific ENSO-like SST mode is also identified in the data for the CFSv2, GFDL-CM2.1 and NASA-GMAO models for the first mode, and the COLA, IRI-AC, and IRI-DC models for the second mode.

The heterogeneous correlation map of the pan-Pacific ENSO-like SVD SST mode from the observational data shows a positively weak correlation with precipitation over the southern and northwestern regions of the CONUS (right, first row of figure 2). This suggests that a warm phase of ENSO and the cold phase of PDO are linked to more precipitation over some parts of CONUS, although these teleconnections are generally weak for this period, 1982–2012. However, the correlation maps for the NMME models indicate either

[Table 1. Squared covariance fractions (SCFs) and temporal correlation coefficients of the three leading SVD modes from global sea surface temperatures and contiguous United States precipitation from observational data and six climate forecast NMME models. Bold represents the pan-Pacific ENSO-like SVD modes from observational data and climate forecast models.]
Figure 2. Homogeneous (left) and heterogeneous (right) correlation maps of the pan-Pacific ENSO-like SVD SST mode for global SSTs and CONUS precipitation during 1982–2012. Those correlation maps are represented the areas with p-value less than 0.1.

much stronger or much weaker teleconnections than those in the observations with model-specific spatial patterns, while all of them are of the correct sign. The CFSv2 pan-Pacific ENSO-like SVD SST mode is strongly positively correlated with its forecasted precipitation over the midwestern and central US. The pan-Pacific ENSO-like mode from COLA is weakly associated with variations in CONUS precipitation since the mode explains only 8% of SCF (table 1). For the GFDL model, the pan-Pacific ENSO-like mode plays a major role in interannual variations of summer precipitation over the MW explaining 37% of the variances (the regional average of the square of temporal correlation coefficients from the heterogeneous map). The IRI-AC and IRI-DC pan-Pacific ENSO-like SST modes are positively correlated with their respective forecasted precipitation across the CONUS. Finally, the NASA-GMAO model pan-Pacific ENSO-like SST mode relates to precipitation over the central US and from the southeast through to the northwest. For the MW region, the pan-Pacific ENSO-like SVD mode from observations explains only 4% of summer precipitation variances for 1982–2012 while the same mode from the climate models explain 19% (CFSv2), 31% (COLA), 37% (GFDL), 11% (IRI-AC), 19% (IRI-DC) and 17% (NASA) of their forecasted summer precipitation variances.

We also carried out an SVD analysis for spring (see supplementary figure 1 available at stacks.iop.org/ERL/9/034005).
To assess actual predictability for MW drought, we plot a Taylor diagram for observed and forecasted MW precipitation anomalies for 1982–2012 (figure 3(a)). The standard deviations are derived from observed and forecasted MW summertime precipitation anomalies. Overall, the climate forecast models show generally poor predictive skill for MW summer precipitation, with the best performing model, NASA-GMAO, having a temporal correlation coefficient slightly over 0.5. All models but one underestimate the interannual variability of observed MW precipitation (standard deviation of observed precipitation is 0.6 mm d\(^{-1}\)) by 30–60%. In particular, the variability from the IRI-AC and IRI-DC models is only 30% of the observed value. Only the GFDL overestimates the interannual variability of MW precipitation by about 30% (standard deviation = 0.8 mm d\(^{-1}\)).

To understand the importance of pan-Pacific conditions in generating MW summer precipitation, we plot another Taylor diagram from the time series of MW precipitation and the scores of the pan-Pacific ENSO-like SVD PREC mode from the observational and model data (figure 3(b)). The scores are derived by projecting the MW precipitation anomalies onto the mode. The scores indicate strong temporal correlation coefficients (0.76–0.85) but not necessarily in the same order as the SVD mode number (table 1), which is not guaranteed using SVD. The standard deviations are used in the same way as for figure 3(a) since here we use normalized time series of the loadings of the pan-Pacific ENSO-like SVD PREC mode. Some climate models overestimate the role of this mode in producing MW summer precipitation while other models show comparable strength of the coupling between their forecasted MW summer precipitation and the pan-Pacific ENSO-like SVD PREC mode. CFSv2 and GFDL show strong coupling with temporal correlation coefficients greater than 0.8. These strong temporal and spatial couplings might explain why the GFDL model shows stronger precipitation anomalies over the MW region than other models depending on the strength of the pan-Pacific ENSO-like SVD PREC mode, regardless of the coincidence with actual extreme events over the CONUS over the last three decades. The 1983 and 1988 drought events are good examples of this. CFSv2 and GFDL fail to forecast the 1983 drought showing a strong positive signal in the loadings of the pan-Pacific ENSO-like SVD PREC mode, while they succeed to predict the 1988 drought by showing the opposite signal (not shown). In fact, the cause of 1983 drought has been
Figure 4. Same as figure 2 except for three different periods: (a) 1922–1951, (b) 1952–1981, and (c) 1982–2008. Those correlation maps are represented the areas with p-value less than 0.1.

explained by the uniqueness of a combination between a very strong negative phase over the north Pacific and a warm phase over the tropical Pacific (Ting and Wang 1997).

3.3. Changing strength of pan-Pacific teleconnections (1915–2008)

The role of pan-Pacific SSTs in modulating CONUS precipitation has been variable over time. For example, McCabe and Dettinger (1999) found that western US precipitation was weakly related to ENSO during 1920–1950 compared to 1950–80. Wang et al (2007) demonstrated that the La Niña phase of ENSO in recent years forces a continental-scale persistent high pressure anomaly during the summer which is related to central US drought. Also, SSTs over the north Pacific contribute to interannual summer precipitation over the Central US with a comparable magnitude with SSTs over the tropical Pacific (Ting and Wang 1997). The North Atlantic driven atmospheric circulation is modified by ENSO (Hu and Feng 2012). Over the recent decades, the characteristics of ENSO have changed (An and Jin 2000), the phase of PDO has shifted to the negative phase, and a warm phase of AMO has been persistent. The findings from these previous studies and the current study raise the following question: how have pan-Pacific teleconnections with MW summer precipitation changed over decadal timescale and has this impacted the skill of the NMME models?

To answer this question, we repeat the SVD analysis for three different periods, 1922–1951, 1952–1981, and 1982–2008 (figures 4(a), (b), and (c), respectively), between the ERSST v3b SSTs and the UW-Extended precipitation dataset. Again, the datasets are detrended over each period. During 1922–1951, the first SVD mode relates to regions of the tropical and north Pacific (top, figure 4(a)) and to MW precipitation (bottom, figure 4(a)). The sign of the coupling is different to that from the SVD analysis for 1982–2012 (top, figure 2), indicating that the La Niña state of the tropical Pacific and the cold phase of PDO are related to above-normal MW summer precipitation. During 1952–1981, the homogeneous correlation map of the first SVD mode from the SST data shows the opposite sign to 1922–1951, while it is still related to MW summer precipitation. This suggests that the sign of pan-Pacific ENSO-like teleconnections changed in the early 1950s (top, figure 4(b)). During 1982–2008, the pan-Pacific ENSO-like pattern is the first SVD SST mode (top, figure 4(c)), however its influence is only on northwestern US summertime precipitation. The sign of the homogeneous and heterogeneous maps from the first SVD SST mode are consistent with the sign of the SVD analysis for 1982–2012. These results reaffirm that the role of global SSTs in inducing summer precipitation over the CONUS has varied with different coupled spatial patterns over the last 100 years (McCabe and Dettinger 1999, MacCabe et al 2003, Hu and Huang 2009 and Hu and Feng 2012).

4. Conclusions

The observational data indicate that there is a great deal of variability in the mechanisms for reductions in MW summer precipitation. Previous studies have shown that La Niña is the leading driver of drought in the MW, especially in the winter to spring, but the strength of this teleconnection in the summer has weakened and the precipitation footprint has shifted over the past decades. However, most of the NMME climate models underestimate the MW summer precipitation variances, leading to predictions of relatively normal precipitation. The GFDL model stands out as having strong coupling between SSTs and precipitation, and thus overestimates MW summer precipitation variances, and generally predicts either extreme dry or wet anomalies more often than those from the observational data (e.g. droughts of the severity of 2012 are predicted six times during 1982–2012). Therefore, the models are limited in their ability to predict MW precipitation
anomalies even at zero month lead time, despite their skill in predicting pan-Pacific SST variability at seasonal or longer time scales. Because Pacific SSTs did not play a major role in the 2012 drought (Kumar et al 2013, Hoerling et al 2013), and droughts in general over the last 30 years, the skillful prediction of Pacific SSTs may actually hinder the prediction of MW summer precipitation due to the underestimation of the variances in the most models and overly strong coupling in two models. The prediction of the 2012 drought by the NMME models was in fact fortuitous due to the erroneous coupling with pan-Pacific SSTs. This study shows that the role of pan-Pacific ENSO-like variability on CONUS precipitation has changed over the last century with teleconnections weakening over the past 30 years. The attribution of these changes is still unclear: whether it derives from either multi-decadal variation of SSTs or changes in large-scale circulation and SSTs forced by anthropogenic impacts. Since the late 1970s, ENSO has been modulated by the interdecadal climate shift (Wang 1995). However, global warming has contributed to the modulation of ENSO due to the ‘delayed response’ from deeper ocean temperatures in the tropical eastern Pacific (An et al 2008). Also, there has been a shift to more frequent central Pacific type ENSO events in recent years which have contributed to the weakening (strengthening) the impact on the MW (southwestern) US precipitation at seasonal scale (Mo 2010). Due to poor understanding of the attribution of these changes in ENSO characteristics and their impact on precipitation over the CONUS, seasonal forecast skill based on SSTs remains limited.

As mentioned above, forcing from the Pacific does not matter for the 2012 drought and for most previous droughts over the past 30 years. However, SSTs are important from the model perspective and will sometimes fortuitously give rise to skillful predictions. It should be noted, however, that droughts before the 1980s do show a connection with Pacific SSTs from observations (figure 4), suggesting that model skill may be improved before the 1980s. Confirmation of this would require hindcasts back to the early part of the 20th century. Addressing these issues is critical for improving the current state of predictive skill for seasonal drought not only for the MW, but globally as well.

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