8-9-2019

Recent Ogallala Aquifer Region Drought Conditions as Observed by Terrestrial Water Storage Anomalies from GRACE

Yongjun Zhang
Kansas Climate Center

Xiaomao Lin
Kansas State University, xlin@ksu.edu

Prasanna Gowda
Kansas State University

David Brown
Kansas State University

Zachary Zambreski
Kansas Climate Center

See next page for additional authors

Zhang, Yongjun; Lin, Xiaomao; Gowda, Prasanna; Brown, David; Zambreski, Zachary; and Kutikoff, Seth, "Recent Ogallala Aquifer Region Drought Conditions as Observed by Terrestrial Water Storage Anomalies from GRACE" (2019). *Publications from USDA-ARS / UNL Faculty*. 2191.
https://digitalcommons.unl.edu/usdaarsfacpub/2191

Authors

Yongjun Zhang, Xiaomao Lin, Prasanna Gowda, David Brown, Zachary Zambreski, and Seth Kutikoff

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

AMERICAN WATER RESOURCES ASSOCIATION

Recent Ogallala Aquifer Region Drought Conditions as Observed by Terrestrial Water Storage Anomalies from GRACE

Yongjun Zhang, Xiaomao Lin, Prasanna Gowda, David Brown, Zachary Zambreski, and Seth Kutikoff

Research Impact Statement: The value of GRACE is not just in the diagnosis of drought events but also in the improvement of the predictive power of remote signals, then improving water resource management on a regional scale.

ABSTRACT: Recent severe drought events have occurred over the Ogallala Aquifer region (OAR) during the period 2011–2015, creating significant impacts on water resources and their use in regional environmental and economic systems. The changes in terrestrial water storage (TWS), as indicated by the Gravity Recovery and Climate Experiment (GRACE), reveals a detailed picture of the temporal and spatial evolution of drought events. The observations by GRACE indicate the worst drought conditions occurred in September 2012, with an average TWS deficit of ~8 cm in the northern OAR and ~11 cm in the southern OAR, consistent with precipitation data from the Global Precipitation Climatology Project. Comparing changes in TWS with precipitation shows the TWS changes can be predominantly attributable to variations in precipitation. Power spectrum and squared wavelet coherence analysis indicate a significant correlation between TWS change and the El Nino-Southern Oscillation, and the influence of equatorial Pacific sea surface temperatures on TWS change is much stronger in the southern OAR than the northern OAR. The results of this study illustrate the value of GRACE in not just the diagnosis of significant drought events, but also in possibly improving the predictive power of remote signals that are impacted by nonregional climatic events (El Nino), ultimately leading to improved water resource management applications on a regional scale. ***Editor's note****: This paper is part of the featured series on Optimizing Ogallala Aquifer Water Use to Sustain Food Systems. See the February 2019 issue for the introduction and background to the series.*

(KEYWORDS: drought; precipitation; time series analysis; terrestrial water storage (TWS); Ogallala Aquifer region (OAR); GRACE.)

INTRODUCTION

The Ogallala Aquifer is one of the world's largest unconfined freshwater aquifers supporting irrigated agriculture in the central United States (U.S.). With a total area of approximately 450,000 km^2 and covering parts of eight states (South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas; see Figure 1), the Ogallala Aquifer region (OAR) is dominated by agriculture (41%) and rangeland (56%) and is known as one of the major agricultural production regions of the world. Over 175,000 km^2 of cropland (Homer et al. 2007; McGuire 2009, 2014) produce more than $35 billion in crops each year (Basso et al. 2013).

The climate of the OAR is mostly semiarid, with a distinct east-west gradient in average annual

Paper No. JAWRA-18-0154-P of the *Journal of the American Water Resources Association* (JAWRA). Received November 13, 2018; accepted August 9, 2019.

Kansas Climate Center (Zhang, Lin, Zambreski, Kutikoff), Kansas State University, Manhattan, Kansas, USA; and Grazinglands Research Laboratory (Gowda, Brown), USDA Agricultural Research Service, El Reno, Oklahoma, USA (Correspondence to Lin: xlin@ksu.edu).

Citation: Zhang, Y., X. Lin, P. Gowda, D. Brown, Z. Zambreski, and S. Kutikoff. 2019. "Recent Ogallala Aquifer Region Drought Conditions as Observed by Terrestrial Water Storage Anomalies from GRACE." *Journal of the American Water Resources Association* 1–12. https://doi.org/10.1111/1752-1688.12798.

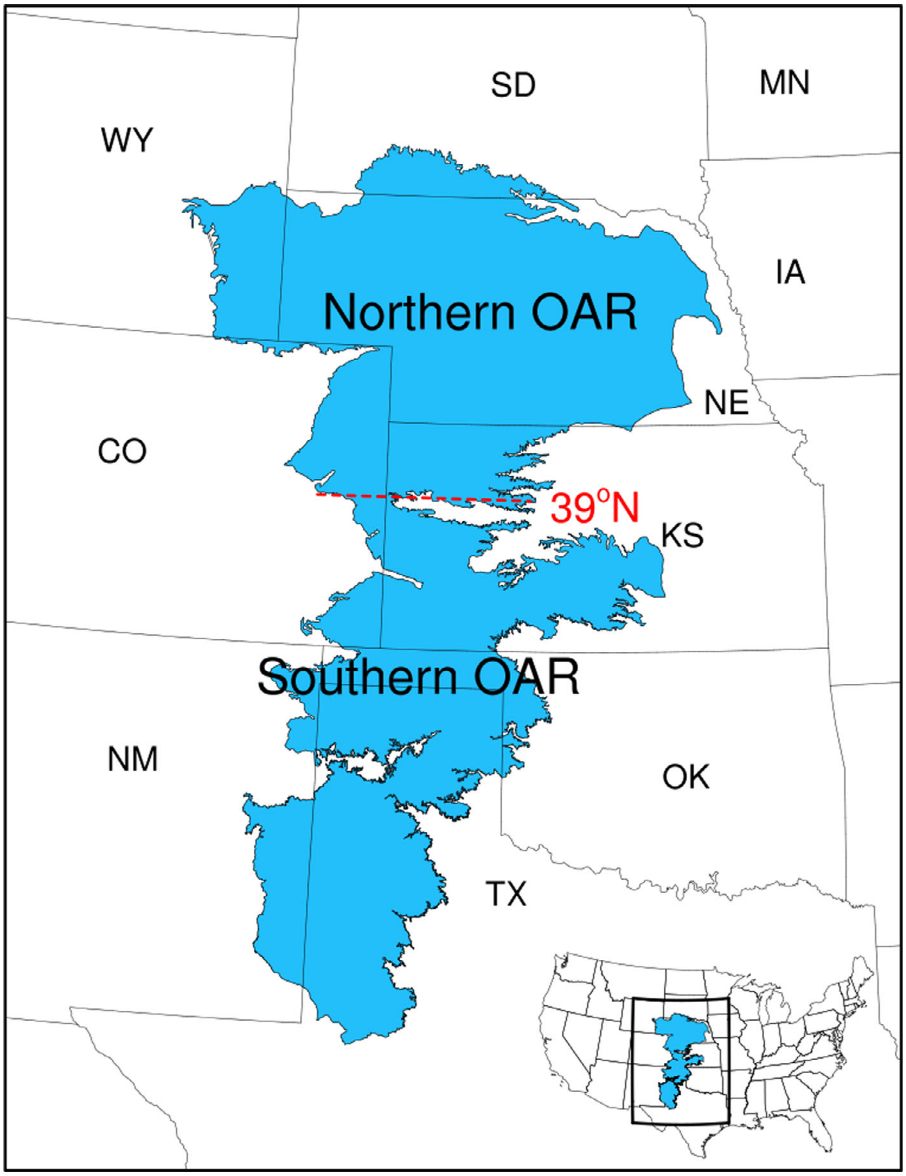

FIGURE 1. Map of the Ogallala Aquifer region (OAR) in the United States. The dashed red line indicates the division between the northern and southern OAR. WY, Wyoming; SD, South Dakota; MN, Minnesota; IA, Iowa; CO, Colorado; NE, Nebraska; KS, Kansas; NM, New Mexico; OK, Oklahoma; TX, Texas.

precipitation ranging from 400 mm in the west to 800 mm in the east with a clear south-north slope in mean annual pan evaporation from 2,700 mm in the south to 1,500 mm in the north (Gutentag et al. 1984; Shafer et al. 2014). With low precipitation and high pan evaporation, agriculture in the OAR is heavily dependent on irrigation with more than 95% of the water extracted from the Ogallala Aquifer used for crop production. In addition, the OAR is also the principal source of water for 1.9 million people (USGS 2006). Due to the large demand for agricultural and drinking water supplies, groundwater levels in the region have declined by an average of 3.9 m over the entire aquifer area since predevelopment (1950s) with some areas exhibiting declines of up to 71 m (McGuire 2009). Stress on the aquifer is projected to increase in the future, with less summer rainfall, longer rain-free periods, and drier summers expected (Shafer et al. 2014). Hence, accurate monitoring and quantification of water resources in the OAR, both now and in the future, are essential for sustaining agricultural production, ecosystem health, and community well-being.

Terrestrial water storage (TWS), a major component of the global water cycle, is determined by all physical phases of water stored above and below the surface of the Earth. This includes soil moisture, snow and ice, canopy water storage, and groundwater, which strongly influences water, energy, and biogeochemical fluxes and thereby plays a major role in the Earth's climate system (Famiglietti 2004; Niu and Yang 2006). Changes in TWS not only reflect variations in fresh water resources, but also serve as an indicator of Earth's climate system variability. However, traditional in situ methods of monitoring precipitation and soil moisture have generally been inadequate to evaluate the variations of TWS across spatial scales (Dai 2011; Famiglietti and Rodell 2013). Since 2002, the Gravity Recovery and Climate Experiment (GRACE) consisting of two satellites has provided monthly measurements of Earth's gravity field which can be used to retrieve approximate monthly changes in TWS (Rodell and Famiglietti 2002; Tapley et al. 2004; Famiglietti and Rodell 2013; Thomas et al. 2014). A number of studies have shown that GRACE data can capture natural water storage variations very well compared to observations. As a result, changes in TWS retrieved from GRACE can reflect the sum of accumulated precipitation, evapotranspiration, and surface and subsurface runoff providing a reliable measure of abnormal climate conditions such as droughts and floods. Examples of such applications include Yeh et al. (2006) and Swenson and Wahr (2006), who concluded that the GRACE-based method of groundwater storage change performed reasonably well in Illinois and Oklahoma. Rodell et al. (2007) used GRACE to assess TWS for the Mississippi River basin and its sub-basins, and Long et al. (2013) confirmed the 2011 severe drought event in Texas using TWS data retrieved from GRACE. A recent study (Vishwakarma et al. 2018) indicates that there is about 2 cm error in terms of equivalent water height at a small size catchment (~63,000 km^2) when retrieving TWS from GRACE, and this error could be decreased accordingly as the catchment size increases. Considering the large size of OAR (~450,000 km^2), the TWS changes thus can be reconstructed from GRACE, which might serve as a drought monitoring tool in water-limited OAR.

Validation of the accuracy of GRACE-based analyses of TWS can be obtained via comparison to the National Climate Assessment — Land Data Assimilation System (NCALDAS) which generates high-quality and high-resolution terrestrial water and energy balance stores from best-available observations and model outputs (Xia et al. 2012; Kumar et al. 2016, 2017). As an integrated terrestrial water analysis system, NCALDAS can also be used to represent changes in TWS. A recent example of the application of NCALDAS is Kumar et al. (2016), who presented a time series of daily and monthly averaged TWS over the Northeast, Midwest, Great Plains, and Southwest regions of the continental U.S. based on NCALDAS data.

For the OAR, previous studies have mainly focused on analyses of groundwater storage from GRACE in the U.S. High Plains (Strassberg et al. 2007, 2009; Scanlon et al. 2012; Crosbie et al. 2013), whereas less attention has been paid both to the more southern portions of the OAR and to the temporal variability in TWS and its usefulness as an estimator of drought. In this paper, we examine changes in TWS from GRACE satellites for the OAR, with the aim of improving our understanding of recent extreme drought events in the OAR. This work is based largely on Houborg et al. (2012), who showed that GRACE data can be used to indicate drought conditions more accurately and objectively compared to traditional drought monitors that do not account for soil moisture and groundwater conditions. The specific objectives of this paper are (1) to use GRACE data to estimate TWS variations for the OAR for the period 2003–2015, (2) to compare GRACE-based estimations of TWS with NCALDAS data, and (3) to examine recent severe drought events in the OAR as well as their underlying climatological causes.

DATA AND METHODS

Evaluating Changes in TWS from GRACE

We used GRACE release 05 (RL05) monthly data, provided by the Center for Space Research, University of Texas at Austin, in the form of spherical harmonic Stokes coefficients up to degree and order 60. Several tests (Huang et al. 2013; Zhang et al. 2015; Nie et al. 2016) proved that RL05 is more accurate than previously released GRACE products for the analysis of TWS. Monthly GRACE data use spans over 16 years, from April 2002 through March 2017. For this study, a total of 145 monthly (approximately) TWS measurements taken between January 2003 and December 2015 are included in the raw datasets. This excludes missing data from the following months: June 2003, January 2011, June 2011, May 2012, October 2012, March 2013, August 2013, September 2013, February 2014, December 2014, and June 2015. These missing data were interpolated using a bilinear interpolation method (Zhang et al. 2015). Anomalous TWS fields were obtained by subtracting out the multi-year mean field (based on an average of 2004–2009).

Evaluating Changes in TWS from NCALDAS

We used NCALDAS to retrieve TWS variations over the OAR during the period 2003–2015 (Kumar et al. 2006, 2014; Xia et al. 2012; Liu et al. 2015). NCALDAS forcing data are derived from the North American Regional Reanalysis (NARR) which features a 32-km spatial resolution and a three-hour temporal resolution (Xia et al. 2012; Kumar et al. 2016). NARR-based variables used in NCALDAS include 2-m air temperature, 2-m specific humidity, 10-m wind speed, surface pressure, precipitation, incoming solar radiation, and incoming longwave radiation. For this study, the model outputs produced by the NCALDAS-Noah land surface scheme were used. These data are available from 1979 to present at daily intervals and monthly average soil moisture (2-m column depth) and snow water equivalent are computed at each grid point for this period. The soil moisture profile includes four layers at 10, 40, 100, and 200 cm from the soil surface downward. Because groundwater was not modeled by NCALDAS, modeled TWS used in this study is defined as the sum of soil moisture content and snow water equivalent (Chen et al. 2009, 2010). The NCALDAS data are available at https://ldas.gsfc.nasa.gov/NCA-LDAS/.

GPCP Precipitation Data

The Global Precipitation Climatology Project (GPCP) is an effort of the World Climate Research Program and its key Global Energy and Water Cycle Experiment to produce community analyses of global precipitation. GPCP provides a long time series of monthly and sub-monthly resolution precipitation data on a global scale. GPCP Version-2 monthly precipitation with a 2.5 × 2.5 degree spatial resolution are utilized in this study; these data are fully independent of the precipitation data from NCALDAS-Noah (Adler et al. 2003, 2012, 2017; Huffman et al. 2009). The spatial resolution in GPCP precipitation is relatively coarse, but this dataset is high-quality and the comparable spatial resolutions as the GRACE data. GPCP precipitation data are available at https://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html.

El Nino-Southern Oscillation

The El Nino-Southern Oscillation (ENSO), an interannual ocean-atmosphere oscillation in the tropical Pacific Ocean, is recognized to have a significant impact on the climate of the Great Plains. Previous studies have shown that ENSO influenced the location of the Great Plains low-level jet (GPLLJ) (Cook et al. 2008; Weaver et al. 2009; Wang and Cheng 2009; Barandiaran et al. 2013), consequently affecting precipitation (e.g., Hu and Feng 2001; Yang et al. 2007; Ruiz-Barradas and Nigam 2010). Phillips et al. (2012) showed that TWS, as one of the key factors in the hydrologic balance equation, was related to ENSO. Therefore, the relationship between GRACE TWS and an ENSO index may be indicative of the physical understanding of the occurrence of drought events in the OAR. In this study, the Nino3.4 index, derived from normalized sea surface temperatures (SST) in the tropical Pacific region (5°N–5°S, 170°–20°W), was used as a representative measure of ENSO (Figure 6c). We applied power spectrum analysis to a time series of Nino SST 3.4 and GRACE TWS anomalies to detect their predominant timescales. Before calculating these power spectra, all raw time series data were detrended.

RESULTS

GRACE and Model TWS Estimates

A previous study (Barandiaran et al. 2013) showed that seasonal precipitation in the northern Plains peaks in summer, where the southern Plains receives more rain in late spring, consistent with increased strength and extent of the GPLLJ and a northward shift of the upper-level jet stream (Wang and Cheng 2009). Precipitation during the months of April-June has decreased substantially in the southern Plains, whereas increasing in the northern Plains since 1979 suggesting that a north-south boundary of ~39°N (figure 1a in Barandiaran et al. 2013) delineates different precipitation patterns, or water cycles. Therefore, our results and discussion will focus on two subregions, the northern OAR and southern OAR (Figure 1).

First the TWS time series from GRACE and NCALDAS over the OAR during the period of 2003–2015 was examined (Figure 2). Similar to the findings of Houborg et al. (2012), there is an obvious seasonal pattern in TWS with spring-summer peaks and fall troughs which is also found in many other basins in the U.S. (Rodell et al. 2007; Famiglietti et al. 2011). For the entire period of study, GRACE and NCALDAS showed good temporal covariance of TWS. Figure 2a shows that GRACE observations agreed well with NCALDAS in terms of TWS anomalies before 2010 over the northern OAR; however, GRACE observations indicated much larger TWS seasonal variations after 2010 than NCALDAS did. In addition, NCALDAS systematically had a lower TWS after 2010 over this region. Based on the TWS changes from NCALDAS, the northern OAR experienced a long-term drought event beginning in 2010 which peaked in 2012. The GRACE data, in contrast, indicated the northern OAR drought did not begin until 2012, then quickly recovered. One possible reason for the large TWS differences between GRACE and NCALDAS is that the TWS estimation from NCALDAS is only balanced by soil moisture and surface snow and ice, whereas surface water and groundwater also account for a portion of the TWS measurement in GRACE (Cai et al. 2014). For this particular timing (after 2010) and region (northern OAR), the surface water and groundwater played a more important relative role on TWS anomalies than in prior years.

As shown in Figure 2b, both GRACE measurements and NCALDAS estimates show a similar annual cycle over the southern OAR for the period 2003–2015, with a coefficient of determination as high as 0.78 at the 99% confidence level. Both the GRACE and NCALDAS time series indicated an abrupt decrease in TWS in 2010, which remained low until 2015 indicating a reasonably long-term drought in the south ORA during 2011–2015. Prior to the onset of drought conditions in 2011, there was no significant change in TWS, however, beginning with the drought in 2011, a steep decline in TWS of 3.8 mm/yr occurred between May 2011 and July 2013. The lowest TWS anomaly over the south ORA was found in August (NCALDAS) and September (GRACE) 2012 (−9.36 and −11.45 cm, respectively) corresponding to the 2012 extreme drought. This result is consistent with previous studies (Houborg et al. 2012; Rippey 2015) which indicate GRACE and NCALDAS TWS anomaly signals over the southern OAR provide a good metric of drought conditions as observed by the U.S. Drought Monitor (https://droughtmonitor.unl.edu/Maps/MapArchive.aspx).

GRACE showed much larger TWS in 2011 over the northern OAR than the southern OAR, indicating that the southern OAR suffered an extreme one-year drought event, whereas the northern OAR experienced relatively wet conditions. Although both subregions experienced severe drought in 2012 and 2013, quantitative measurement of drought conditions indicated that the southern OAR drought was much more severe than the northern OAR drought. After 2013, the drought ended and conditions returned to near-normal status in the northern OAR, as the GRACE data indicated (Figure 2a), but in the southern OAR, drought conditions continued through 2015.

In order to examine the spatial and temporal evolution of drought events in the OAR, the yearly average GRACE TWS changes for 2003 through 2015 were computed (Figure 3). Figure 3 clearly illustrates the evolution of drought conditions during the 13-year period of analysis. The northern OAR varied from slight dryness (2003–2007) to wetness (2008–2011), and then to severe drought (2012–2013). After that, conditions returned to near-normal status. In the southern OAR, wetness (2004, 2005, and 2007), slight dryness (2008–2010), and then drought (2011–

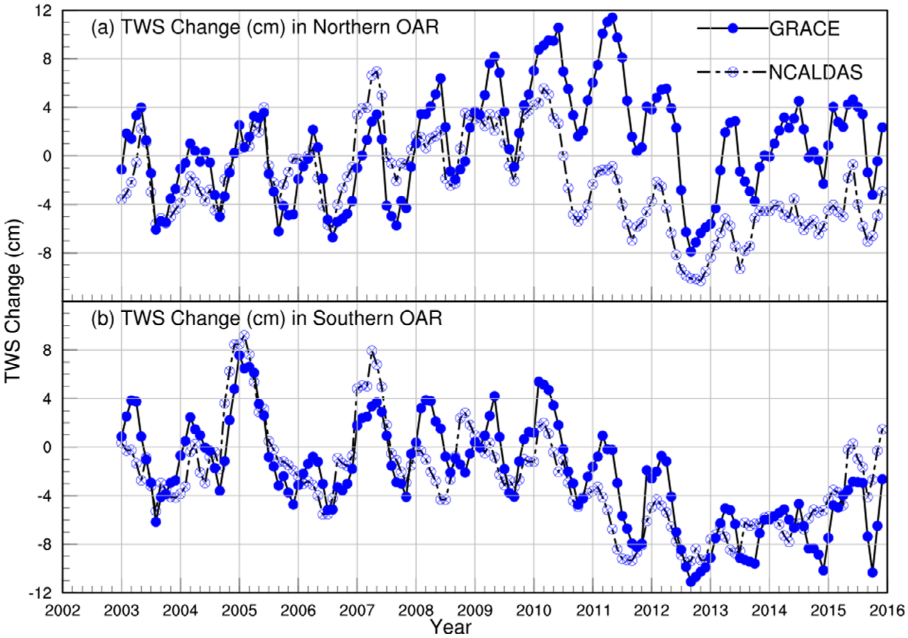

FIGURE 2. Comparison of terrestrial water storage (TWS) change in the OAR from Gravity Recovery and Climate Experiment (GRACE) and National Climate Assessment — Land Data Assimilation System (NCALDAS). (a) TWS change (cm) in the northern OAR, and (b) TWS change (cm) in the southern OAR.

2015) were observed. Overall, this summary concurs with recent surface observation-based studies (Damberg and AghaKouchak 2014; Yuan and Quiring 2014; Zhao et al. 2017), satellite MODIS-observed studies (Zhou et al. 2017), and modeling studies (Feng et al. 2017).

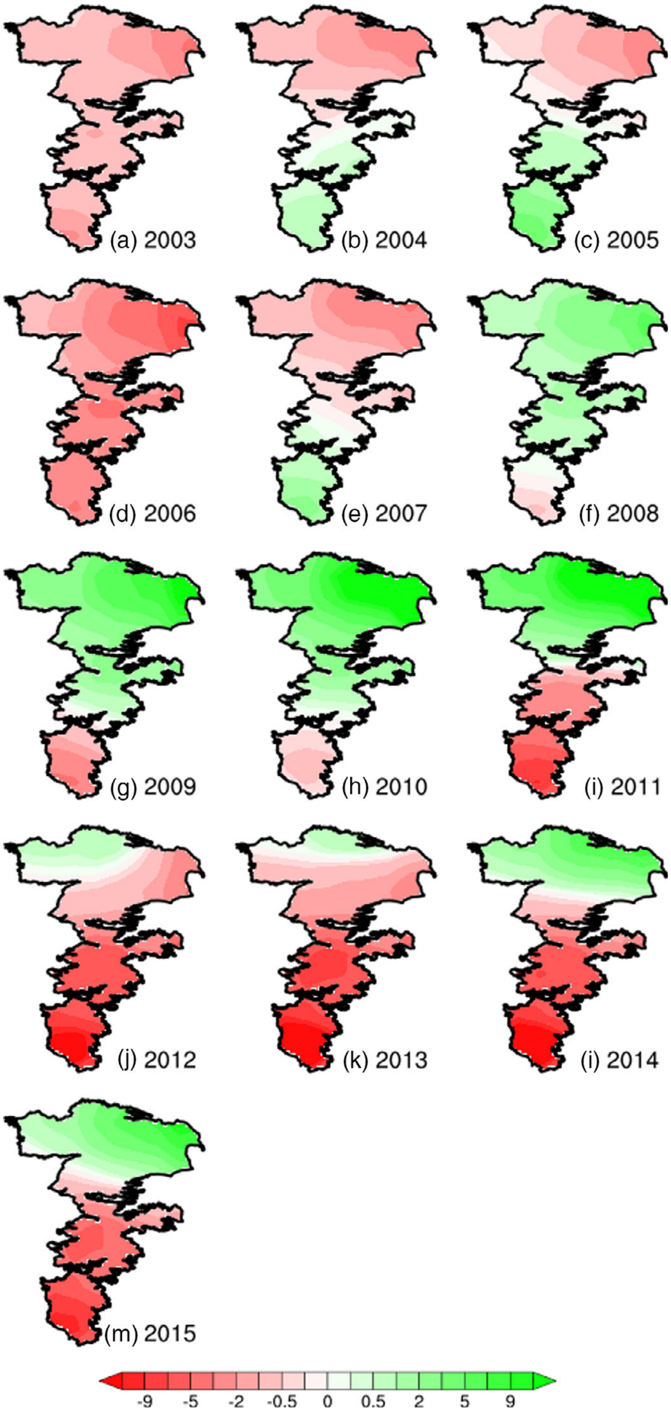

FIGURE 3. Evolution of yearly TWS deficits from GRACE in the OAR.

As noted in Figure 3, the OAR experienced very dry conditions in 2003 and 2006. This is consistent with records from the National Centers for Environmental Information (NCEI) which highlighted the combination of high temperatures and low precipitation (Figure 4) that led to these two drought events (NOAA/NCEI 2004, 2007). In addition, the U.S. Department of Agriculture reported that the 2006 wheat harvest in Oklahoma was one of worst in 50 years due to drought, wildfires, high winds, hail storms, pests, and frost damage. These on-the-ground impacts illustrate how GRACE TWS observations could be useful in the reconstruction and validation of drought events.

To further illustrate the development of the 2011–2012 drought event, monthly TWS anomalies were displayed for a 24-month period from December 2010 to November 2012 (Figure 4). As Figure 4 indicated the 2011 drought began in spring 2011 over the southern OAR and peaked in fall 2011. The southern OAR suffered extreme drought, whereas the northern OAR showed wetness during 2011. Drought conditions improved by January 2012 due to increased precipitation over the southern OAR (Figure 5), however, more severe drought conditions returned to this subregion in May 2012 and continued through the summer and fall. By July 2012, the drought had spread over the entire OAR. The event lasted nearly eight months until being partially alleviated by improved rainfall in April 2013 over the northern OAR, whereas drought continued to intensify in the southern OAR. By July 2013, drought conditions had gradually improved across the entire OAR. In spring 2014, increasing precipitation broke a two-year pattern of drought in the northern OAR, whereas drought conditions again plagued the southern OAR through 2015.

When compared with monthly precipitation totals for the period 2011 through 2015 (Figure 5), precipitation increases did not materialize during summer 2011 over the southern OAR as would typically be expected, and this negative precipitation anomaly led to the onset of drought in this area. Less rainfall during summer 2012 was an additional possible contributor to the 2012 drought over the entire OAR. The low precipitation from 2013 through 2014 continued to worsen drought conditions over the southern OAR. These anomalies may have been caused by cool surface temperatures in the eastern equatorial Pacific (La Nina). The dramatic decrease in precipitation during this period is consistent with observed drought conditions over the OAR (Figures 4 and 5), suggesting that less precipitation was most likely the biggest contributor to the massive decline in TWS. According to some studies, the 2012–2013 drought over the central Great Plains was the most severe in

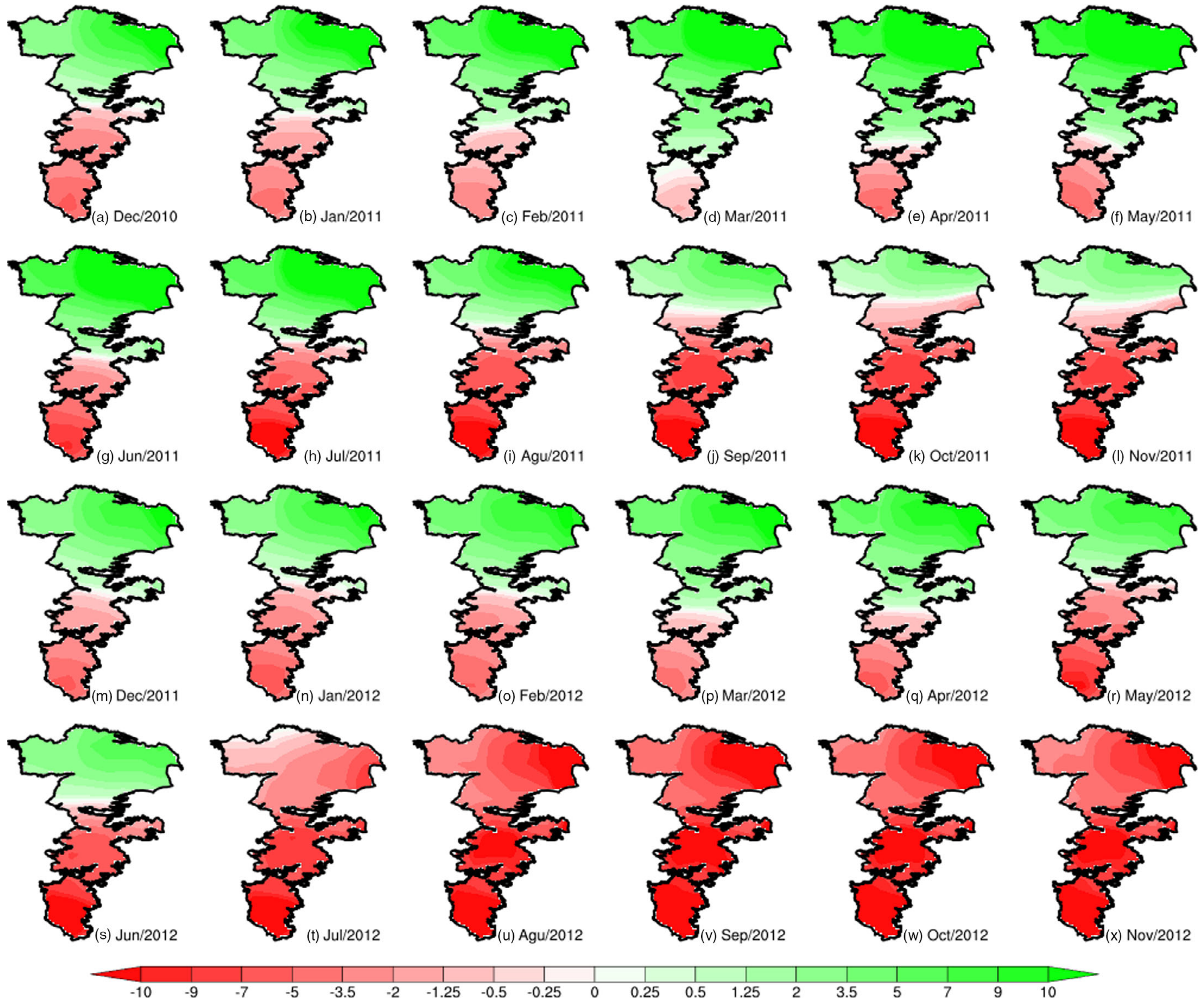

FIGURE 4. Monthly TWS anomalies during a 24-month period from December 2010 to November 2012.

117 years (Hoerling et al. 2014), an assertion which is well-aligned with the TWS analyses presented here.

Evidence from Climatological Precipitation

Accumulated yearly precipitation from the GPCP (Adler et al. 2003) are shown in Figure 5a and 5b for the northern and southern OAR for the period 2003–2015. The four-year period from 2011 to 2014 was the driest period in the southern OAR, consistent with GRACE observations (Figure 3). During 2011, the southern OAR received significantly less precipitation (up to over 50 cm) than average, whereas the northern OAR received a near-normal amount of precipitation over the same period. During 2012 and 2013, both the southern and northern OAR suffered their most severe drought events since 2003 with maximum annual precipitation deficits of 30 cm. In 2014, the southern OAR suffered drought again, whereas the northern OAR recovered and received up to over 10 cm more precipitation than normal. The extreme drought event of 2011–2012 over the entire OAR was the second driest meteorological event on record for the region, with summer precipitation at 40% of long-term means (Long et al. 2013).

Relationship between GRACE TWS and ENSO

As indicated in Figure 6a, the spectrum of Nino3.4 SST is characterized by a high and significant

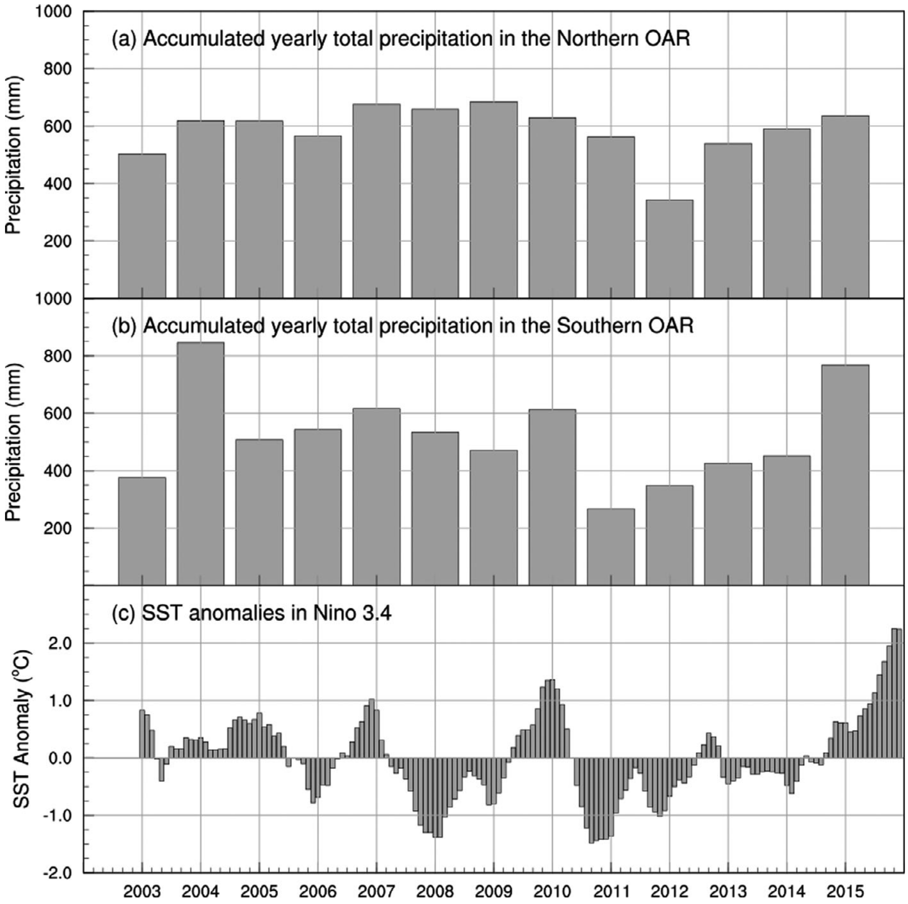

FIGURE 5. Accumulated yearly total precipitation in (a) the northern OAR, (b) southern OAR, and (c) sea surface temperatures (SST) anomalies in Nino3.4.

concentration of variance at multi-year time scales with a peak at 43 months (about 3.6 years) consistent with previous studies (Watanabe et al. 2011). Because of the brevity (January 2003–December 2015) of the Nino3.4 SST record used here, multi-decadal periods were not detected. In addition, Figure 6a clearly showed that the significant periodicity in the Nino3.4 SST time series occurred from 21.5 to 43 months, or approximately 2 to 3.5 years. For the GRACE TWS time series, 43-month periods (3.6 years) are commonly found in both the southern and northern OAR (Figure 6b and 6c).

GRACE TWS in the northern OAR showed a clear oscillatory behavior between drought and wet phases with a period of 2–7 years, but in the southern OAR, there is no relative high-frequency variation. In other words, the power spectrum analysis indicated that periods of 3.6–7 years can be found in the southern OAR. The 2- to 7-year periodic fluctuation in Nino3.4 SST has been widely studied, with the northern OAR more likely to be influenced by El Nino than the southern OAR. For example, Cook et al. (2008) found higher rainfall in the northern Great Plains and reduced precipitation in the southern Great Plains consistent with projected climate change. Barandiaran et al. (2013) reported that north of 40°N, the Great Plains received more precipitation, whereas substantial decreases in total precipitation were evident south of 40°N over the past 30 years. This seesaw mechanism of precipitation agrees well with the observed TWS difference between the southern and northern OAR since 2010.

Figure 7 shows squared wavelet coherence between Nino3.4 SST and TWS anomalies. As suggested in a previous study (Grinsted et al. 2004; Xu et al. 2014), wavelet analysis (Torrence and Compo 1998) can be used to examine the cause and effect relationship between two time series at different time scales. In this instance, the two time series were detrended to remove seasonal changes (semi-annual and annual cycles), then standardized by subtracting their mean and dividing by their standard deviation (Schruben 1985). As Figure 7b indicates, high coherence between Nino3.4 SST and TWS anomalies at the scales between 14 and 31 months in the southern

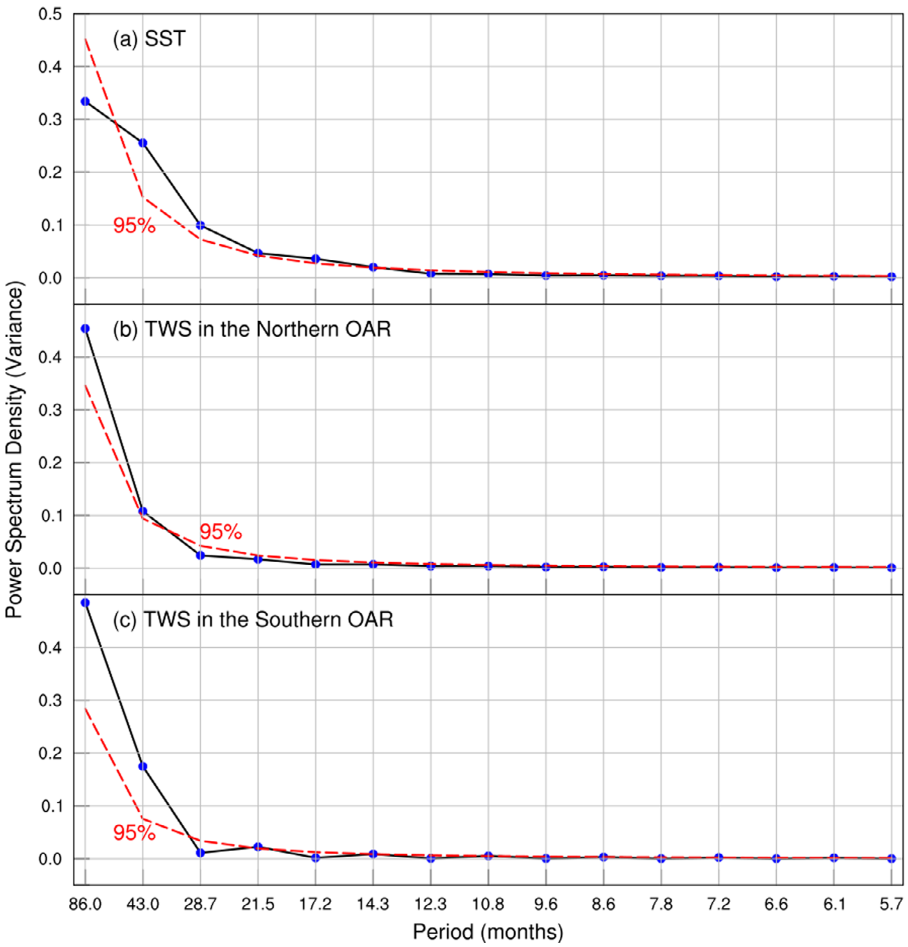

FIGURE 6. Power spectrum analysis on Nino3.4 SST (a), monthly TWS anomalies in the northern OAR (b), and monthly TWS anomalies in the southern OAR (c).

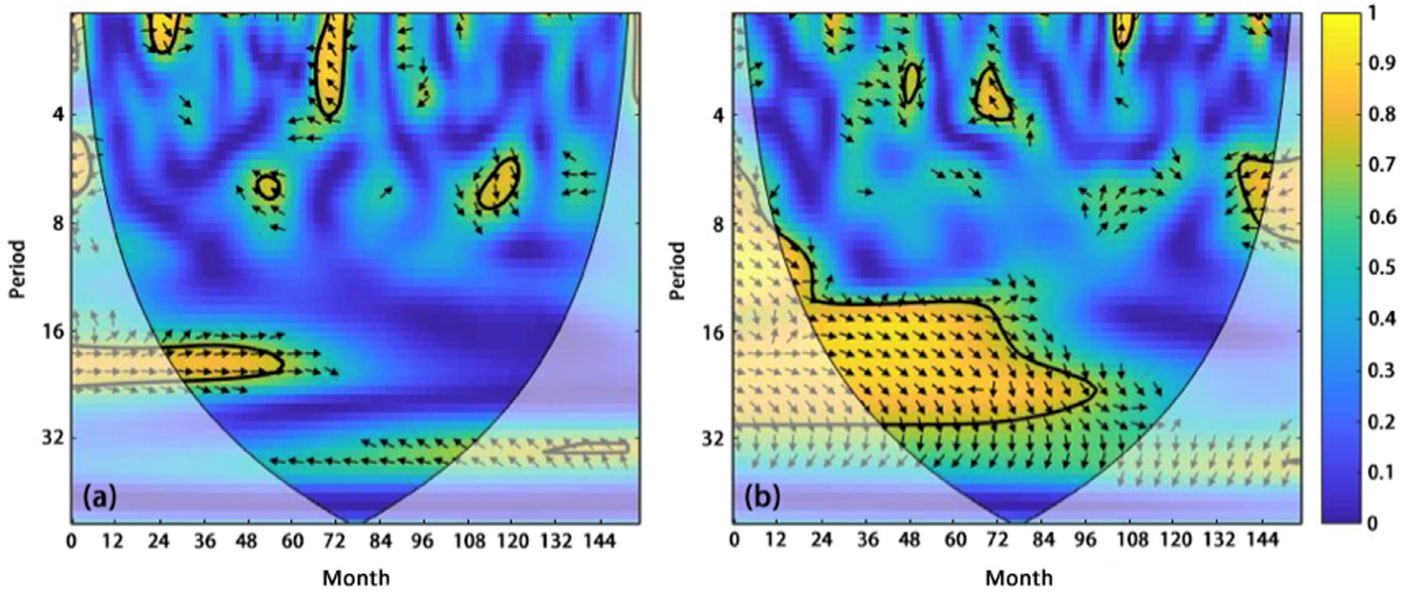

FIGURE 7. Analysis of squared wavelet coherence between the Nino3.4 SST and TWS in the northern OAR (a), and in the southern OAR (b). Arrows represent phase relationship with right (left) arrows indicating positive (negative) correlations and lag (lead) of Nino3.4 SST is denoted by upward (downward) arrows.

OAR is found, indicating a cause and effect relationship between these two time series in this region. TWS anomalies appear to be driven by Nino3.4 SST at ~2-year scale over the 2005–2011 period corresponding to the main mode variability. Phase relationships are shown by the arrows where a positive correlation is represented by an arrow pointing to the right, and a negative correlation is depicted by one pointing the left; leadership of the first variable (Nino3.4 SST in this study) is shown by a downwards pointing arrow and lag of the first variable is indicated by an upward pointing arrow. Therefore, as shown in Figure 7b, the mean phase angle within regions at a 95% confidence interval is ~45° indicating that the Nino3.4 SST and TWS anomalies are neither in phase nor out of phase, but that the Nino3.4 SST leads the TWS variation by 45° on average for the periods of 14–31 months per cycle. In other words, the Nino3.4 SST variation leads the TWS change by 1–4 months (i.e., approximately 45° [14–31]/360°). As suggested by Yang et al. (2007), the Great Plains precipitation is strongly related to the Nino3.4 SST, and the most significant relationship appears when the SST leads the precipitation by one month. Since precipitation is only one of the four major parameters (along with groundwater, evapotranspiration, and runoff) contributing to TWS change (Yeh et al. 2006), there is more temporal variability in the SST-TWS relationship than the SST-precipitation relationship. In the northern OAR, the significant phase angle is about zero, along with a very limited significant zone but which were located from 17 to 24 months over the 2005–2007 period. Therefore, the impact of Nino3.4 SST on the northern OAR presented no significant lags detected on the TWS anomalies.

CONCLUSIONS

In this study, GRACE data have been shown to capture extreme climatic events such as droughts and floods on a regional scale. As a result, GRACE offers an alternative and independent method to monitor changes in TWS and the underlying hydrological dynamics. For those locations and situations where in situ observations are limited, GRACE data can be especially useful for water resource monitoring and management applications.

This study focused on the spatial and temporal variations in TWS and precipitation in the OAR during the period 2003–2015. In addition, power spectrum and squared wavelet coherence analyses were used to detect the possible correlation between TWS and ENSO. We conclude that TWS changes over the OAR during the period 2003–2015 have the following characteristics:

1. Measured changes in GRACE TWS can be a promising tool as it provides an alternative and useful hydro-climatological index for the OAR. GRACE TWS changes provide a detailed picture of the temporal and spatial evolution of severe drought events over the OAR during the past 13 years. The 2012 drought in the northern OAR and 2011–2015 drought in the southern OAR, which are observed in the GRACE TWS data, are consistent with GPCP precipitation analyses.
2. NCALDAS observations are found to perform well in the southern OAR, in terms of correlation with TWS variations, but NCALDAS overestimates drought conditions after 2010 in the northern OAR. This discrepancy may be partially explained by the lack of surface water and groundwater components in NCALDAS.
3. Changes in GRACE TWS during the period 2003–2015 follow increases and decreases in precipitation, which are closely connected to El Nino and La Nina events. Specifically, drought and flood conditions recorded in the GRACE TWS data correlated well with the Nino3.4 SST index. Our analysis clearly indicates that an El Nino (La Nina) event is associated with high (low) precipitation in the southern OAR, but the correlation between ENSO and precipitation in the northern OAR is relatively weaker. The power spectrum analysis indicates that significant correlations between TWS and ENSO are present, and the wavelet coherence analysis shows that the influence of Nino3.4 SST on TWS changes is much stronger in the southern OAR than the northern OAR.

ACKNOWLEDGMENTS

This work was supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2016-68007-25066 “Sustaining agriculture through adaptive management to preserve the Ogallala aquifer under a changing climate.” This manuscript is contribution number 20-007-J from the Kansas Agricultural Experiment Station.

LITERATURE CITED

Adler, R., G. Gu, and G. Huffman. 2012. “Estimating Climatological Bias Errors for the Global Precipitation Climatology Project (GPCP).” *Journal of Applied Meteorology and Climatology* 51: 84–99. https://doi.org/10.1175/JAMC-D-11-052.1.

Adler, R., G. Gu, M. Sapiano, J. Wang, and G. Huffman. 2017. “Global Precipitation: Means, Variations and Trends during the

Satellite Era (1979–2014).” *Surveys in Geophysics* 38: 679–99. https://doi.org/10.1007/s10712-017-9416-4.

Adler, R., G. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, et al. 2003. “The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present).” *Journal of Hydrometeorology* 4 (6): 1147–67. https://doi.org/10.1175/15257541(2003)004<1147:TVGPCP>2.0.CO;2.

Barandiaran, D., S. Wang, and K. Hilburn. 2013. “Observed Trends in the Great Plains Low-Level Jet and Associated Precipitation Changes in Relation to Recent Droughts.” *Geophysical Research Letters* 40: 6247–51. https://doi.org/10.1002/2013GL058296.

Basso, B., A. Kendall, and D. Hyndman. 2013. “The Future of Agriculture over the Ogallala Aquifer: Solutions to Grow Crops More Efficiently with Limited Water.” *Earth’s Future* 1 (1): 39–41. https://doi.org/10.1002/2013EF000107.

Cai, X., Z. Yang, Y. Xia, M. Huang, H. Wei, L. Leung, and M. Ek. 2014. “Assessment of Simulated Water Balance from Noah, Noah-MP, CLM, and VIC over CONUS Using the NLDAS Test Bed.” *Journal of Geophysical Research-Atmospheres* 119: 13751–70. https://doi.org/10.1002/2014JD022113.

Chen, J., C. Wilson, B. Tapley, L. Longuevergne, Z. Yang, and B. Scanlon. 2010. “Recent La Plata Basin Drought Conditions Observed by Satellite Gravimetry.” *Journal of Geophysical Research* 115: D22108. https://doi.org/10.1029/2010JD14689.

Chen, J., C. Wilson, B. Tapley, Z. Yang, and G. Niu. 2009. “2005 Drought Event in the Amazon River Basin as Measured by GRACE and Estimated by Climate Model.” *Journal of Geophysical Research* 114: B05404. https://doi.org/10.1029/2008JB006056.

Cook, K., E. Vizy, Z. Launer, and C. Patricola. 2008. “Springtime Intensification of the Great Plains Low-Level Jet and Midwest Precipitation in GCM Simulations of the Twenty-First Century.” *Journal of Climate* 21: 6321–40. https://doi.org/10.1175/2008JCLI2355.1.

Crosbie, R., B. Scanlon, F. Mpelasoka, R. Reedy, J. Gates, and L. Zhang. 2013. “Potential Climate Change Effects on Groundwater Recharge in the High Plains Aquifer, USA.” *Water Resources Research* 49: 3936–51. https://doi.org/10.1002/wrcr.20292.

Dai, A. 2011. “Drought under Global Warming: A Review.” *WIREs Climate Change* 2: 45–65. https://doi.org/10.1002/wcc.81.

Damberg, L., and A. AghaKouchak. 2014. “Global Trends and Patterns of Drought from Space.” *Theoretical and Applied Climatology* 117 (3–4): 441–48. https://doi.org/10.1007/s00704-013-1019-5.

Famiglietti, J.S. 2004. “Remote Sensing of Terrestrial Water Storage, Soil Moisture and Surface Waters.” *Washington DC American Geophysical Union Geophysical Monograph Series* 150: 197–207. https://doi.org/10.1029/150GM16.

Famiglietti, J.S., M. Lo, S.L. Ho, J. Bethune, K.J. Anderson, T.H. Syed, S.C. Swenson, C.R. de Linage, and M. Rodell. 2011. “Satellites Measure Recent Rates of Groundwater Depletion in California’s Central Valley.” *Geophysical Research Letters* 38: L03403. https://doi.org/10.1029/2010GL046442.

Famiglietti, J.S., and M. Rodell. 2013. “Water in the Balance.” *Science* 340: 1300–01. https://doi.org/10.1126/science.1236460.

Feng, S., M. Trnka, M. Hayes, and Y. Zhang. 2017. “Why Do Different Drought Indices Show Distinct Future Drought Risk Outcomes in the U.S. Great Plains?” *Journal of Climate* 30: 265–78. https://doi.org/10.1175/JCLI-D-15-0590.1.

Grinsted, A., J. Moore, and S. Jevrejeva. 2004. “Application of the Cross Wavelet Transform and Wavelet Coherence to Geophysical Time Series.” *Nonlinear Processes in Geophysics* 11 (5–6): 561–66. https://doi.org/10.5194/npg-11-561-2004.

Gutentag, E., F. Heimes, N. Krothe, R. Luckey, and J. Weeks. 1984. “Geohydrology of the High Plains Aquifer in Parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.” U.S. Geological Survey Professional Paper 1400B, 66 pp.

Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager. 2014. “Causes and Predictability of the 2012 Great Plains Drought.” *Bulletin of the American Meteorological Society* 95: 269–82. https://doi.org/10.1175/BAMS-D-13-00055.1.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel, and J. Wickham. 2007. “Completion of the 2001 National Land Cover Database for the Conterminous United States.” *Photogrammetric Engineering & Remote Sensing* 73: 337–41.

Houborg, R., M. Rodell, B. Li, R. Reichle, and B. Zaitchik. 2012. “Drought Indicators Based on Model-Assimilated Gravity Recovery and Climate Experiment (GRACE) Terrestrial Water Storage Observations.” *Water Resources Research* 48: W07525. https://doi.org/10.1029/2011WR011291.

Hu, Q., and S. Feng. 2001. “Variations of Teleconnection of ENSO and Interannual Variation in Summer Rainfall in the Central United States.” *Journal of Climate* 14: 2469–80.

Huang, Y., M.S. Salama, M.S. Krol, R.V. Velde, A.Y. Hoekstra, Y. Zhou, and Z. Su. 2013. “Analysis of Long-Term Terrestrial Water Storage Variations in the Yangtze River Basin.” *Hydrology and Earth System Sciences* 17: 1985–2000. https://doi.org/10.5194/hess-17-1985-2013.

Huffman, G., R. Adler, D. Bolvin, and G. Gu. 2009. “Improving the Global Precipitation Record: GPCP Version 2.1.” *Geophysical Research Letters* 36: L17808. https://doi.org/10.1029/2009GL040000.

Kumar, S., C. Peters-Lidard, D. Mocko, R. Reichle, Y. Liu, K. Arsenault, Y. Xia, et al. 2014. “Assimilation of Remotely Sensed Soil Moisture and Snow Depth Retrievals for Drought Estimation.” *Journal of Hydrometeorology* 15: 2446–69. https://doi.org/10.1175/JHM-D-13-0132.1.

Kumar, S., C. Peters-Lidard, Y. Tian, P. Houser, J. Geiger, S. Olden, L. Lighty, et al. 2006. “Land Information System: An Interoperable Framework for High Resolution Land Surface Modeling.” *Environmental Modelling and Software* 21: 1402–15. https://doi.org/10.1016/j.envsoft.2005.07.004.

Kumar, S., S. Wang, D. Mocko, C. Peters-Lidard, and Y. Xia. 2017. “Similarity Assessment of Land Surface Model Outputs in the North American Land Data Assimilation System.” *Water Resources Research* 53: 8941–65. https://doi.org/10.1002/2017WR020635.

Kumar, S., B. Zaitchik, C. Peters-Lidard, M. Rodell, R. Reichle, B. Li, M. Jasinski, et al. 2016. “Assimilation of Gridded GRACE Terrestrial Water Storage Estimates in the North American Land Data Assimilation System.” *Journal of Hydrometeorology* 17: 1951–72. https://doi.org/10.1175/JHM-D-15-0157.1.

Liu, Y., C. Peters-Lidard, S. Kumar, K. Arsenault, and D. Mocko. 2015. “Blending Satellite-Based Snow Depth Products with In Situ Observations for Streamflow Predictions in the Upper Colorado River Basin.” *Water Resources Research* 51: 1182–202. https://doi.org/10.1002/2014WR016606.

Long, D., B. Scanlon, L. Longuevergne, A. Sun, D. Fernando, and H. Save. 2013. “GRACE Satellite Monitoring of Large Depletion in Water Storage in Response to the 2011 Drought in Texas.” *Geophysical Research Letters* 40: 3395–401. https://doi.org/10.1002/grl.50655.

McGuire, V.2009. “Water-Level Changes in the High Plains Aquifer, Predevelopment to 2007, 2005–2006, and 2006–2007.” *U.S. Geological Survey Scientific Investigations Report 2009–5019*, 9 pp. http://pubs.usgs.gov/sir/2009/5019/.

McGuire, V.2014. “Water-Level Changes and Change in Water in Storage in the High Plains Aquifer, Predevelopment to 2013 and 2011–2013.” *U.S. Geological Survey Scientific Investigations Report 2014–5218*, 14 pp. https://doi.org/10.3133/sir20145218.

Nie, N., W. Zhang, Z. Zhang, H. Guo, and N. Ishwaran. 2016. “Reconstructed Terrestrial Water Storage Change (ΔTWS) from

1948 to 2012 over the Amazon Basin with the Latest GRACE and GLADS Products." *Water Resources Management* 30 (1): 279–94. https://doi.org/10.1007/s11269-01511611.

Niu, G., and Z. Yang. 2006. "Assessing a Land Surface Model's Improvements with GRACE Estimates." *Geophysical Research Letters* 33: L07401. https://doi.org/10.1029/2005GL025555.

NOAA/NCEI (National Oceanic and Atmospheric Administration/ National Centers for Environmental Information). 2004. "State of the Climate: Drought for Annual 2003." https://www.ncdc.noaa.gov/sotc/drought/200313.

NOAA/NCEI (National Oceanic and Atmospheric Administration/ National Centers for Environmental Information). 2007. "State of the Climate: Drought for Annual 2006." https://www.ncdc.noaa.gov/sotc/drought/200613.

Phillips, T., R. Nerem, B. Kemper, J. Famiglietti, and B. Rajagopalan. 2012. "The Influence of ENSO on Global Terrestrial Water Storage Using GRACE." *Geophysical Research Letters* 39: L16705. https://doi.org/10.1029/2012GL052495.

Rippey, B. 2015. "The U.S. Drought of 2012." *Weather and Climate Extremes* 10: 57–64. https://doi.org/10.1016/j.wace.2015.10.004.

Rodell, M., J. Chen, H. Kato, J.S. Famiglietti, J. Nigro, and C. Wilson. 2007. "Estimating Groundwater Storage Changes in the Mississippi River Basin (y) Using GRACE." *Hydrogeology Journal* 15: 159–66. https://doi.org/10.1007/s10040-006-0103-7.

Rodell, M., and J.S. Famiglietti. 2002. "The Potential for Satellite-Based Monitoring of Groundwater Storage Changes Using GRACE: The High Plains Aquifer, Central US." *Journal of Hydrology* 263: 245–56. https://doi.org/10.1016/S0022-1694(02)00060-4.

Ruiz-Barradas, A., and S. Nigam. 2010. "Great Plains Precipitation and Its SST Links in Twentieth-Century Climate Simulations, and Twenty-First- and Twenty-Second-Century Climate Projections." *Journal of Climate* 23: 6409–29. https://doi.org/10.1175/2010JCLI3173.1.

Scanlon, B., C. Faunt, L. Longuevergne, R. Reedy, W. Alley, V. McGuire, and P. McMahon. 2012. "Groundwater Depletion and Sustainability of Irrigation in the US High Plains and Central Valley." *Proceedings of the National Academy of Sciences of the United States of America* 109 (24): 9320–25. https://doi.org/10.1073/pnas.1200311109.

Schruben, L.1985. "Overview of Standardized Time Series." In *Proceedings of the 1985 Winter Simulation Conference*, edited by D. Gantz, G. Blais, and S. Solomon, 115–18. San Francisco, CA: Society for Computer Simulation.

Shafer, M., D. Ojima, J. Antle, D. Kluck, R. McPherson, S. Petersen, B. Scanlon, and K. Sherman. 2014. "Ch 19: Great Plains Climate Change Impacts in the United States." *In The Third National Climate Assessment*, edited by J. Melillo, T. Richmond, and G. Yohe, 441–61. https://doi.org/10.7930/J0Z31WJ2.

Strassberg, G., B. Scanlon, and D. Chambers. 2009. "Evaluation of Groundwater Storage Monitoring with the GRACE Satellite: Case Study of the High Plains Aquifer, Central United States." *Water Resources Research* 45: W05410. https://doi.org/10.1029/2008WR006892.

Strassberg, G., B. Scanlon, and M. Rodell. 2007. "Comparison of Seasonal Terrestrial Water Storage Variations from GRACE with Groundwater-Level Measurements from the High Plains Aquifer (USA)." *Geophysical Research Letters* 34: L14402. https://doi.org/10.1029/2007GL030139.

Swenson, S., and J. Wahr. 2006. "Post-Processing Removal of Correlated Errors in GRACE Data." *Geophysical Research Letters* 33: L08402. https://doi.org/10.1029/2005GL025285.

Tapley, B., S. Bettadpur, M. Watkins, and C. Reigber. 2004. "The Gravity Recovery and Climate Experiment: Mission Overview and Early Results." *Geophysical Research Letters* 31: L09607. https://doi.org/10.1029/2004GL079920.

Thomas, A., J. Reager, J.S. Famiglietti, and M. Rodell. 2014. "A GRACE-Based Water Storage Deficit Approach for Hydrological Drought Characterization." *Geophysical Research Letters* 41: 1537–45. https://doi.org/10.1002/2014GL059323.

Torrence, C., and G. Compo. 1998. "A Practical Guide to Wavelet Analysis." *Bulletin of the American Meteorological Society* 79: 61–78. https://doi.org/10.1175/15200477(1998)079<0061:APGTWA>2.0.CO;2.

USGS (United States Geological Survey). 2006. "Water Use in the United States: U.S. Geological Survey Data." http://water.usgs.gov/wateruse/.

Vishwakarma, B., B. Devaraju, and N. Sneeuw. 2018. "What is the Spatial Resolution of GRACE Satellite Products for Hydrology?" *Remote Sensing* 10: 3395–401. https://doi.org/10.3390/rs10000852.

Wang, S., and T. Cheng. 2009. "The Late-Spring Maximum of Rainfall over the U.S. Central Plains and the Role of the Low-Level Jet." *Journal of Climate* 22: 4696–709. https://doi.org/10.1175/2009JCLI2719.1.

Watanabe, T., A. Suzuki, S. Minobe, T. Kawashima, K. Kameo, K. Minoshima, Y.M. Aguilar, et al. 2011. "Permanent El Nino during the Pliocene Warm Period Not Supported by Coral Evidence." *Nature* 471: 209–11. https://doi.org/10.1038/nature09777.

Weaver, S., S. Schubert, and H. Wang. 2009. "Warm Season Variations in the Low-Level Circulation and Precipitation over the Central United States in Observations, AMIP Simulations, and Idealized SST Experiments." *Journal of Climate* 22: 5401–20. https://doi.org/10.1175/2009JCLI2984.1.

Xia, Y., K. Mitchell, M. Ek, J. Sheffield, B. Cosgrove, E. Wood, L. Luo, et al. 2012. "Continental-Scale Water and Energy Flux Analysis and Validation for the North American Land Data Assimilation System Project Phase 2 (NLDAS-2): 1. Intercomparison and Application of Model Products." *Journal of Geophysical Research* 117: D03109. https://doi.org/10.1029/2011JD016048.

Xu, L., X. Lin, J. Amen, K. Welding, and D. McDermitt. 2014. "Impact of Changes in Barometric Pressure on Landfill Methane Emission." *Global Biogeochemical Cycles* 28: 679–95. https://doi.org/10.1002/2013GB004571.

Yang, S., X. Ding, D. Zheng, and Q. Li. 2007. "Depiction of the Variations of Great Plains Precipitation and Its Relationship with Tropical Central-Eastern Pacific SST." *Journal of Applied Meteorology and Climatology* 46: 136–53. https://doi.org/10.1175/JAM2455.1.

Yeh, P., S. Swenson, J.S. Famiglietti, and M. Rodell. 2006. "Remote Sensing of Groundwater Changes in Illinois Using the Gravity Recovery and Climate Experiment (GRACE)." *Water Resources Research* 42: W12203. https://doi.org/10.1029/2006WR005374.

Yuan, S., and S. Quiring. 2014. "Drought in the U.S. Great Plains (1980–2012): A Sensitivity Study Using Different Methods for Estimating Potential Evapotranspiration in the Palmer Drought Severity Index." *Journal of Geophysical Research — Atmosphere* 119: 10996–1010. https://doi.org/10.1002/2014/JD021970.

Zhang, Z., B. Chao, J. Chen, and C. Wilson. 2015. "Terrestrial Water Storage Anomalies of Yangtze River Basin Droughts Observed by GRACE and Connections with ENSO." *Global and Planetary Change* 126: 35–45. https://doi.org/10.1017/j.gloplacha.2015.01.002.

Zhao, M., G.A.I. Velicogna, and J.S. Kimball. 2017. "Satellite Observations of Regional Drought Severity in the Continental United States Using GRACE-Based Terrestrial Water Storage Change." *Journal of Climate* 30: 6297–308. https://doi.org/10.1175/JCLI-D-16-0458.s1.

Zhou, Y., X. Xiao, G. Zhang, P. Wagle, R. Bajgain, J. Dong, C. Jin, et al. 2017. "Quantifying Agricultural Drought in Tallgrass Prairie Region in the U.S. Southern Great Plains through Analysis of a Water-Related Vegetation Index from MODIS Images." *Agricultural and Forest Meteorology* 246: 111–22. https://doi.org/10.1016/j.agrformet.2017.06.007.