Concurrent increases in wet and dry extremes projected in Texas and combined effects on groundwater

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Abstract

The US state of Texas has experienced consecutive flooding events since spring 2015 with devastating consequences, yet these happened only a few years after the record drought of 2011. Identifying the effect of climate variability on regional water cycle extremes, such as the predicted occurrence of La Niña in winter 2017–2018 and its association with drought in Texas, remains a challenge. The present analyses use large-ensemble simulations to project the future of water cycle extremes in Texas and assess their connection with the changing El Niño–Southern Oscillation (ENSO) teleconnection under global warming. Large-ensemble simulations indicate that both intense drought and excessive precipitation are projected to increase towards the middle of the 21st century, associated with a strengthened effect from ENSO. Despite the precipitation increase projected for the southern Great Plains, groundwater storage is likely to decrease in the long run with diminishing groundwater recharge; this is due to the concurrent increases and strengthening in drought offsetting the effect of added rains. This projection provides implications to short-term climate anomaly in the face of the La Niña and to long-term water resources planning.

1. Introduction

Before Hurricane Harvey hit the US state of Texas in August 2017, heavy precipitation events of non-hurricane origins have already caused multiple floods since April 2015 with devastating consequences. The May 2015 flood resulted from over 400 mm above-normal rainfall falling on Texas (Wang et al 2015). Then, the May 2016 flood took 12 lives and caused historic river levels, making it the fifth major flood event and the second 500 year flood in the Houston area. As shown in figure 1(a), the precipitation anomaly over the 13 months from May 2015 through May 2016 reveals a marked increase centered around Oklahoma, which is the upstream of many rivers that run through the southern Great Plains (SGP). The timing of these recent spring floods coincides with SGP’s rainy season (figure 1(b)). Starting in April, a ‘spring trough’ develops west of the SGP and it interacts with the developing low-level jet (LLJ) to form the convergence of moisture fluxes (Helfand and Schubert 1995), leading to the May–June rainfall peak over the SGP (Higgins et al 1997, Wang and Chen 2009). The synoptic conditions associated with floods in 2015 and 2016 during April–June (AMJ, defined for spring) are not too distinct from each other, both featuring a quasi-stationary trough west of the SGP (supplementary figure S1 available at stacks.iop.org/ERL/13/054002/mmedia) generating short waves and squall lines. In May 2015, the developing El Niño further deepened this quasi-stationary trough while enhancing the LLJ (Wang et al 2015). Global warming acted to strengthen the El Niño teleconnection (Meehl and Teng 2007, Stevenson et al 2012) that affects the SGP. Hurricanes such as Harvey also produce excessive rainfall and can lead to flood, but these weather systems are random
in nature and linking them to large-scale forcing is difficult (van Oldenborgh et al. 2017).

The succession of the post-2014 floods in Texas could lead the society into overlooking the risk in the comeback of severe droughts. In 2011, Texas underwent an intense drought and associated heat waves that was unprecedented (Nielsen-Gammon 2012) making it the worst 1 year drought on record (Fernando et al. 2016). Both the strong La Niña and anthropogenic warming played a role in the severity and increased probability of this record drought (Rupp et al. 2012), suggesting that the El Niño-related 2015 flood is the opposite pattern of the 2011 drought. Given the robust influence of the El Niño–Southern Oscillation (ENSO) on the SGP’s precipitation (Lee et al. 2014, Liang et al. 2014, Liang et al. 2015) and the role of global warming in strengthening this ENSO influence (Rupp et al. 2012, Stevenson et al. 2012, Wang et al. 2015), it is reasonable to anticipate a drying tendency, or even drought, to occur over the SGP in the face of a (future) La Niña event.

As of November 2017, the NOAA Climate Prediction Center (CPC) indicated a 70% chance for a La Niña to develop through February 2018. Given the emergence of this La Niña event, we decided to analyze the risk of severe drought to occur in the SGP, similar to that of the 2011 condition, and evaluate climate model projections of its water cycle extremes represented by excessive wet season and severe drought.

2. Data sources

Forty members of climate simulation were produced by the Community Earth System Model version 1’s Large Ensemble Project (CESM-LE) with spatial resolution of 0.9 degrees longitude x 1.25 degrees latitude (Kay et al. 2015). The simulations cover two periods: (1) 1920–2005 with historical forcing including greenhouse gases, aerosol, ozone, land use change, solar and volcanic activity, and (2) 2006–2080 with RCP8.5 forcing (Taylor et al. 2012). The ensemble spread of initial conditions is generated by the commonly used ‘roundoff differences’ method (Kay et al. 2015). CESM-LE was used here partly because it performs well on the depiction of the ENSO cycle and its teleconnection over the North Pacific and North America (Wang et al. 2015, Yoon et al. 2015). Of note, the land surface model used in the CESM-LE does not include the process of anthropogenic groundwater withdrawal.

For observational data, we use the NCEP/NCAR Reanalysis (R1) (Kalnay et al. 1996) that starts in 1948 in order to analyze interdecadal changes. Other datasets include the Extended Reconstructed Sea Surface Temperature (ERSST, v3b) derived from the International Comprehensive Ocean–Atmosphere Dataset (Smith and Reynolds 2003) for the ENSO indexing and the NOAA Precipitation Reconstruction over Land (PREC/L) gridded product (Chen et al. 2002) of 0.5° degree resolution.

3. Results

Based on the SGP domain outlined in figure 1(a), the CESM-LE simulation of the region’s monthly precipitation is shown in figure 1(c) for the historical (1940–1985) and a ‘near-future’ (2010–2060) periods. In terms of climatology, CESM-LE captured the spring rainy season but underestimates the secondary rainfall peak in fall. Overall, precipitation in the SGP is projected to increase throughout the year with a larger increase in spring (April–June or AMJ), in which the precipitation increase amounts to 15%–20%. Subsequently, we examine the El Niño impact on the SGP’s spring precipitation based upon the precipitation composites; this is determined by the sea surface temperature anomalies (SSTA) of the NINO3.4
Figure 2. Ensemble precipitation differences (P) between the El Niño and La Niña composites (see text) during the April–June seasons of (a) 1940–1985 and (b) 2010–2060; the blue contours outline the significance level of \( p < .001 \). (c)–(d) Similar to (a)–(b) but for the 250 hPa geopotential height difference (\( \Delta Z \)) ensembles for the same two periods.

region (170°–140°W, 5°S–5°N) being greater than 0.5 °C in the spring and 1 °C in the preceding winter (less than −0.5 °C/-1 °C for La Niña). This threshold is applied to each ensemble member and the observation as well, to depict the difference of the precipitation composites between El Niño and La Niña. The observational analysis during 1950–1995 (figure 2(a)) shows anomalous precipitation over southeastern Texas and part of Oklahoma and Louisiana, a known feature. In the near-future simulations (figure 2(c)) and the historical simulations (figure 2(b)), there is a marked increase in the ensemble mean precipitation composite difference between El Niño and La Niña in the SGP. Furthermore, a similar precipitation analysis using the Coupled Model Intercomparison Project Phase 5 (CMIP5), which is shown in supplemental figure S2 by following Wang et al (2015), reveals corresponding precipitation patterns as well. That both the CESM-LE and CMIP5 simulations capture the general pattern and intensification of the ENSO-related precipitation anomalies in the SGP suggests an impact from anthropogenic climate warming.

In terms of the atmospheric circulation associated with ENSO and its changing teleconnection, figures 2(e) and (f) show the CESM-LE-generated geopotential height differences at 250 hPa; these are generally in agreement with the observed pattern in figure 2(d) including the synoptic trough west of Texas. The El Niño-associated low-pressure anomaly west of Texas is enhanced by about 35% during 2010–2060 (figure 2(f)), while the broad-scale teleconnection pattern remains similar to the historical simulations (figure 2(e)). We should note that a sign reversal in figure 2 indicates the La Niña influence on precipitation reduction in Texas. We should note that seasonal rainfall anomalies in the SGP are not only controlled by ENSO but by other circulation factors as well. Nonetheless, a further sliding correlation analysis between the SGP precipitation and the ENSO cycle, based on different climate models and a different precipitation observation, yields the same outcome of an amplified ENSO impact (supplemental figure S2).

Next, we examine the prevailing circulation pattern modulating the SGP by plotting in figure 3 the anomalous 250 hPa geopotential height that is regressed...
Figure 3. CESM LE’s 250 hPa geopotential height anomalies ($\Delta Z$) regressed with the normalized spring precipitation averaged in Texas (outlined) for the periods of (a) 1940–1985 and (b) 2010–2060 during the April–June season.

with the SGP precipitation during AMJ. A low-pressure anomaly to the west of Texas appears to be the dominant feature embedded in a zonally oriented short-wave train, which is different from the long-wave dominant pattern induced by ENSO (figures 2(d)–(f)). There is not an apparent difference in the anomalous circulation’s magnitude over Texas between the two time periods, suggesting that the common circulation features affecting the spring precipitation in Texas will not change. However, the strengthened ENSO teleconnection can become increasingly important to modulate or amplify this circulation feature. We should also note that other major circulation processes may compensate the ENSO teleconnection and that the sample sizes between figures 2 and 3 are different.

To examine the changing association between spring precipitation anomalies in the SGP and the ENSO cycle, we next compute the precipitation’s 15 year sliding correlations with the spring NINO3.4 SST anomaly from the observation and CESM-LE data; this is shown in figure 4(a). There is a clear decadal-scale fluctuation in the observation with a more pronounced increase after year 2000. The CESM-LE produces a gradual increase and it becomes persistently significant after 2000, at the 95% level. These results echo Wang et al (2015)’s observational and modeling analyses that the SGP’s spring precipitation response to the ENSO teleconnection has intensified and this trend is projected to continue. Other recent studies (Guilyardi et al 2012, Yoon et al 2015,
Zhou et al (2014) also suggest that the changing tropical heat release associated with the ENSO-related teleconnection has amplified its regional impacts worldwide.

Perhaps a greater implication of these analyses can be revealed by the concurrence of a hot summer following a dry spring, loosely describing a flash drought in the central US (Otkin et al 2016). Here, hot summers are defined as the July–September (JAS) surface air temperature exceeding 1 standard deviation (sd.) above the mean, while dry springs refer the AMJ precipitation deficit of 1 sd. below the mean. These are computed within a 15 year running window. This analysis is based on the fact that severe drought in the SGP usually accompanies a below-normal spring/rainy season followed by a hotter-than-normal summer season (Long et al 2013, Nielsen-Gammon 2012). As shown in figure 4(b), the observed drought occurrence has increased after the 1990s, though it appears to be part of a multi-decadal variation. In the CESM-LE, the drought occurrence increases persistently throughout the 21st century. Likewise, the 15 year running occurrence of extremely wet springs (figure 4(c); defined by the AMJ precipitation deficit of 2 sd. below the mean), is projected to increase after 2015 despite a downturn after 2050. By comparing figures 4(b) with (c), it appears that the disparity between their latter trends is caused by a further increase in dry springs. This downturn in figure 4(c) is likely due to internal model variability such as that drives the earlier turnarounds in the historical period. Regardless, the ENSO impact on the JAS precipitation change in the SGP is also projected to amplify, as shown in supplemental figure S3 following the composites of figures 2(c) and (d).

To quantify the effect of the changing ENSO teleconnection on the extreme wet/dry spring and summer in the SGP, we further compute the frequencies of (a) back-to-back wet springs consisting of AMJ precipitation anomalies greater than 1 sd. occurring in two consecutive years, (b) same as (a) but only for those occurring with an El Niño winter in between, and (c) reversal of (b) for consecutive two dry summers with the JAS precipitation deficits below 1 sd. occurring with a La Niña winter in between; these are computed within a 30 year window and shown in figure 5. In the observation, the period of 1985–2015 exhibits a distinctly higher frequency in all three cases than the earlier 30 years. Meanwhile, the CESM-LE projects an almost linear increase in both the El Niño-associated wet springs and the La Niña-accompanied dry summers toward the end of the 21st century. Given the difference between the observation and CESM-LE simulations revealed in figures 4 and 5, one has to take into account that even a sophisticated model like the CESM-LE remains a limited tool to understand the complicated climatological processes involving interannual variation, global warming and associated extremes.

4. Implication on groundwater

At face value, an increasingly wet climate in the SGP (cf. figure 1(c)) would suggest a net increase in the water storage, but how the concurrent increase in dry summers affect the groundwater storage in the SGP in the future remains unclear. Analyzing the CESM-LE’s groundwater outputs, the trends of the 1956–2080 period are computed for groundwater storage anomalies and groundwater recharge. The
simulated groundwater storage anomalies are shown in figure 6(a) from 1956–2080 averaged every 30 year, relative to the mean of 1956–1985. The result indicates a significant decrease with a rate of approximately −1.5 cm per decade in the future. Figure 6(b) shows the simulated groundwater recharge rate from 1956–2080, in which the decline in the recharge rate becomes negative after around 2015. While an increase in annual precipitation is projected in the SGP, it seems that the increase in surface evapotranspiration plays a substantial role in affecting the terrestrial water budget; this leads to a smaller infiltration and a reduction in the groundwater recharge and soil water.

5. Concluding remarks

The US southern Great Plains has experienced an alternation of severe drought and extreme flood since 2010 with devastating consequences. We have analyzed large-ensemble simulations that project the future of extreme wet and dry seasons in the SGP and assessed their association with the changing ENSO teleconnection under global warming. Both intense drought and excessive precipitation are projected to increase towards the middle of the 21st century and this projection is associated with a strengthened relation with ENSO teleconnections. The findings presented here echo the documented effect of El Niño in strengthening the anthropogenic warming-induced increase in summer rainfall elsewhere in the world, such as central China (Yuan et al 2018). Despite the projected increase in precipitation over the SGP, groundwater storage is anticipated to decrease with diminishing groundwater recharge; this is primarily due to the surface warming and projected increase in summer drought that reduces infiltration. These, subsequently, offset the effect of increased precipitation. The analysis presented here may be model-dependent and requires further verification using more sophisticated land surface models and/or subsurface observations.
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References

Chen M, Xie P, Janowiak J E and Arkin P A 2002 Global land precipitation: a 50 yr monthly analysis based on gauge observations J. Hydrometeorol. 3 249–66

Fernando D N, Mo K C, Fu R, Pu B, Bowerman A, Scanlon B R, Solis R S, Yin L, Mace R E and Mioduszewski I R 2016 What caused the spring intensification and winter demise of the 2011 drought over Texas? Clim. Dyn. 47 3077–90

Guilyardi E, Bellenger H, Collins M, Ferrett S, Cai W and Fernando D N, Mo K C, Fu R, Pu B, Bowerman A, Scanlon B R, Chen M, Xie P, Janowiak J E and Arkin P A 2002 Global land exchanges J. Hydrometeorol. 3 249–66

Helfand H M and Schubert S D 1995 Climatology of the simulated great plains low-level jet and its contribution to the continental moisture budget of the United States J. Clim. 8 784–806

Higgins R, Yao Y, Yarosh E, Janowiak J E and Mo K 1997 Influence of the great plains low-level jet on summertime precipitation and moisture transport over the central United States J. Clim. 10 481–507

Kalnay E et al 1996 The NCEP/NCAR 40 year reanalysis project Bull. Am. Meteorol. Soc. 77 437–71

Kay J, Deser C, Phillips A, Mai A, Hannay C, Strand G, Arblaster J, Bates S, Danabasoglu G and Edwards J 2015 The community earth system model (CESM) large ensemble project: a community resource for studying climate change in the presence of internal climate variability Bull. Am. Meteorol. Soc. 96 1333–49

Lee S-K, Mapes B E, Wang C, Enfield D B and Weaver S J 2014 Springtime ENSO phase evolution and its relation to rainfall in the continental US Geophys. Res. Lett. 41 2013GL059137

Liang Y-C, Lo M-H and Yu J-Y 2014 Asymmetric responses of land hydroclimatology to two types of El Niño in the Mississippi River Basin Geophys. Res. Lett. 41 582–8

Liang Y-C, Yu J-Y, Lo M-H and Wang C 2015 The changing influence of El Niño on the great plains low-level jet Atmos. Sci. Lett. 16 512–17

Long D, Scanlon B R, Longuevergne L, Sun A Y, Fernando D N and Save H 2013 GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas Geophys. Res. Lett. 40 3395–401

Meehl G A and Teng H 2007 Multi-model changes in El Niño teleconnections over North America in a future warmer climate Clim. Dyn. 29 779–90

Nielsen-Gammon J W 2012 The 2011 Texas drought Texas Water J. 3 59–95

Otto J A, Anderson M C, Hain C, Svoboda M, Johnson D, Mueller R, Tadesse T, Wardlow B and Brown J 2016 Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought Agric. Forest Meteorol. 218 280–42

Rupp D, Mote P, Massey N, Rye C, Jones R and Allen M 2012 Did human influence on climate make the 2011 Texas drought more probable Bull. Am. Meteorol. Soc. 93 1052–4

Smith T M and Reynolds R W 2003 Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997) J. Clim. 16 1495–510

Stevenson S, Fox-Kemper B, Jochum M, Neale R, Deser C and Meehl G 2012 Will there be a significant change to El Niño in the twenty-first century? J. Clim. 25 2129–45

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98

van Oldenborgh G J, van der Wiel K, Antonia S, Roop S, Julie A, Friederike O, Karsten H, Sihan L, Gabriel V and Heidi C 2017 Attribution of extreme rainfall from Hurricane Harvey, August 2017 Environ. Res. Lett. 12 124009

Wang S-Y and Chen T-C 2009 The late-spring maximum of rainfall over the US central plains and the role of the low-level jet J. Clim. 22 4696–709

Wang S-Y, Huang W-R, Hsu H-H and Gillies R R 2015 Role of the strengthened El Niño teleconnection in the May 2015 floods over the southern Great Plains Geophys. Res. Lett. 42 8149–6

Yoon J-H et al 2015 Increasing water cycle extremes in California and relation to ENSO cycle under global warming Nat. Commun. 6 8657

Yuan X, Wang S and Hu Z-Z 2018 Do climate change and El Niño increase likelihood of Yangtze River extreme rainfall? Bull. Am. Meteorol. Soc. 5113–7

Zhou Z-Q, Xie S-P, Zheng X-T, Liu Q and Wang H 2014 Global warming–induced changes in El Niño teleconnections over the North Pacific and North America J. Clim. 27 9030–64