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California from Drought to Deluge Within the Framework of Winter Stationary Waves

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1. Introduction

The multiyear drought in California (2012-2016) was broken by a dramatic reversal in the form of extreme precipitation and flooding in early 2017. The widespread floods led to the declaration of yet another State of Emergency, this time from a very different perspective vis-a-vis the 2014 drought. Many studies that were motivated by the post-2014 drought have focused on the persistent high-pressure ridge stationed off the West Coast during the height of the drought (GRL-AGU 2015; Wang *et al.* 2014; Swain *et al.* 2014). In the winter of 2016-2017, an enhanced low-pressure trough appeared in the same location, initiating and directing sequential atmospheric river events toward California and causing high precipitation. We would like to underline that the dramatic appearance of this enhanced trough in 2016-2017 is "the other side of the coin"; this flip side was implied and even projected in some previous studies (Wang *et al.* 2014; Singh *et al.* 2016; Yoon *et al.* 2015a) analyzing the drought-producing ridge.

2. Diagnostics

One prominent feature associated with the drought winters of 2013-2015 was the extreme warm-West/cool-East surface temperature anomaly pattern in North America, accompanied by a pronounced "ridge-trough" circulation pattern in the upper atmosphere. Collectively, this temperature-wave pattern is referred to as the North American winter "dipole" (Singh *et al.* 2016; Yoon *et al*. 2015a; Wang *et al*. 2015; Swain *et al.* 2016), which coincides with the winter-mean stationary waves (indicated in Figure 1 by contours and "x/+"). The winter stationary waves establish the climatologically warmer west and colder east forming the surface temperature division of North America. Any perturbation of the climatological ridge in the west can excite downwind amplification of the eastern trough through Rossby wave dispersion and vice versa, so the two are very much anticorrelated (Wang *et al.* 2014). Consequently, an amplification of the stationary wave leads to enhancement of such differences in the atmospheric circulation and surface temperature, while a weakened stationary wave reverses it.

In early 2017, the cool-West/warm-East surface temperature pattern did indeed suggest a reversal of the dipole from that of the 2013-2015 winters. By plotting the 250-hPa geopotential height anomalies (ΔZ) during November 2016-January 2017, one can observe an opposite-phase wave pattern (Figure 1a), as compared to that for the 2013-2014 drought winter (Figure 1b). Spatial correlation analysis of ΔZ computed between the two winters yielded a significant value of -0.86, supporting their reverse correspondence. Figure 1c displays the dipole index constructed by the ΔZ difference between the ridge and trough centers, following previous studies (Wang *et al.* 2014; Singh *et al.* 2016). The 2016-2017 winter features a significantly low value, in contrast to the record high value in 2013-2014, suggesting that the 2016-2017 winter circulation leading to the California deluge resembles a reversal of the 2013-2015 situation. Though not shown here, the detrended sea surface temperature anomalies (SSTA) in the 2013-2014 and 2016-2017 winters are also

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opposite, with a significant spatial correlation of -0.7 in the North Pacific Ocean. More importantly, the 7-year running variance of the dipole index (Figure 1c light blue line) shows a pronounced increase since the beginning of the 21st century, and this dipole amplification is projected to continue (Yoon *et al.* 2015; Wang *et al.* 2015).

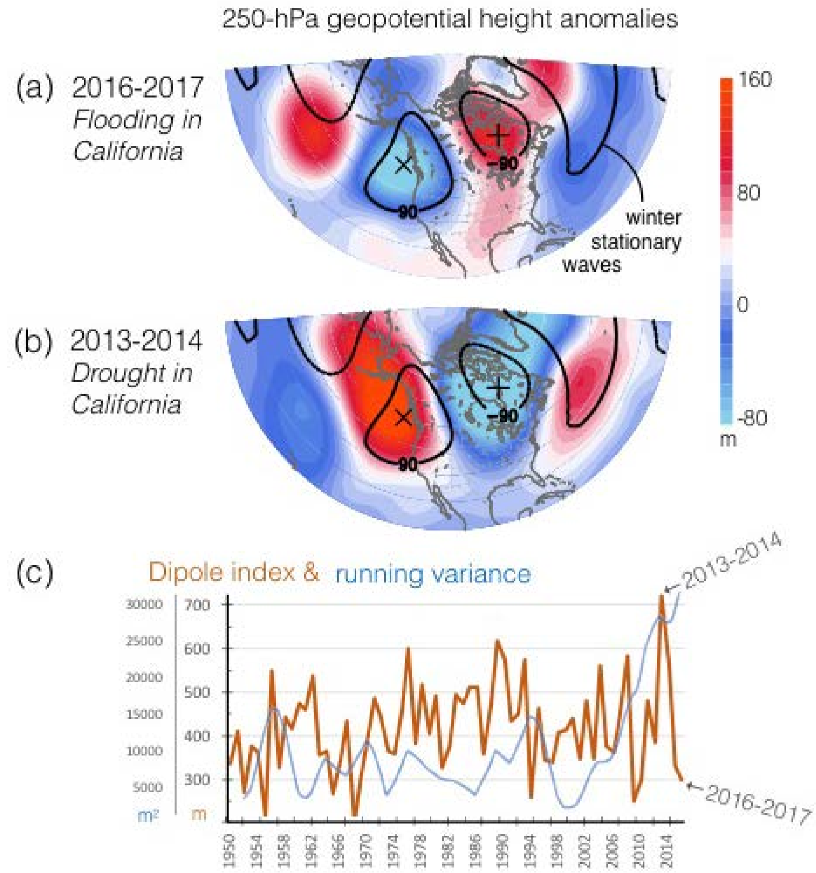

Fig. 1 November–January climatological geopotential height at 250 hPa (contour, with the zonal mean removed) depicting the atmospheric stationary waves, overlaid with the anomalies (shading) during (a) the flooding winter of 2016–2017 and (b) the drought winter of 2013–2014. The dipole location is indicated by × and + symbols over North America. Notice the geographical coincidence of each year's circulation anomalies with the dipole location and the apparent opposite patterns between the two winters. (c) The dipole index from 1950 to 2017 (orange line) along with its 7-year running variance (light blue). Data source is the NCAR/NCEP Global Reanalysis.

To further illustrate the dipole's association with winter precipitation anomalies in North America, we constructed the correlation maps of November-January (NDJ) precipitation with the dipole index for two periods (a) before and (b) after 1985, in comparison with that of three other indices: El Niño/Southern Oscillation (ENSO, *i.e.* the Nino3.4 SSTA), the North Pacific Pattern (NP), and the Pacific Decadal Oscillation (PDO) from https://www.esrl.noaa.gov/psd/data/climateindices/list/. As shown in Figure 2, the dipole's correlation with precipitation has been significant over much of the West Coast ($p<0.01$) encompassing northern and central California, and consistently so throughout the different periods. By comparison, the precipitation correlation with ENSO is much lower and highly fluctuating, averaging to only half of that of the dipole (0.32). Precipitation correlations with NP and PDO reveal weak and unstable association in California (Figure 2). Therefore, given the dipole's persistently high correlation with the California precipitation, its observed and projected amplification implies an increased impact on California's water cycle extremes, which could translate to severe drought and excessive deluge.

There is always a component of internal variability in the atmosphere that underlies the persistence of the North Pacific circulation anomalies and unique regional processes that increase event extremeness (*i.e.* without external forcing from either SSTA or of anthropogenic origin). However, a large body of research (GRL-AGU 2015) has shown evidence of remote teleconnections to North Pacific circulation stagnation through pronounced atmospheric Rossby waves of tropical origin. Warming in the West Pacific (Funk *et al.* 2014), North Pacific (Hartmann 2015), the ENSO region (Stevenson *et al.* 2012), and even the Indian Ocean (McDonald *et al.* 2016) can amplify the drought-producing ridge with differing patterns and temporal characteristics (Funk *et al.* 2014). Coupled model studies (Yoon *et al.* 2015a) have connected the strenthening of the relationship between the dipole and California's precipitation to relevant climate

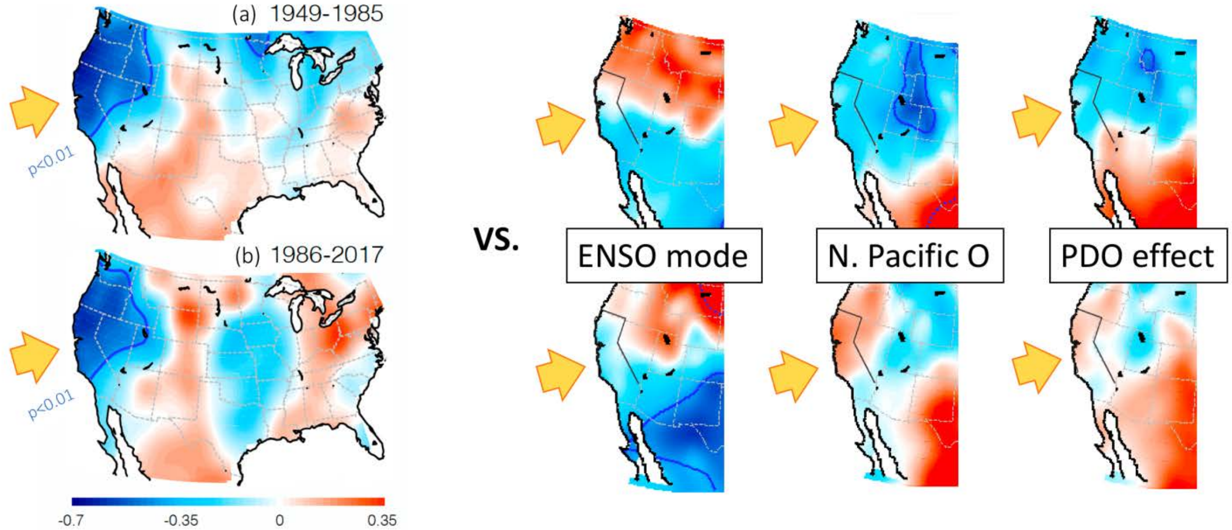

Fig. 2 Correlation maps of the November-January precipitation correlated with (from left to right) the dipole, ENSO, NP, and PDO indices during (a) an earlier period of 1949-1985 and (b) the latter period of 1986-2017. The thick contours outline significant values at the 99% confidence interval. Notice the consistently high correlations over the West Coast with the dipole including California. Precipitation data: PRECipitation REConstruction over Land (PREC/L).

oscillations with resulting projections of an increase of both drought and deluge. Other factors such as midlatitude internal atmospheric dynamics could power drought conditions regardless of ENSO conditions (Teng and Branstator 2016). Furthermore, the extent to which the warming Arctic interacts with the mid-latitude circulation and its influence on the dipole amplification has also entered the debate (Kim *et al.* 2014) suggesting that future sea ice loss may drive large changes in the regional circulation over the North Pacific (Blackport and Kushner 2017). The alternation of extreme wet/dry seasons every few years prompts the growth of vegetation, which increases "fuel" for wildfires and further increase fire danger days (Yoon *et al.* 2015b).

3. Future direction

Despite the debate concerning the causes of the drought-producing ridge in the Northeast Pacific Ocean, the various hypotheses about natural variability did suggest one thing in common: the flip-flop nature of the anomalous circulation. In other words, the amplified ridge in one winter can turn into a deepened trough in another and this tendency appears to have intensified (Figure 1c). Motivated by these recent studies, we suggest that future exploration of extreme climate anomalies in California should focus on attributing the linkages between North American winter atmospheric conditions and teleconnections under a projected warming climate. To improve the predictability of future climate extremes, the community can benefit from having coordinated numerical experiments with multiple models, with region-specific analyses on quantifying the relative importance of the internal/external factors. A cohesive evaluation and assessment should, in theory, result in more well-informed mitigation plans and water management to offset the future hazards and risks that are implied in a warming climate.

(This summary has been adopted from Wang et al. 2017.)

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