Article

Drought in the Western United States: Its Connections with Large-Scale Oceanic Oscillations

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Abstract: In this paper, we applied the Empirical Orthogonal Function (EOF) analysis on a drought index expressed as consecutive dry days (CDD) to identify the drought variability in western United States. Based on the EOF analysis, correlation maps were generated between the leading principle component (PC) of seasonal CDD and sea surface temperature (SST) anomalies to explore the dynamic context of the leading modes in CDD. The EOF analysis indicates that the spatiotemporal pattern of winter CDD is related to an integrated impact from El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO), while summer CDD is mainly controlled by PDO phases. We also calculated seasonal CDD anomalies during selected climatic phases to further evaluate the impacts of large-scale oceanic oscillation on the spatial pattern of droughts. We found that AMO+/PDO− will contribute to a consistent drought condition during the winter in the western United States. El Niño will bring a dry winter to the northern part of western United States while La Niña will bring a dry winter to the southern part. During El Niño years, the drought center changes with the type of El Niño events. Considering the future states of the examined ocean oscillations, we suggest possible drier than normal conditions in the western United States for upcoming decades, and moreover, an intensified drought for the coast areas of the north Pacific region and upper Mississippi River Basin.

Keywords: drought; spatiotemporal variability; ENSO; PDO; AMO; EOF analysis; western United States

1. Introduction

Drought, generally known as periods of short-term or prolonged deficiency in precipitation, is a recurring natural disaster that has considerable impacts on natural habitats, ecosystems, and many economic and social sectors worldwide [1]. The western United States, due to its geographic and climatological characteristics, rapidly changing social dynamics, and pressure from an expanding population, is particularly vulnerable to severe and sustained droughts [2–4]. Proxy climate indicators, such as lake–ocean sediments and tree rings, indicate that the western U.S. and surrounding regions have suffered from severe droughts, posing threats to social and ecological systems [5–9]. Moreover, recent meteorological records revealed an increasing frequency of drought, and this trend may continue in the future [10–12]. It is critical to know the evolution of drought in order to better plan for future drought disasters. Drought in the western United States originated from several large-scale ocean oscillations that reduced moisture transportation to the west. The prediction of future drought is therefore possible if the teleconnections between droughts and natural oscillations are thoroughly

examined. This will provide guidance to deal with possible future droughts that would result in increased food, energy, and water insecurity [13–15].

Drought conditions have been generally associated with quasi-periodic variations in sea surface variables [2,16]. El Niño–Southern Oscillation (ENSO) is the best-known index of the ocean oscillations which are used for the evaluation of U.S. drought variation. It represents the periodical switch of cold and warm states in the tropical eastern Pacific Ocean (warm phase: El Niño; cold phase: La Niña). ENSO reflects the inter-annual variation of climate and is considered to be related to the spatial and temporal pattern of droughts in the western U.S. [17,18]. It is generally believed that El Niño is associated with below-average precipitation and droughts in the Pacific Northwest region [19], while La Niña contributes to below-average runoff and droughts in the southwestern United States [20,21]. However, these responses are not consistent through time [22,23] which suggests that ENSO should not be the only climate fluctuation that influences weather and climate patterns in the western United States.

Recent studies of instrumental records and tree ring reconstructions suggest that U.S. drought variability is mainly controlled by long-term temperature changes in the Atlantic and North Pacific Oceans [2,24,25]. North Pacific climate variations can be characterized by decadal switches (15–25 years) of warm/positive and cold/negative phases. The temperature variation happens above 20° N in the North Pacific Ocean and is known as Pacific Decadal Oscillation (PDO) [26]. The relationships between PDO and extreme precipitation or drought has been mostly studied in terms of its modulation effects on the ENSO–precipitation relationship [27–29]. Compared to PDO, North Atlantic climate variations are characterized by a longer period fluctuation of sea surface temperature (SST) and have a multi-decadal variation between warm/positive and cold/negative phases. This is known as Atlantic Multi-Decadal Oscillation (AMO), of which the periodical length is about 60 years [30,31]. The warm phase of AMO is accompanied by an increased probability of drought in the western United States [24]. Studies by Seager et al. [32] and Schubert et al. [33] indicate that the Atlantic SST anomalies contribute to sustaining drought in the western United States. Rather than AMO alone, the AMO modulation effect of ENSO on drought has been found to be more dominant [34].

As indicated by previous studies, droughts in the western U.S. may be controlled by the complicated interactions between the natural ocean oscillation discussed above. In other words, it is the integrated or modulated effects of these natural oscillations, rather than a single factor from them, that dominate the spatial and temporal patterns of droughts in the western U.S. To investigate the integrated effects of these oceanic oscillations on droughts, Drought-Related SST Forcing patterns are mostly examined using current climate models [35–37]. In this study, drought-related SST anomaly patterns are investigated using statistical methods. The aim of this study is to provide a comprehensive analysis of spatiotemporal variability of drought in the western United States and how it is impacted by the large-scale ocean oscillations in the Pacific and North Atlantic Ocean. We seek to: (1) Determine the connections between seasonal droughts and the examined ocean oscillations; (2) investigate the integrate effects of ocean oscillations on the spatial and temporal pattern of droughts; and (3) investigate the possible drought scenarios for the upcoming decades.

2. Data and Methods

Various indices have been developed to quantify a drought including the Palmer drought severity index (PSDI) [38], standardized precipitation index (SPI) [39,40], rainfall anomaly index (RAI) [41], etc. Each of them has its own strengths and weaknesses. For example, PSDI, probably the most widely used regional drought index, accounts for the temperature and soil characteristics. However, it is limited by (1) its inherent time scale, which is more suitable for agricultural impacts than hydrological droughts, (2) assumptions that all precipitation is rain, which lead to unreliable values during winter seasons, and (3) slow responses to developing and diminishing droughts [42,43]. SPI is another widely used drought index. However, it is considered to be impacted by the length of the precipitation record and the type of probability distribution which is used to fit the precipitation series [44]. In this paper, consecutive

dry days (CDD) are used to characterize the drought in the western United States. CDD is the duration index representing periods of excessive dryness and is calculated as maximum number of consecutive dry days (daily precipitation <1 mm). It represents the length of the longest dry spell during a certain period. In this study, the CDD of winter (October–March) and summer (April–September) was calculated. It is considered an integrated CDD period when the summer/winter CDD extends to the winter/summer period. It is worth noting here that CDD is selected not because it is better than PDSI in winter or SPI to describe drought. It is easy to calculate because it requires only the precipitation records at a daily temporal scale and is not limited by the length of the records. There is also no probability distribution involved in the calculating processes. On the other hand, CDD has not been widely used in drought evaluation; the application of CDD as a drought index could thus provide new and valuable results for comparisons of drought evaluations using different drought indices.

Grid CDD value was calculated using the NOAA Climate Prediction Center (CPC) Daily US Unified Precipitation Data (quality-checked to eliminate duplicated and overlapping stations) (CPC daily Unified Precipitation Data are available from [45]). Standard deviation and buddy checks were also applied to the datasets [46]. The daily data were gridded into a $0.25^\circ \times 0.25^\circ$ resolution over the region covering $140\text{--}60^\circ$ W and $20\text{--}60^\circ$ N. The general coverage over the western United States could have been considered despite the fact that it had a sparser precipitation network than the eastern U.S. [47,48]. CPC daily precipitation spans from 1948 to present. However, the last decade of the CPC precipitation record was not included because of the apparent lack of consensus on the related AMO phase.

The leading modes of variability of CDD were investigated using Empirical Orthogonal Function (EOF) analysis [49]. This method aims to identify and extract the spatiotemporal modes which are ordered with respect to their representations of data variance and their measured "importance" or "contribution". For this study, the EOF analysis was conducted using the modified code writing in NCAR Command Language (NCL) (available from [50]). The square root of cosine of the latitude was applied to the calculated grid CDD for latitudinal distortions. The obtained EOFs displayed the spatial pattern while the corresponding Principle Components (PCs) exhibited the temporal pattern. The independence of eigenvectors was tested following a rule of thumb [51] and used to determine the number of retained EOFs.

To explore the relationships between the leading modes in CDD and SST, we generated a correlation map which showed the correlation coefficient between PCs and the SST time series. Our calculations were based on Kaplan SST V2 data [52]. The Kaplan SST V2 data consisted of monthly anomalies from 1856 to the present on a $5^\circ \times 5^\circ$ grid.

To examine the impacts of large scale ocean oscillation on drought conditions, we classified ENSO into three different ENSO types defined by Kim et al. (Table 1) [53]: Eastern Pacific warming (EPW) is generally regarded as conventional El Niño warming, which could be identified when Niño 3 region (5° N– 5° S, 150° W– 90° W) warming is larger than 1 standard deviation (SD); Central Pacific warming (CPW) is a recognized warming phase in the central Pacific region, which could be identified when Niño 4 region (5° N– 5° S, 160° E– 150° W) warming is larger than 1 SD and in the meantime, Niño 3 stays below this range; and Eastern Pacific cooling (EPC) is regarded as a conventional La Niña event, which could be defined when Niño 3 or Niño 3.4 region (5° N– 5° S, 170° W– 120° W) is cooler than 1 SD. We also classified periods of positive (warm) and negative (cold) PDO and AMO combinations (Table 1) based on PDO (PDO time series are available from [54]) and AMO time series (AMO time series are available from [55]). Summer and winter CDD anomalies were calculated for these periods. A permutation re-sampling method was applied to test the statistical significance of the anomaly patterns [29]. We randomly sampled sets of years (N years) without replacement from the study period, N equals the number of years in each climatic phase (for example, N equals 9 for EPW as there are 9 years for EPW events). The sampling process was repeated 1000 times, and during each sampling process, we calculated the grid CDD anomaly (the CDD anomaly was obtained as the difference between CDD value of selected years and average CDD value of the whole study period) for each

randomly sampled year. The seasonal average CDD anomaly is considered significantly anomalous at 0.1 level if its magnitude exceeds the 95th or 5th percentile of the CDD anomaly, determined by the random permutations.

Table 1. El Niño–Southern Oscillation (ENSO) event and Pacific Decadal Oscillation–Atlantic Multi-decadal Oscillation (PDO–AMO) combinations.

ENSO Event	Years
EPW	1951, 1957, 1963, 1965, 1972, 1976, 1982, 1987, 1997
CPW	1969, 1991, 1994, 2002, 2004, 2009
EPC	1949, 1955, 1964, 1970, 1971, 1973, 1975, 1985, 1988, 1995, 1998, 1999, 2007
PDO–AMO Combinations	Years
AMO+ PDO–	1948–1963; 1999–2009
AMO– PDO–	1964–1976
AMO– PDO+	1977–1994
AMO+ PDO+	1995–1998

3. Results and Discussion

3.1. The Spatiotemporal Pattern of Droughts Based on EOF Analysis

The EOF modes of CDD were evaluated for both summer and winter periods using the EOF analysis program coded with NCL. Figures 1a and 2a show EOF patterns determined by the EOF analysis program. Figures 1c and 2c are the associated time series (or principle component). Figures 1b and 2b are the correction maps generated by spatial plots of corrections between selected PC of seasonal CDD and grid sea surface temperature (SST) anomalies. The first EOF mode was selected for our analysis based on the independent test [51]. The other modes were not discussed because they were not independent or not distinct from their nearest neighbors. The first mode of winter CDD explains 31.2% of the total variance. The correlation map (Figure 1a) shows a north–south dipolar pattern. The north region is centered at the eastern part of the Pacific Northwest and western part of the Upper Mississippi River Basin. The larger south region covers most of the Great Basin and Colorado River Basin as well as southern California. The PC of the first mode negatively correlates with SST anomalies north of 20° N in the North Pacific Ocean (considered PDO), positively correlates with SST anomalies over the central eastern Pacific Ocean (considered ENSO SST field), and negatively correlates with SST anomalies over the North Atlantic Ocean (considered as AMO SST field). The complex relationships between the first PC of the winter CDD and SST anomalies indicate that spatiotemporal patterns of winter CDD result from an integrated effect of several large-scale ocean oscillations (Figure 1b).

For the summer period, the first EOF explains 13.5% of the total variance of summer CDD and displays a north–south dipolar spatial pattern. However, the north region is much larger than that of the winter CDD, which covers the whole area of the North Pacific Region and Upper Mississippi River Basin. In contrast, the south region is much smaller and centered in the southwestern arid desert region. The first PC of the summer CDD correlates with SST anomalies north of the North Pacific Ocean. However, it is not like the typical PDO SST map, as part of the summer SST anomaly lies south of the 20° N in the North Pacific Ocean. One possible reason is that there may be some modulated effects either from ENSO or other unknown factors on PDO, which needs future research.

Figure 1. Empirical Orthogonal Function (EOF) analysis of winter consecutive dry days (CDD): (a) Spatial pattern of the winter CDD (1948–2009); (b) correlation coefficient between principle component (PC) and annual sea surface temperature (SST) anomalies; (c) the corresponding principal components of winter CDD. Contoured lines indicate regions with significant correlations at 0.05 level. The Western Pacific is not shown as there is no significant SST anomaly in this region.

Figure 2. EOF analysis of summer CDD: (a) Spatial pattern of the summer CDD (1948–2009); (b) Correlation coefficient between PC and annual SST anomalies; (c) the corresponding principal components of summer CDD. Contoured lines indicate regions with significant correlations at 0.05 level. Western Pacific is not shown as there is no significant SST anomaly in this region.

3.2. The Relation between Large-Scale Ocean Oscillations and Seasonal Droughts

Figure 1 indicates a complicated relationship between winter CDD and multiple ocean oscillations. Winter CDD is related to both ENSO conditions and the climatic phases of PDO and AMO. Considering the different temporal scale between the ENSO phase and PDO–AMO phases, our analysis was

conducted separately on different ENSO types and PDO–AMO combinations. ENSO is the dominant mode of inter-annual variability in the Tropics, and it has been connected to the drought variability of the western United States [17,56]. El Niño and La Niña represent warm/positive and cold/negative phases of ENSO. Traditional El Niño is characterized by eastern Pacific warming (EPW), but recent studies have identified a new type of El Niño with its maximum warming in the equatorial central Pacific (CPW) [57,58]. The two different El Niño events may lead to different atmospheric teleconnections and further impact on the delivery of water vapor [59]. To investigate how different ENSO types could influence the spatiotemporal distribution of CDD, three ENSO types were classified and listed in Table 1. The remaining years during the study period were considered normal years. The grid CDD anomaly during each ENSO type (for example, EPW) was calculated by subtracting the average CDD value during EPW years with the average CDD value during the whole period. Then, the standardized CDD anomaly was determined for each grid. Figure 3 is the map which displays the standardized CDD anomaly for each grid (the same as CPC grid). The spatial pattern of winter CDD anomalies displays an obvious north–south dipole pattern during EPW, CPW, and EPC years (Figure 3a–c). This pattern disappears during normal years (Figure 3d). During EPW and CPW years, the southwestern United States experience less than normal CDD while the northwestern states experience larger than normal CDD. In other words, the northwestern United States will suffer more drought events during El Niño years (EPW and CPW) while the southwestern United States will encounter more drought events during La Niña years (EPC). This is consistent with previous studies that El Niño is associated with below-average precipitation and droughts in the Pacific Northwest region while La Niña contributes to below-average runoff and droughts in the southwestern United States [19–21]. Although the spatial patterns of drought are similar in EPW and CPW years, the action centers do present some difference: During EPW years, the drought center is mainly located in the Upper Mississippi River Basin while in the CPW years, the drought center expands to the coast area of the north Pacific Region, which is consistent with conclusions from Yu and Zou that CPW produces an enhancing drying effect on the Ohio–Mississippi Valley and north Pacific Region [60]. Moreover, the wet region during CPW years is much larger to the north than that during EPW years. To evaluate the coupling effects of PDO and AMO, four periods are identified covering all possible groups of PDO and AMO phases (Table 1). The length of the AMO+/PDO+ group is only 3 yrs during the study period. As a result, we did not discuss the CDD anomalies during AMO+/PDO+ as it may have introduced random errors to the analysis. The spatial pattern of drought is more consistent for the whole western United States when PDO and AMO are opposite phases (Figure 4a,b). Most of the western United States is under drought conditions (larger than normal CDD) during AMO+/PDO– and wet conditions (less than normal CDD) during AMO–/PDO+ (Figure 4c). This confirms the findings from McCabe et al. [24] that the western U.S. bears a drought condition in AMO+ while the phase of PDO determines the location of the drought center (the drought center tends to be in the northern part during PDO+ and the southern part during PDO–). During AMO–/PDO–, there is no obvious spatial pattern. The physical mechanism behind it is that the large-scale oceanic oscillations introduce or are associated with different pressure patterns that control the storm track position into the western U.S. El Niño is associated with deep Aleutian Low which forces the storm track southwards, the jet stream over the Pacific Ocean becomes less wavy and splits into a strengthening subtropical jet stream near the equator, and a weaker polar jet stream and can result in less storms and below-average precipitation across the Pacific Northwest during winter and early spring. In contrast, during La Niña years, the Pacific jet stream carves north and enters North America through the Pacific Northwest, diverting storms and precipitation away from the southwestern U.S., thus, bringing drier-than-average winter conditions to the Southwest. The physical mechanism of Atlantic SST anomalies on the western U.S. drought is still not clear based on current studies. It could be that Atlantic SST anomalies influence the southerly flow on the western flank of the North Atlantic and change the strength of westerlies across the mid-latitudes and thus, can have a modulation effect on precipitation patterns far away from the North Atlantic region.

Figure 3. Winter CDD anomalies (standardized) for (a) Eastern Pacific warming (EPW), (b) Central Pacific warming (CPW), (c) Eastern Pacific cooling (EPC), and (d) normal years. Contoured lines indicate regions with significant correlations at 0.1 level.

Figure 4. Winter CDD anomalies (standardized) for different AMO/PDO combinations. Contoured lines indicate regions with significant correlations at 0.1 level.

The summer CDD is mainly dominated by the PDO phase as indicated by the EOF analysis (Figure 2). As a result, the standard summer CDD anomalies during different PDO phases were calculated and presented in Figure 5. It shows that the western United States is under drought mode during summer when PDO is in the negative phase (cold phase) and wet mode when PDO is in the positive phase (warm phase). The spatial pattern is consistent for the whole western United States during each PDO phase.

Figure 5. Summer CDD anomalies (standardized) for different PDO phases. Contoured lines indicate regions with significant correlations at 0.1 level.

3.3. Future Drought Scenarios Based on the Prediction of Ocean Oscillations

Based on the analysis, long term predictions of drought conditions in the western United States may be partly explained if future predictions of ocean oscillations are available. AMO is considered to have returned to its positive phase in 1995 and will continue to be positive for the next one to three decades [30,61–63]. Current negative PDO may continue based on simulations from multiple climate models [64,65]. Future forecasting of ENSO states are more reliable as short term (<8 months) [66–68] rather than long term predictions. The frequency of CPW has been predicted to increase due to various reasons suggested by Jin et al. [69], Timmermann et al. [70], and Yeh et al. [58]. However, one recent study by Cai et al. [71] shows that EPW exhibits a robust increased frequency due to global warming as predicted by current climate models. This finding is valuable in climatic research but also needs further assessment when other climate models are available. Regardless of the uncertainty of the future frequency of EPW and CPW, an increased El Niño frequency is expected in the future. In this situation, the drought conditions during summer will continue. The northwestern United States will be in a drought mode during winter and this drought condition will become even worse for the Upper Mississippi River Basin.

4. Conclusions

In summary, we have examined the spatiotemporal pattern of seasonal drought conditions (represented by CDD) in the western United States and how this pattern could be impacted by large scale ocean oscillations. We found that winter CDD is related to an integrated impact of ENSO, PDO, and AMO while summer CDD is mainly controlled by PDO phases. Our results also indicated that AMO+/PDO– will contribute to a consistent drought condition during winter over the whole western United States. El Niño will bring a dry winter to the northern part of the American West while La Niña will bring a dry winter to the Southwest, which confirms and strengthens findings from previous studies [19–21,24]. In particular, it is clear that the drought center and drought severity changes with the type of El Niño events: The more frequent shifts of El Niño locations from the Eastern Pacific region to the Central Pacific region may force the tropospheric jet streams further southward with profound impacts on the prevalence of extended droughts in the western U.S.

Moreover, the results could be used for long-term prediction of the seasonal drought conditions over the western U.S. The persistence of the current AMO+ state, the projection of negative PDO, and the increasing El Niño frequency will lead to a dry summer and winter in the western U.S. Moreover, the coastal area of the North Pacific region and Upper Mississippi River Basin will suffer from even worse dry conditions due to the increasing frequency of CPW.

It is worth noting that besides the ocean oscillations discussed in this study that influence the seasonal variations of droughts, other factors such as anthropogenic global warming and human water consumption style also appear to be important. Global warming is likely to enhance the evaporative demand and alter monsoon circulation and thus, is responsible for intensifying the meteorological drought [72–74]. Human water consumption, on the other hand, leads to more severe hydrological droughts [75,76]. These impacts on future drought could be investigated by numerical modeling or statistical analysis on current global climate model outputs [77]. However, it is still a big challenge to investigate the nonlinear interactions between these natural oscillations and human impacts. An extension of current research to investigate the integrated effects of the natural and the anthropogenic on future drought evolution is the subject of ongoing work.

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