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Pacific and Atlantic Ocean influence on the spatiotemporal variability of heavy precipitation in the western United States

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ABSTRACT

In this study, we test our hypothesis that no single index such as El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multi-decadal Oscillation (AMO) or North Atlantic Oscillation (NAO) derived from the Pacific and Atlantic Oceans can explain the multi-scale temporal variability and spatial distribution of heavy precipitation in the western United States. Instead, it may be possible to utilize a characterization of their integrated effect or some other unidentified factors which reflects the combined physical oceanic–atmospheric processes that occur. For this purpose, Empirical orthogonal function (EOF) analysis is performed on summer (April–September) and winter (October–March) heavy precipitation expressed as total precipitation when daily precipitation is larger than 95th percentile (R95) to indentify the leading modes of variability during the period 1948–2009. The correlation between the principle components (PCs) of each EOF mode with Sea Surface Temperature (SST) anomalies is evaluated. The analysis has shown that the leading modes of R95 variability and the connections between local R95 and SST over western United States are seasonally dependent. The first EOF mode of summer R95 is associated with AMO. The first two EOF modes of winter R95 are related to an integrated effects of ENSO, PDO, and NAO which explain nearly half (49%) of the spatial and temporal variance in R95 in this region. Additionally, the coupled effects of these three oceanic–atmospheric oscillations on winter R95 are evaluated by investigating the ENSO-R95 responses modulated by a combination of different PDO and NAO phases. Based on our analyses and predicted future states of these oceanic–atmospheric oscillations, we suggest possible heavy precipitation scenarios for upcoming decades which may be useful to forecasters and water managers.

1. Introduction

The western United States is undergoing rapidly changing social dynamics, pressure from an expanding population and a greater risk of water shortage and flooding (Piechota et al., 2004; Mote et al., 2005; Hamlet and Lettenmaier, 2007). As a result, the system becomes more vulnerable to the climatic extremes. A long-term view into the spatiotemporal pattern of precipitation extremes is expected to help plan for flood disasters (Yang et al., 2010). Several large-scale oceanic and atmospheric oscillations are thought to affect the delivery of moisture to the United States, thus influencing the spatiotemporal distribution of precipitation extremes. The predictability of future precipitation extreme scenarios is therefore possible if we can thoroughly understand the relationship between spatiotemporal variability of precipitation extremes and large-scale ocean oscillations, and will help us prepare for the future possible extreme precipitation scenarios in the west United States, which can be useful to water resources engineers and managers.

Recent research regarding the influences of quasi-periodic variations in sea surface variables has shown growing promise for long-range probabilistic forecasts of precipitation extremes. Several oceanic–atmospheric indices are used to explain the variability of precipitation extremes in the United States. The best known of these is ENSO with two basic phases (warm phase: El Niño; cold phase: La Niña) of the tropical eastern Pacific Ocean. ENSO helps to explain the occurrence of heavy winter precipitations at inter-annual temporal scales in the western United States (Cayan et al., 1999; Meehl et al., 2007). The extreme precipitation is sensitive to the ENSO phase: Most of the southwest United States experiences more than double heavy precipitation events during El Niño years compared to La Niña years (Cayan et al., 1999).

The PDO is another well-known oceanic index, which may help to depict the decadal variability of precipitation extremes. It is distinguished by warm and cold phases at decadal-scale periods of the North Pacific Ocean north of 20°N (Mantua et al., 1997). Correspondence between extreme events and PDO was investigated by Hidalgo (2004) suggesting that PDO phase is correlated with above- and below-average precipitation in the Colorado River Basin. Other

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available studies focus on the modulation of PDO cycle on the ENSO-precipitation signal (McCabe and Dettinger, 1999; Gutzler et al., 2002; Brown and Comrie, 2004; Kurtzman and Scanlon, 2007; Arriaga-Ramírez and Cavazos, 2010; Wise, 2010; Timm et al., 2011; Cai and van Rensch, 2012).

Besides the two well-known indices, the recently developed index of the AMO is also found to be associated with the multi-decadal variability of boreal summer precipitation and extreme events (Enfield et al., 2001; Sutton and Hodson, 2005; Wang et al., 2006; Curtis, 2008; Mo et al., 2009). This long-term fluctuation of SST in the North Atlantic Ocean exhibits a multi-decadal shift between warm and cool periods with each lasting about 30 years (Kerr, 2000; Enfield et al., 2001). The warm phase (AMO+) is accompanied by a reduced rainfall over most of the United States (Enfield et al., 2001) including northwest United States and Great Plains (Wang et al., 2006) and an increase in precipitation intensity in southwest and coastal southeast United States (Curtis, 2008). The cool phase, on the contrary, has an opposite relationship with precipitation and extremes in these regions (Feng et al., 2011; Oglesby et al., 2012). Another long term oscillation associated with North Atlantic Ocean is NAO which is an atmospheric oscillation with two action centers located near Iceland and subtropical Atlantic. This pattern is identified in northern Europe, and the eastern United States. It is found to affect extreme precipitation regionally, such as on the eastern seaboard of the United States (Zhang et al., 2010). However, regions far away from the northern Atlantic Ocean also experience significant NAO-related impact (Visbeck et al., 2001).

Most current studies focus on the relationship between total precipitation and the large-scale oceanic–atmospheric oscillations. Changes in the total precipitation are responsible for disproportionate changes in precipitation extremes, but they don't always go in the same trend (Easterling et al., 2000). As a result, independent studies into the spatiotemporal variability of precipitation extremes shaped by the large-scale ocean oscillation are necessary. However, there have been relatively few studies regarding the spatiotemporal variability of precipitation extremes caused by multi-scale temporal fluctuations of SST in both Pacific Ocean and North Atlantic Ocean such as PDO and AMO.

Available studies mostly investigate the impacts of large-scale oceanic–atmospheric oscillations especially the impacts of ENSO on precipitation extremes (Cayan et al., 1999; Meehl et al., 2007). However, it is highly possible that spatiotemporal variations in the occurrence of precipitation extremes in the western United States involve complex interactions between the Atlantic and Pacific Oceans (represented by ENSO, PDO, AMO, and NAO in this paper). We hypothesize that no single feature from them can explain all the spatiotemporal variations: it is the integrated effect of them or some other unidentified factors that control the multi-scale temporal variability and spatial distributions of precipitation extremes in this region.

In this paper, we strive to offer a comprehensive analysis of impacts from Pacific and North Atlantic Ocean on the spatiotemporal variability of precipitation extremes in western United States. We seek here to, (1) determine how much variance of seasonal (summer period: April–September; winter period: October–March) precipitation extremes these ocean oscillations including ENSO, PDO, AMO, and NAO explain; (2) understand the integrated impacts from Pacific and North Atlantic Ocean on multi-scale temporal variability and spatial distributions of seasonal precipitation extremes; and (3) explore possible extreme precipitation scenarios for the upcoming decade based on the projected conditions of the three oceanic indices (Latif and Barnett, 1996; Yeh et al., 2009; Lapp et al., 2012).

2. Data and methods

Analyses for this study are based on NOAA Climate Prediction Center (CPC) Daily US Unified Precipitation data (available from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/). This dataset is derived from 3 sources including NOAA's National Climate Data Center (NCDC) daily co-op stations from 1948, CPC dataset (River Forecast Centers data 1st order stations from 1992), and daily accumulations from hourly precipitation dataset from 1948. The daily data were gridded at a horizontal resolution of 0.25° × 0.25° using inverse-distance weighting interpolation algorithms of Cressman (1959). Quality control methods such as "duplicate station check", "buddy check", and standard deviation check were conducted against the dataset to exclude the keypunch errors and extreme values errors and to compare it with daily rain gauge data correspondingly (Higgins and Center, 2000). Although the station density used for this dataset is sparser in the west than the eastern two-thirds of the United States, the general coverage over this region could be considered (Chen et al., 2008; Higgins et al., 2008).

Five key indices (Table 1) suggested by Frich et al. (2002) are usually chosen for the analysis of changing precipitation patterns. The five indices cover changes in intensity, frequency and duration of precipitation events and belong to 5 different categories (Alexander et al., 2006; Yang et al., 2011): (1) percentile-based indices (R95), (2) absolute indices representing maximum or minimum values within a season or year (R5D), (3) threshold indices defined as the number of days on which a temperature or precipitation value falls above or below a fixed threshold (R10), (4) duration indices representing periods of excessive warmth, cold, wetness or dryness or in the case of growing season length, period of mildness (CDD), and (5) other indices such as intensity index (SDII). R95 is used to measure heavy precipitation that exceeds 95 percentile thresholds which covers, but does not limit to most extreme precipitation events in a year (Alexander et al., 2006). R5D represents very heavy precipitation. R10 calculates the annual count of days when daily precipitation is larger than10 mm. Threshold indices such as R10 are region dependent. R10 is not necessarily meaningful in a global scope especially in the Intermountain West with a heterogeneous precipitation (Alexander et al., 2006). CDD represents the length of the longest dry period in a year and focuses more directly on the evaluation of droughts. SDII accounts for both the total amount of annual precipitation and the number of days when rainfall exceeds 1 mm. Rather than capturing the tail of the distribution such as R95 and R5D, SDII is more likely to show the middle of the distribution. Given the great spatial variability of precipitation in the West, R95 is selected for the calculation of the seasonal extreme precipitation based on the CPC daily precipitation data.

EOF analysis (Lorenz, 1956; Preisendorfer, 1988; Roxy et al., 2013) is applied to the seasonal R95 for finding out the leading modes of variability. This method is a decomposition of dataset by orthogonal functions. It investigates the variability of a single field such as one scalar variable (Temperature, Precipitation, etc). The method finds both spatial and temporal patterns of variability, and measures the "importance" or "contribution" of each pattern. In this paper, the EOF analysis is used to understand the spatiotemporal structure of the long-term variations of the seasonal precipitation extremes over

Table 1
Five indices of precipitation extremes as described by Frich et al. (2002).[a]

Index	Definitions	Units
R10	Total count of days when RR ≥ 10 mm	days
CDD	Maximum number of consecutive dry days with RR < 1 mm	days
R5D	Maximum 5-day precipitation total	mm
SDII	Total precipitation divided by the number of wet days	mm/day
R95	Total precipitation when RR > 95th percentile	mm

[a] Abbreviations are as follows: RR, daily precipitation. A wet day is defined when RR ≥ 1 mm, and a dry day is defined when RR < 1 mm.