

The Spatiotemporal Characteristics of Extreme Precipitation Events in the Western United States

Peng Jiang¹ · Zhongbo Yu² · Mahesh R. Gautam³ ·
Kumud Acharya¹

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Abstract Changes in the frequency or intensity of extreme precipitation events would have profound impacts on both human society and the natural environment. In this paper, we present the results of a comprehensive analysis of the spatiotemporal changes of extreme precipitation in the western United States. The analyses explore the spatial characterization of the El Nino-Southern Oscillation (ENSO)-extreme precipitation response pattern and identify the multi-scale temporal variability in precipitation extremes in the western United States. Results indicate: (1) Extreme precipitation expressed in indices such as seasonal count of days when precipitation is large than 10 mm (R10), seasonal maximum 5-day precipitation (R5D), maximum length of dry spell (CDD), and seasonal total precipitation exceeding 95 percentile (R95) have a dipolar pattern and a transition zone which separates the west into two main dipolar centers regarded as Pacific Northwest and Desert Southwest. The simple precipitation intensity index (SDII) has little correlation with large scale natural oscillations over most of the west. (2) The spatial distributions of annual trend of R10, R5D, SDII, and R95 have seasonal variability in southern California and Lower

✉ Peng Jiang
peng.jiang@dri.edu

✉ Zhongbo Yu
zyu@hhu.edu.cn

¹ Division of Hydrologic Sciences, Desert Research Institute, 755 E Flamingo Road, Las Vegas, NV 89119, USA

² State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China

³ Division of Flood Management, California Department of Water Resources, Sacramento, CA 95821, USA

Colorado River Basin. (3) There are consistent multi-year bands ranging from 2 to 20 years in the R10, R5D, CDD, and R95 winter time series which may be caused by the inter-decadal or multi-decadal modulation of ENSO effects on precipitation extremes. The results can provide beneficial reference to the prediction of precipitation extremes in the west.

Keywords Spatiotemporal variability · Extreme precipitation · Large-Scale Ocean oscillation · Enso · Dipolar pattern · Multiscale temporal variability

1 Introduction

Changes in the frequency or intensity of extreme precipitation events would have profound impacts on both human society and the natural environment (Sena et al. 2012; Vasiliades et al. 2015; Yilmaz and Perera 2015). Research into possible changes of precipitation extremes in a changing climate in the United States involve; (1) the effects of large-scale climate fluctuations on extreme precipitation (Cayan et al. 1999; Gershunov 1998; Gershunov and Barnett 1998; Jiang et al. 2013b; Kunkel et al. 2003; Meehl et al. 2007), and (2) trends in precipitation extremes under human-induced climate change (Adamowski et al. 2010; Easterling et al. 2000; Groisman et al. 2005; Groisman et al. 2001; Karl and Knight 1998; Karl et al. 1995; Kunkel et al. 1999; Yu et al. 2015). It is expected that an intensification of precipitation extremes will happen as global warming induces a large increase in atmospheric water vapor content which makes a more accelerated hydrological cycle (Allen and Ingram 2002; Houghton 2001; Meehl et al. 2000; Semenov and Bengtsson 2002). Thus, human-induced global warming introduced an increasing trend in the extremes of precipitation over US during the past few decades (Meehl et al. 2000; Min et al. 2011; Zhang et al. 2007). Meanwhile, Kunkel et al.(2003) suggested the natural variability makes a non-negligible contribution to the recent extreme precipitation values as extreme precipitation events have higher frequencies for all durations and return periods during 1895–1905 period when there is little enhanced greenhouse gas forcing than 1900–2000. It is also found that the changing extreme precipitation is sensitive to the ENSO phase (Cayan et al. 1999; Meehl et al. 2007; Vasiliades et al. 2015). Most of the southwest U.S. experienced more than double heavy precipitation events during El Nino years compared to La Nina years (Cayan et al. 1999), and anomalously intense precipitation in the Southwest U.S. expanded eastward (Meehl et al. 2007). These studies indicate that both the human-induced climate change and natural variability are important contributors to the intensification of precipitation extremes.

Previous researches have addressed the spatial variations of extreme precipitation (Darand and Daneshvar 2014; Jiang et al. 2016; Saidi et al. 2015; Shi et al. 2015; Yilmaz and Perera 2015; Yuan et al. 2015). However, they examined the spatial variability of extreme precipitation using climate divisions, sparse stations, climate regions, or states which cover large areas in the west and therefore may neglect the spatial variability in a finer scale as needed for the intermountain west with a heterogeneous precipitation distribution. Redmond and Koch (1991), Brown and Comrie (2004), and Wise (2010) introduced the concept of precipitation dipole transition zone that an east-west region in which the ENSO-precipitation relationship

is weak (hereafter regarded as ‘transition zone’) divides the west United States into Northwest and Desert Southwest where the precipitation exhibits an opposite response to Southern Oscillation Index (SOI) (hereafter regarded as ‘dipole’ or ‘dipolar pattern’). As an extension of their research, questions like ‘do precipitation extreme indices have the similar dipolar patterns?’, and if so, ‘what’s the boundary between these dipole centers?’ have not been answered.

Studies on the temporal variability of extreme precipitation events mainly concentrated on annual trend of different extreme precipitation indices. However, studies by Cayan et al. (1999), Karl and Riebsame (1989), Ryu et al. (2010), and Jiang et al. (2013a) indicated that extreme precipitation events are corresponded to long term climate oscillations such as ENSO and Pacific Decadal Oscillation (PDO) in the southwest United States. As a result, extreme precipitation may have multi-scale temporal characteristics. It is necessary to understand the evolution of extreme precipitation event in the perspective of multi-scale temporal variabilities ranging from season, annual, inter-annual to decadal variations.

Our work strives to offer a comprehensive analysis of spatiotemporal changes in precipitation extremes in western United States. We seek to: (1) determine the spatial characterization of the ENSO-extreme precipitation response pattern; and (2) identify multi-scale temporal variability in precipitation extremes in the western United States. The western United States is undergoing rapidly changing social dynamics and pressure including increasing population and a greater risk of water shortage (Mote 2006; Mote et al. 2005; Piechota et al. 2004). Better understanding of spatial correlation between large scale climate pattern and extreme precipitation and the multi-scale temporal variability of different extreme precipitation indices due to the natural climate variability and human-induced climate change will benefit water resource management and climate forecasting in this area.

2 Data and Methods

2.1 Grid Precipitation Data and Ocean Oscillation Index

Analyses for this study are based on NOAA Climate Prediction Center (CPC) Daily US Unified Precipitation Data at 0.25-by-0.25° resolution (*available from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <http://www.esrl.noaa.gov/psd/>*), and monthly ocean indices including Southern Oscillation Index (SOI) (obtained from the University of East Anglia’s Climatic Research Unit). The CPC daily data used in this study 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 data were gridded using a Cressman Scheme (Cressman 1959).

2.2 Definition of Extreme Indices

In this study, five key indices (Table 1) suggested by Frich et al.(2002) were chosen to analyze the spatial characterization of the ENSO-extreme precipitation response

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	Annual total precipitation when RR > 95th percentile	mm

^a Abbreviations are as follows: RR, daily precipitation. A wet day is defined when $RR \geq 1$ mm, and a dry day is defined when $RR < 1$ mm

pattern and multi-scale temporal variability in precipitation extremes. The five selected indices cover changes in intensity, frequency and duration of precipitation events and belong to 5 different categories as suggested by *Alexander et al. (2006)*: (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). Most indices used in previous studies (*Alexander et al. 2006*; *Yang et al. 2011*) are defined in the same way.

2.3 Spatial Characterization of the ENSO-Extreme Precipitation Response Pattern

The spatial characterization of the ENSO-extreme precipitation response pattern was analyzed base on the SOI-precipitation extreme indices connection. Earlier studies (*Redmond and Koch 1991*; *Wise 2010*) have shown that Jun-Nov average SOI exhibits strong relationship with winter precipitation in the west. In this study, the five indices in Table 1 were obtained for the winter period (Oct-Mar). Correlation between Jun-Nov SOI and each of the five indices listed in Table 1 was calculated for each 0.25°-by-0.25°grid. The transition zone were defined as *Wise(2010)* suggested, which shows weak ENSO-extreme precipitation relationship based on the correlation coefficient and divides the west into two main regions with opposite extreme-precipitation responses to ENSO phase. Coefficient Correlation Test was conducted at 0.05 level for each grid. The boundary of the transition zone and dipole centers was delineated by the line that separates the grids in which the correlation was considered significant from the grids in which the correlation was considered insignificant at 0.05 level.

2.4 Multi-Scale Temporal Variability of Extreme Precipitation Indices

For the analysis of multi-scale temporal variability of extreme precipitation indices, annual trend, inter-annual fluctuations, and inter-decadal oscillations of five selected extreme indices were examined in this study. The annual trend was expressed in linear trend for each CPC grid while inter-annual and inter-decadal fluctuations were

analyzed using wavelet analysis for 5 regions including the Great Basin, Pacific Northwest, California, Upper Colorado River Basin (UCRB), and Lower Colorado River Basin (LCRB). Wavelets have become a popular mathematical tool as they are capable of providing localized information by breaking the time series into both the time and frequency domains (Westra and Sharma 2006). They are powerful to analyze the non-stationary extreme precipitation time series where variability cannot be explained by a single natural oscillation.

3 Results

3.1 Dipolar Pattern of Extreme Precipitation

The correlation between five indices of precipitation extremes, as well as total precipitation during the winter period (Oct-Mar) and Jun-Nov SOI exhibits dipolar patterns and has a transition zone (Fig. 1.). They display some similarities but substantial differences among them in terms of the position of north-to-south dipolar region and the width of the transition zone. The SOI is in positive (negative) correlation with RTOT, R10, R5D, SDII, and R95 in the northern (southern) sections of dipole, while the correlation between SOI and CDD is in an opposite pattern. For all the indices, especially RTOT, the Southwest is more strongly and cohesively correlated with SOI than the Northwest. Both the position and area of the dipolar pattern of R5D and R95 are very similar. They have two main anomalous areas outside of the transition zone which may result from the effect of topography: a region with low elevation in eastern Washington and eastern side of Rocky Mountains. This is similar with the findings from Wise (2010). The transition zones of R5D and R95 are wider than the one of RTOT. For R10, the dipolar regions lie outwards to the west. The Northern section is restricted to Pacific Northwest Basin and the Southern section is restricted to California basin and Lower Colorado River Basin (LCRB). CDD exhibits an opposite dipolar pattern to the other indices as it represents the extreme dry conditions while the other indices express extreme wet conditions. The dipolar region of CDD shifts eastwards compared to the dipolar region of the other extreme indices and the southern section is much larger than the northern one. Compared to the other four extreme indices and total precipitation, SDII lacks an obvious dipolar pattern, most part of the western area has near-zero correlation coefficient. The correlation coefficient in the coastal area is higher and exhibits a dipolar pattern. However, in most areas, the correlation is not statistically significant.

3.2 Multi-Scale Temporal Variability of Extreme Precipitation Indices

Multi-scale temporal variability of extreme precipitation indices is conducted by showing spatial distribution of annual trend and regional inter-annual to decadal variability of summer and winter extreme precipitation indices listed in Table 1. The spatial distribution of annual trend is displayed for the whole Western U.S., but our results presented here are limited to five water-resources regions (USGS, Hydrologic

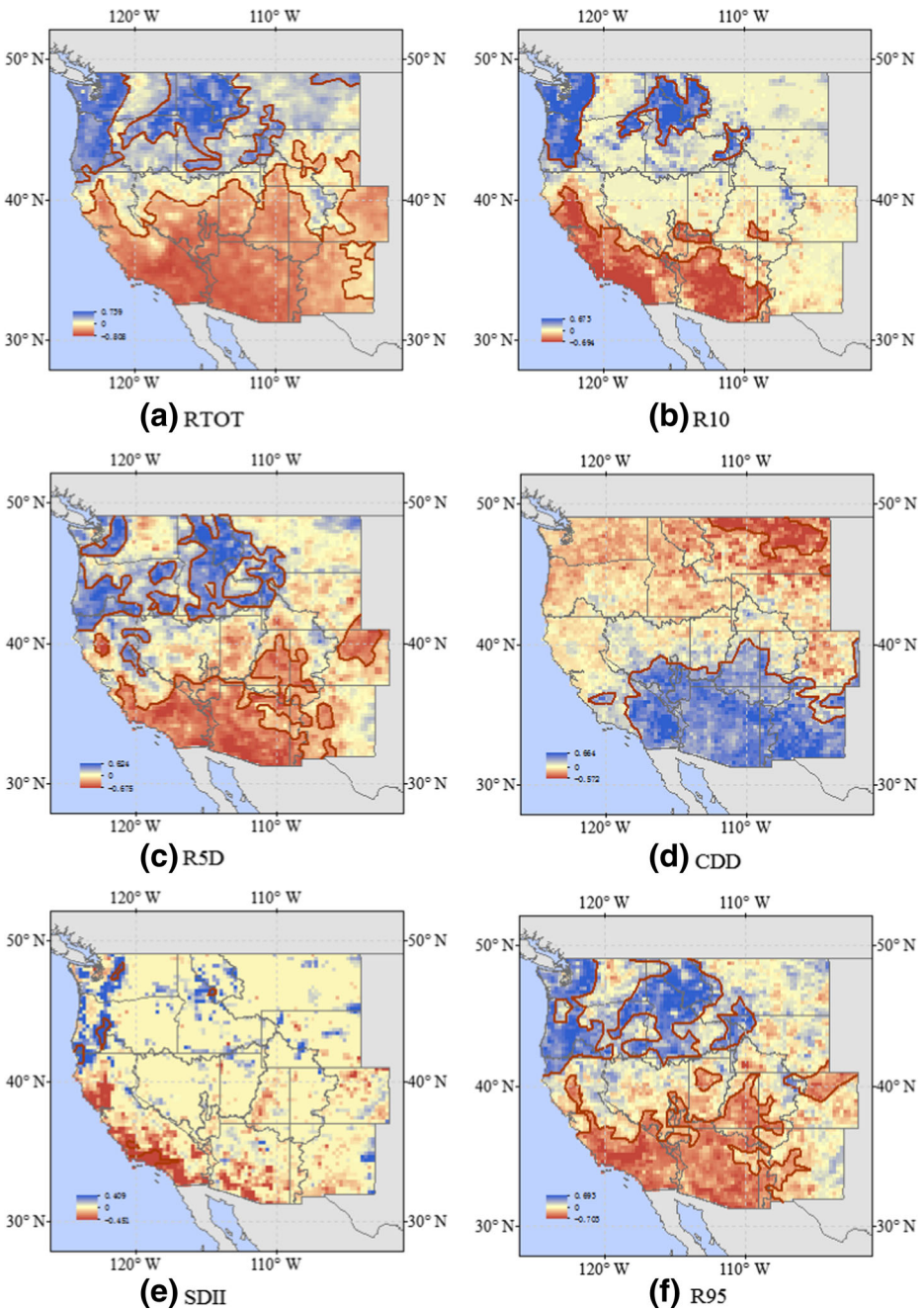


Fig. 1 Correlation coefficients between Jun-Nov SOI and (a) total precipitation during Oct-Mar and (b)-(f) five extreme indices, 1948–2009

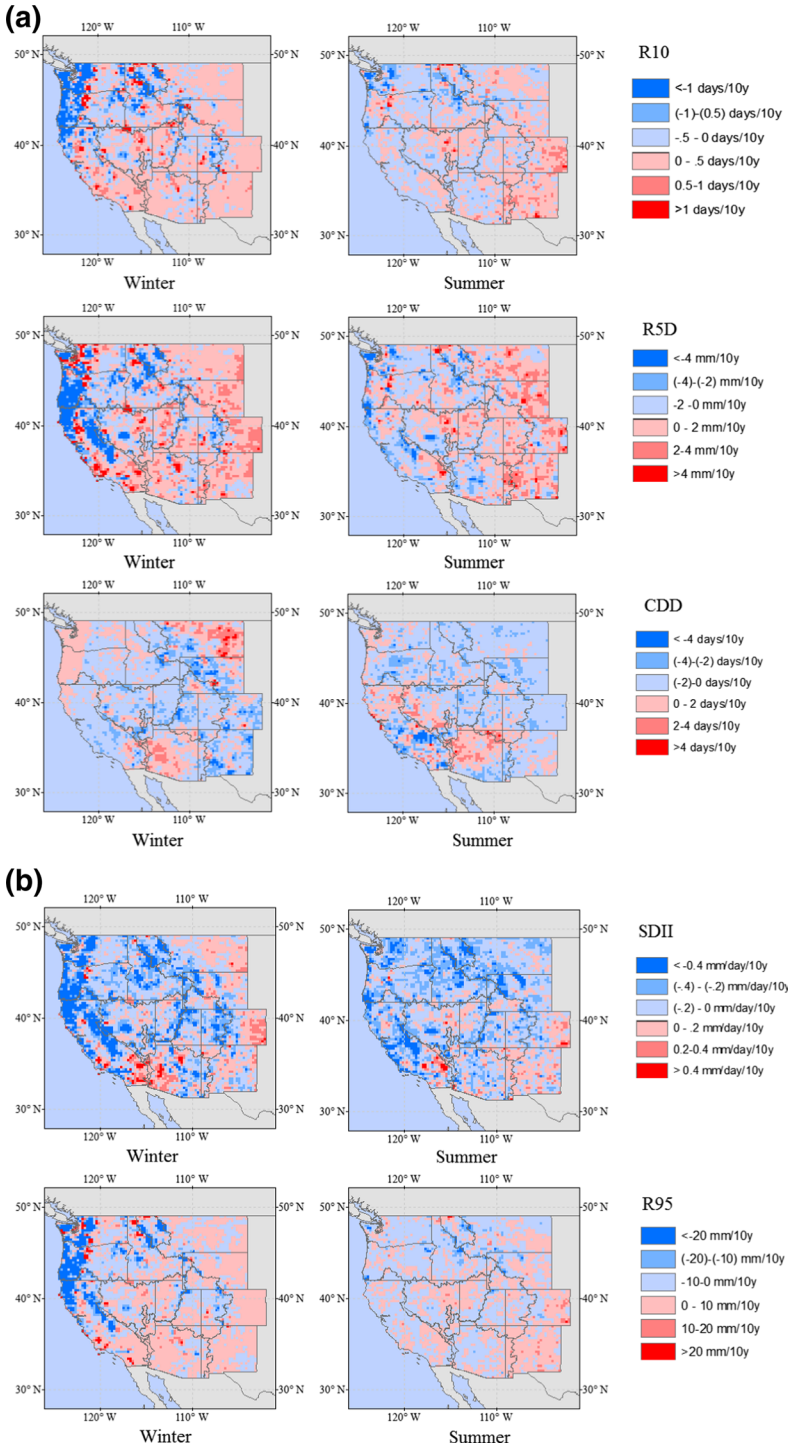


Fig. 2 a. Spatial distributions of annual trends for R10, R5D, and CDD. b. Spatial distributions of annual trends for SDII and R95

Unit Map) including Pacific Northwest (PN), California (CA), Great Basin (GB), Upper Colorado River Basin (UCRB), and Lower Colorado River Basin (LCRB).

3.2.1 Annual Trend of Summer; Winter Extreme Precipitation Indices

Most areas of PN shows negative trends while most parts of the GB and UCRB show a positive trend for R10 in both winter and summer periods. The spatial distribution of annual trend of R10 in central and southern CA and LCRB is season dependent, with a positive trend in winter and a negative trend in summer (Fig. 2-a-R10).

Trends in R5D and R95 are spatially coherent (Fig. 2-a-R5D, Fig. 2-b-R95) during winter and summer. Negative trends are observed in PN, Northern CA, and western GB and Positive trends in eastern GB and UCRB. Southern CA and LCRB have the similar season dependent response for spatiotemporal trends with R10.

For CDD, the spatial distribution of the trends is consistent for seasons. Most regions of PN, CA, GB, and UCRB have a slight negative trend. The LCRB is undergoing a positive trend.

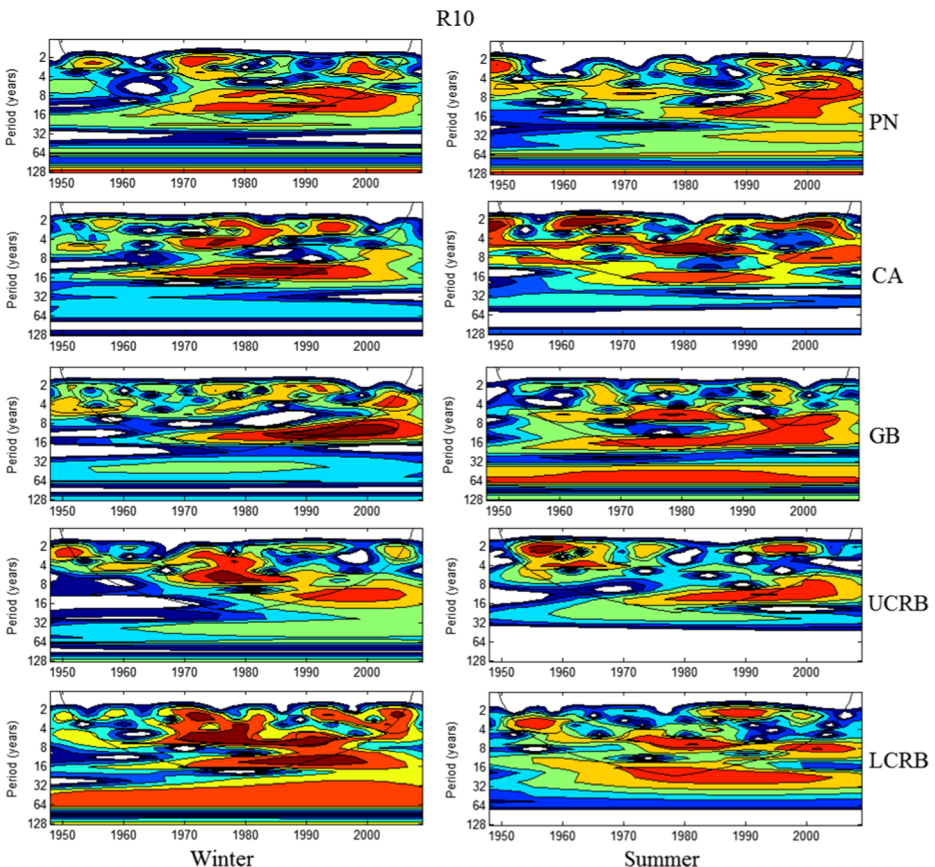


Fig. 3 Local wavelet spectrum for annual R10 time series in five selected regions

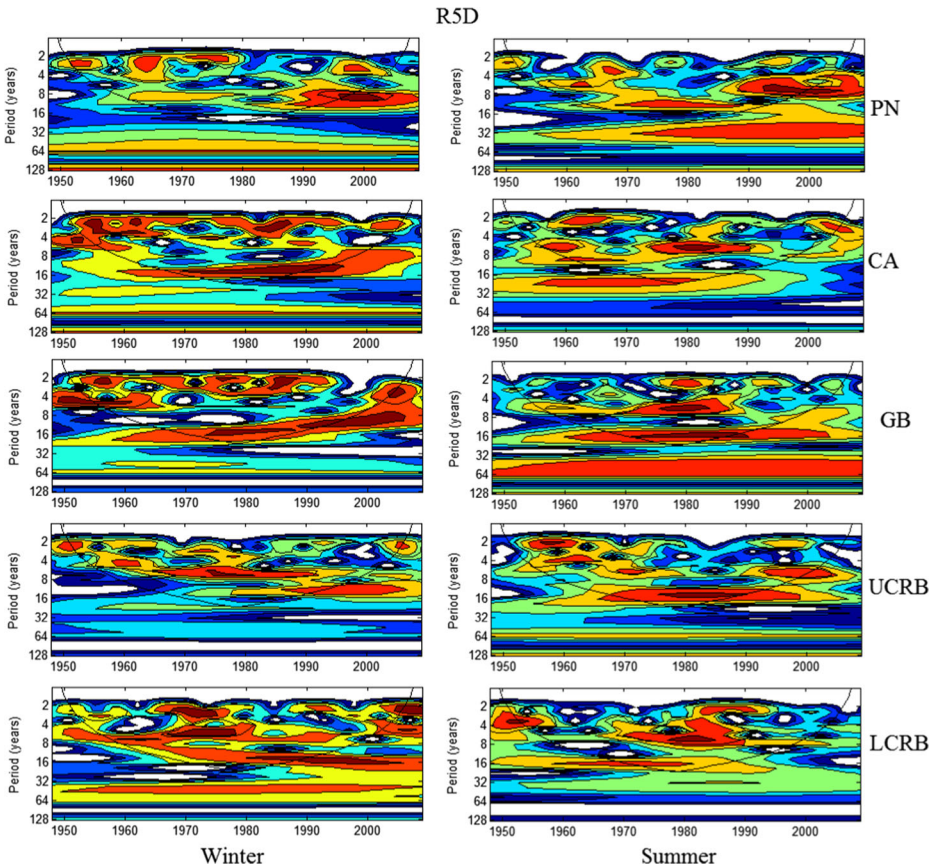


Fig. 4 Local wavelet spectrum for annual R5D time series in five selected regions

Trends in SDII are more homogenous than the other four indices. Most of the western U.S. experiences a decreasing trend in SDII. The regions where increasing trends are detected mainly include the desert region and central valley in CA.

3.2.2 Inter-Annual and Decadal Variability of Extreme Precipitation Indices

For all the extreme indices except SDII, local wavelet spectrum analyses indicate that there are significant 2 to 20 year band for each region (Fig. 3-7). The timing of a specific frequency domain is much more coherent in the winter than in the summer for the whole western United States. For instance, if there is a 2 to 4 year band during 1970 to 1980 for R5 in PN, in most cases, it is expected to see a similar band existing at the same period for the other four regions. There are also some special cases: R10 and R95 time series during the winter period lack a 2 to 8 year band in GB, and CDD time series during the winter period miss the 2 to 8 year band in PN. For SDII, few significant multi-year bands exist during the winter period at all the five select regions. Time series of the extreme indices during summer period also exhibit similar multi-year bands with those during the winter period. However, there are no fixed patterns either for a certain index in different regions or different indices in a certain region.

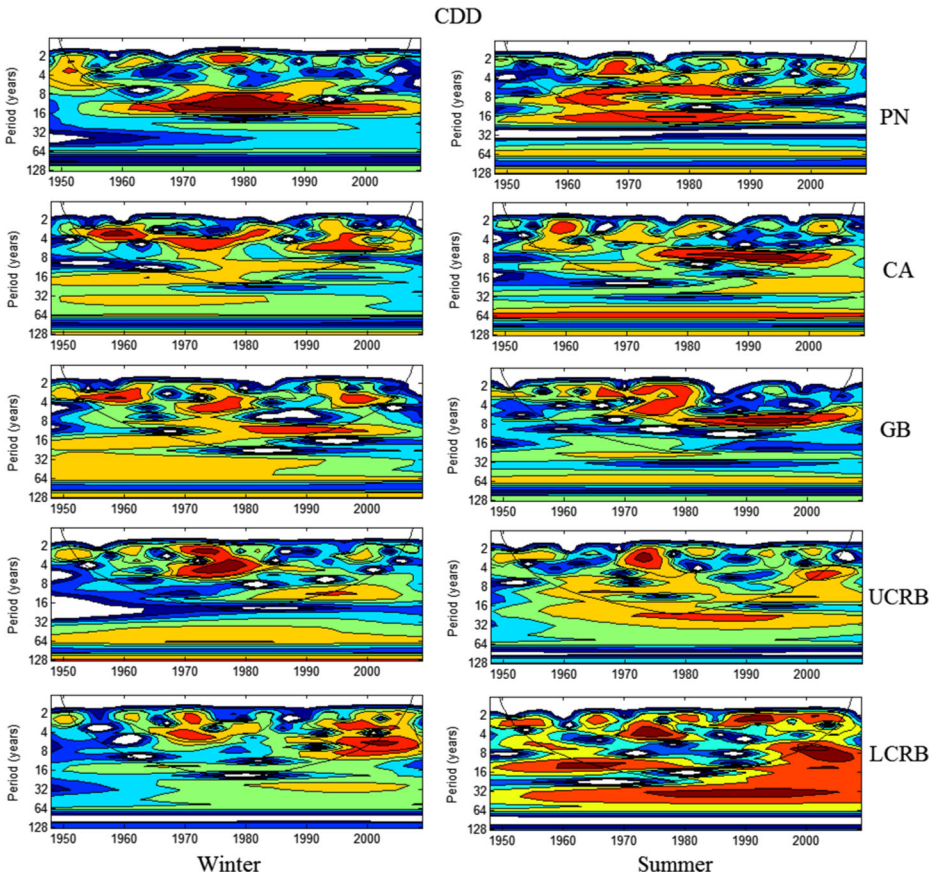


Fig. 5 Local wavelet spectrum for annual CDD time series in five selected regions

4 Discussion and Conclusion

In this study, we have determined the spatial characterization of ENSO-extreme precipitation response pattern and identified the multi-scale variability of extreme precipitation in terms of five extreme indices in the western U.S.

Brown and Comrie (2004) and *Wise(2010)* found that there is a winter precipitation dipolar pattern with ENSO variability west of the continental divide in the west United States. Our study indicates that not only the winter precipitation, but also the extreme precipitation expressed in indices such as R10, R5D, CDD, and R95 have a similar dipolar pattern and a transition zone which separates the west into two main dipolar centers regarded as Pacific Northwest and Desert Southwest. The transition zone of these four indices is wider than the transition zone of total precipitation which includes the northern CA, almost the whole Great Basin, and northern part of UCRB. Within the transition zone, winter extreme precipitation has little relationship with SOI, so prediction of extreme precipitation events based on the forecasting of ENSO states is difficult in this region. In other words, human-induced climate change may account more for the trends in precipitation extremes detected in this transition zone more than ENSO. On the contrary, in the southwest including southern CA and the whole

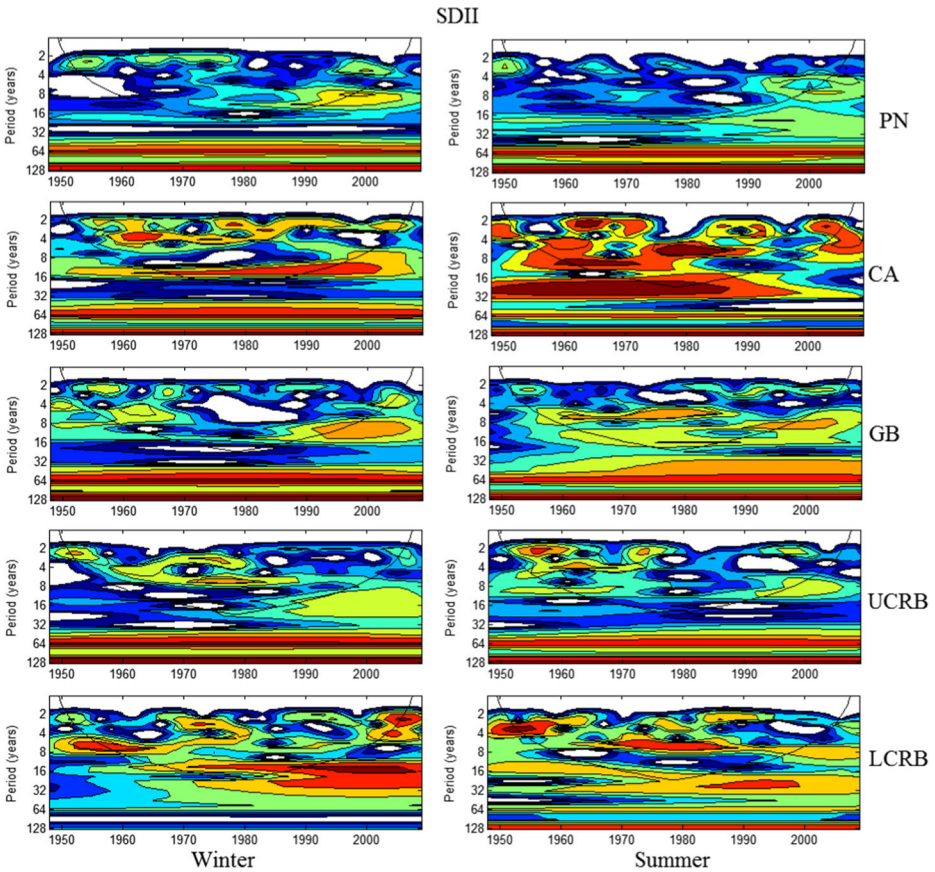


Fig. 6 Local wavelet spectrum for annual SDII time series in five selected regions

LCRB, winter extreme precipitation is significantly correlated with ENSO variability. During the El Niño years, it is expected to see more extreme precipitation events along with longer maximum dry period than in the La Niña years. This is consistent with the results from *Cayan et al. (1999)*. SDII shows no correlation with SOI over most western U.S., suggesting that the SDII doesn't vary with the ENSO states. Physical mechanisms behind wider transition zone and smaller dipolar regions of extreme precipitation compared to the total precipitation have not been investigated in this study and should be a subject for future research.

The spatial distribution of annual trend of R10, R5D, SDII, and R95 has seasonal variability (positive trend in winter season and negative trend in summer season) in southern CA and LCRB, which means that studies on the annual trend of extreme precipitation in this region should be conducted at seasonal scale. There may be no trends for annual extreme precipitation statistics while significant trends for the seasonal extreme statistics. The Colorado River Basin (CRB) (especially Lower basin) confronted the most serious extreme conditions: all the indices show increasing trend during 1948–2009, indicating there are more extreme precipitation events during winter with longer maximum dry period. Together with the rapidly increasing population and projected decreasing trend in the future precipitation amount, the CRB is going into a dry and extreme future.

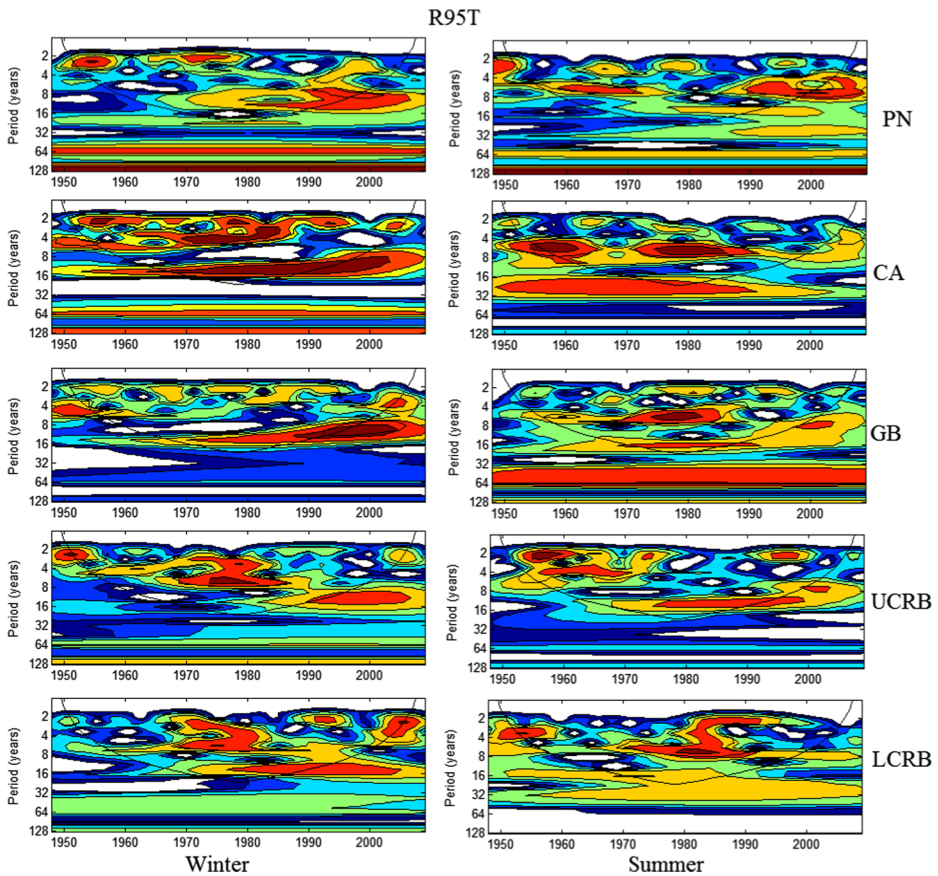


Fig. 7 Local wavelet spectrum for annual R95 time series in five selected regions

The wavelet analyses reveal that there are consistent 2 to 20 year bands in R10, R5D, CDD, and R95 winter series. ENSO phenomenon may occur at periodicities from 2 to 8.5 years (Rodbell et al. 1999). The wider range of periodicities in the extreme precipitation time series indicates that the ENSO alone provides just a part of the picture of extreme precipitation variability, there must be other ocean oscillations which govern the multi-scale variability of extreme precipitation. Besides the best-known ENSO in the Pacific Ocean, another two ocean temperature patterns named Pacific Decadal Oscillation (PDO) (Mantua and Hare 2002) and Atlantic Multi-decadal Oscillation (AMO) (Enfield et al. 2001) have been proved to be closely associated with decadal-length periods of above and below average precipitation and streamflow in the western U.S. Furthermore, variations in extreme events were also found to be significantly related to PDO (Peralta-Hernandez et al. 2009) and AMO (Curtis 2008). The multi-year bands ranging from 2 to 20 years may be caused by the inter-decadal modulation of ENSO impacts on precipitation extremes. The multi-decadal (AMO) modulation of ENSO impacts is not examined in this study as the length of historic records is too short to conduct analysis from AMO effects. GB lies in the transition zone for R10 and R95 where the extreme precipitation has little relationship with ENSO states (Fig. 1-b, f). This

could explain the reason why R10 and R95 time series during the winter period lack a 2 to 8.5 year band in GB. In PN, the CDD is not significantly correlated to SOI which accounts for the missing bands in the CDD time series. There are no significant bands in winter SDII time series, indicating the natural oscillations have little effects on the variability of SDII.

In conclusion, this study has improved the knowledge regarding the spatiotemporal changes of extreme precipitation in the western United States. The delineation of the dipolar regions and transition zone of different extreme indices provides detailed spatial information for regional forecasting on extreme precipitation event. The distinct responses of extreme precipitation events to ENSO in transition zone and dipolar centers may help to quantify the effects of natural oscillations and human-induced warming on extreme precipitation events. In transition zones, ENSO forecast are of little use. Analyses on the trend of precipitation extremes should focus more on the human-induced climate change. In the dipolar regions, the lagged relationship between precipitation extremes and SOI conditions has allowed for long-lead time forecast of precipitation extremes. Meanwhile, we couldn't neglect the fact that the skill of long term prediction of large scale ocean oscillations such as the changing frequency of El Nino or La Nina in a warming future (Vecchi et al. 2008) needs to be improved before we can fully apply this analysis to extreme precipitation forecasting. Despite these limitations, this information from the comprehensive analyses, along with the potential progresses on the PDO predictability and changes in the frequency of ENSO states, can help researchers to predict the future changes of precipitation extremes in the western U.S.

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