

Analysis of Extreme Reversals in Seasonal and Annual Precipitation Anomalies Across the United States, 1895-2014

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ABSTRACT

As population and urbanization increase across the United States, the effects of natural hazards may well increase, as extreme events would increasingly affect concentrated populations and the infrastructure upon which they rely. Extreme precipitation is one natural hazard that could stress concentrated populations, and climate change research is engaging heavy precipitation frequency and its impacts. This research focuses on the less-studied phenomenon of an extreme precipitation reversal - defined as an unusually wet (dry) period that is preceded by an unusually dry (wet) period. The magnitude is expressed as the difference in the percentiles of the consecutive periods analyzed. This concept has been documented only once before in a study that analyzed extreme precipitation reversals for a region within the southwestern United States. That study found that large differences in precipitation from consecutive winters, a hydrologically critical season for the region, occurred more frequently than what would be expected from random chance, and that extreme precipitation reversals have increased significantly since 1960. This research expands upon the previous work by extending the analysis to the entire continental United States and by including multiple temporal resolutions.

Climate division data were used to determine seasonal and annual precipitation for each of nine climate regions of the continental United States from 1895-2014. Precipitation values were then ranked and given percentiles for seasonal and annual data. The season-to-season analysis was performed in two ways. The first examined consecutive seasons (e.g., winter–spring, spring–summer) while the second analyzed the seasonal data from consecutive years (e.g., spring 2014–spring 2015). The annual data represented precipitation for the period October 1–September 30, or the “water year” used by water resource managers. Following the approach of the previous study, a secondary objective of the research was to examine large-scale climate teleconnections for historical relationships with the occurrence of precipitation reversals. The El Niño-Southern Oscillation was chosen for analysis due to its well-known relationships with precipitation patterns across the United States. Results indicate regional expressions of a propensity for extreme precipitation reversals and relationships with teleconnections that may afford stakeholders guidance for proactive management. Precipitation reversal (PR) and extreme precipitation reversal (EPR) values were significantly larger for the second half of the study period for the western United States for the winter-to-winter, spring-to-spring, and year-to-year analyses. The fall-to-fall analysis also revealed changes in PR/EPR values for several regions, including the northwest, the Northern Rockies and Plains, and the Ohio Valley. Relationships between the winter-to-winter PR time series and an index representing the El Niño-Southern Oscillation (ENSO) phenomenon were examined. The winter-to-winter PR time series of the Northern Rockies and Plains region and the South exhibited significant relationships with the time series of Niño 3.4 values. El Niño (La Niña) coincided with more wet-to-dry (dry-to-wet) PR/EPR values for the Northern Rockies and Plains, while El Niño (La Niña) coincided with more dry-to-wet (wet-to-dry) PR/EPR values for the South.

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List of Abbreviations

AMO	Atlantic Multidecadal Oscillation
AR5	Fifth Assessment Report
COOP	Cooperative Observer Network
CR	Climate Region
CR1	Northwest
CR2	West
CR3	Northern Rockies and Plains
CR4	Upper Midwest
CR5	Ohio Valley
CR6	South
CR7	Southwest
CR8	Southeast
CR9	Northeast
DJF	December, January, and February
ENSO	El Niño-Southern Oscillation
EPR	extreme precipitation reversal
ESPR	extreme seasonal precipitation reversal
GPCP	Global Precipitation Climatology Project
HCN	Historical Climatology Network
IPCC	Intergovernmental Panel on Climate Change
NCEI	National Centers for Environmental Information
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PCA	Principal Component Analysis
PR	precipitation reversal
PDO	Pacific Decadal Oscillation
SON	September, October, and November

CHAPTER 1

Introduction

1.1 Precipitation Volatility

According to the National Centers for Environmental Information's (NCEI) *Climatological Rankings*, which is a time series of historically ranked precipitation records from 1895-2015 (<http://www.ncdc.noaa.gov/temp-and-precip/>), the state of Oklahoma experienced its fifth driest October-September period on record during 2005-2006, followed by the 5th wettest October-September period during 2006-2007. The state of Virginia recorded its 2nd driest October-September on record during 2001-2002, followed by the wettest October-September during 2002-2003. Furthermore, for the October-September period during 2009-2010, the state of Texas had its 13th wettest October-September period, followed by the driest October-September on record during 2010-2011. If such reversals in precipitation are common throughout the United States, practitioners whose operations and resources are affected by seasonal-to-annual precipitation must guard against impacts from such volatility. From a broader perspective, the societal impacts may be magnified as the population distribution of the country continues to shift toward urban areas.

According to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the population of the United States was 86% urbanized as of 2014, and mirroring expectations on a global scale, urbanization and population values within the United States are expected to increase in the future (IPCC 2014). The increase in population and urbanization suggests that the effects of natural hazards could increase, as singular, extreme events could affect concentrated populations and therefore a greater number of people and the infrastructure upon which they rely. Extreme precipitation is one natural hazard that could stress

dense populations of people by threatening clean water resources, testing aging infrastructure, and threatening agricultural crops that many from around the world are dependent upon. The likelihood of an increase in extreme precipitation events is put into context within the fifth assessment report (AR5) of the IPCC, which stated that “almost all areas of North America exhibit very likely increases of 5 to 20% in the 20-year return value of extreme precipitation by the mid-21st-century” (IPCC 2014, pg. 1456). AR5 also provided a wide-ranging outlook that states: “Global warming of approximately 2°C (above the preindustrial baseline) is *very likely* to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low-snow years, and shifts toward earlier snowmelt runoff over much of the western USA and Canada. Together with climate hazards such as higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability, these changes are projected to lead to increased stresses to water, agriculture, economic activities, and urban and rural settlements (*high confidence*)” (IPCC 2014, pg. 1443).

According to the AR5 report (IPCC 2013), the global temperature has risen by roughly 1°C since 1880, and conservative estimates suggest that it will likely rise another degree by 2050. Increasing temperatures are thought to increase lower tropospheric water vapor, leading to more intense wet and dry extremes depending on geographic location (Allan and Soden 2008; Held and Soden 2006; Trenberth 1999). The importance of understanding precipitation variability is further underscored by Tsonis (1996) who stated: “Precipitation (rain and snow) provides, through its participation in the global hydrological and energy cycles, most of the heat flux within the atmosphere. For this reason, a knowledge of precipitation variability is important to understanding the behavior and changes of the Earth’s climate system.” (Tsonis 1996, pg. 700)

1.2 Impacts of Precipitation Volatility

The American economy has been affected by extreme weather events through history, including floods and intense precipitation (IPCC 2014). IPCC's AR5 illuminates emerging risks, such as droughts, that could negatively affect the North American economy in the future (IPCC 2014). Two of the sectors affected by climate variability, and especially precipitation variability, are water resources and agriculture (IPCC 2014). Vörösmarty et al. (2000) noted that "one fundamental concern is the impact of this climate change on water supply" (pg. 284), which will likely fluctuate more than in previous decades. Extreme variability in water levels, caused in part by precipitation variability, will likely require more intensive water resource management. For example, even with extensive preparation, Phoenix, Arizona in the semi-arid southwestern United States has a looming threat of water stress if a prolonged drought were to occur (Morehouse et al. 2002). Agriculturalists may also come under increased stress as raising crops and livestock would be more difficult if precipitation variability trends toward the extreme. For example, research tying the El Niño-Southern Oscillation (ENSO) phenomenon to regional weather patterns has shown that there are economic advantages for agriculturalists who account for ENSO when making crop growing decisions (Chen et al. 2001; Hansen et al. 2001; Tack and Ubilava 2013). The effects of extreme precipitation likely are not limited to the water resources and agricultural sectors, as other economic sectors and population centers may also see negative impacts from increasing precipitation variability, including the areas of human health and ecosystem health (IPCC 2014).

According to IPCC's AR5 (IPCC 2013), increased precipitation variability is expected to occur across the globe as Earth's atmosphere and surface continue to warm. The IPCC has also determined that it is "*likely*" that the frequency and intensity of heavy precipitation events over

many land areas will, on average, increase in the near-term (IPCC 2013, pg. 992). These previous statements have been provided with very limited spatial representation, as well as with limited details about whether the frequency of heavy precipitation events and the overall variability of precipitation have already begun to change. Gu et al. (2007) used the Global Precipitation Climatology Project (GPCP) dataset for a 27-year time period (1979-2005) to resolve that while the global linear change of precipitation was near zero, there were positive and negative linear trends for regions of the globe. These linear trends are important but should not be exclusively used to determine past precipitation trends. Martino et al. (2013) examined precipitation variability using station data, and pointed out that many previous precipitation variability studies used data that ended in the mid-1990s, and analyzed small spatial extents. Martino et al. (2013) also stated that the wide variety of climate types across the United States supports its use as a robust study area for precipitation variability studies. This thesis aims to add to the baseline of knowledge regarding precipitation variability in hopes of providing greater context to climate projections by examining precipitation data across the 120-year period 1895-2014 for the large spatial area of the contiguous United States.

1.3 Precipitation Reversals

The focus of this research is extreme precipitation reversals, which are dramatic changes in precipitation anomalies (wet-to-dry or dry-to-wet) generally on relatively coarse spatial (regional) and temporal (seasonal-to-annual) scales. Several past studies of precipitation extremes have focused on individual events as opposed to seasonal and annual totals that have more of an effect on water supply. It is anticipated that a deeper understanding of extreme precipitation reversals in the face of a changing climate will allow precipitation sensitive

stakeholders to make more informed planning decisions related to shorter-term operational issues or to longer-term methodological or infrastructural changes. The work is guided by the following basic research question: Has the warming of the global climate in recent decades coincided with greater volatility in seasonal-to-annual precipitation across the United States? The answer to this question leads to applied questioning involving the degree of risk that any volatility poses for precipitation-sensitive stakeholders across the United States. While this research question is not directly engaged within this thesis, the results of this work help to better understand the value of the question going forward.

This thesis is comprised of four chapters. Chapter 2 will provide a review of the research literature involving precipitation variability. Chapter 3 will provide a climatology of precipitation reversals (PR) for the nine climate regions of the contiguous United States, at multiple time steps including: year-to-year, winter-to-winter, spring-to-spring, summer-to-summer, fall-to-fall, winter-to-spring, spring-to-summer, summer-to-fall, and fall-to-winter. Lastly, Chapter 4 will summarize the work and offer concluding thoughts.

1.4 Study Area

The area of study for this research is the contiguous United States, which coincides with the spatial coverage of the primary data to be used in this research. Data for this large study area will be examined at a finer resolution by using the nine “climate regions” across the contiguous United States as outlined by the National Centers for Environmental Information (NCEI) (Figure 1). These climate regions are comprised of finer resolution climate divisions. Climate divisions were established in the 1950s based on a combination of climatic homogeneity, drainage basin delineations, and crop types (Guttman and Quayle 1996). However, the division boundaries

ultimately follow county boundaries, and regional boundaries ultimately follow state boundaries. The United States was selected as the study area using the same rationale as that of Martino et al. (2013), who stated that the wide range of climate types across the United States makes it a good domain for precipitation studies. The United States was also selected as the study domain based on the quality and quantity of data from across the country.

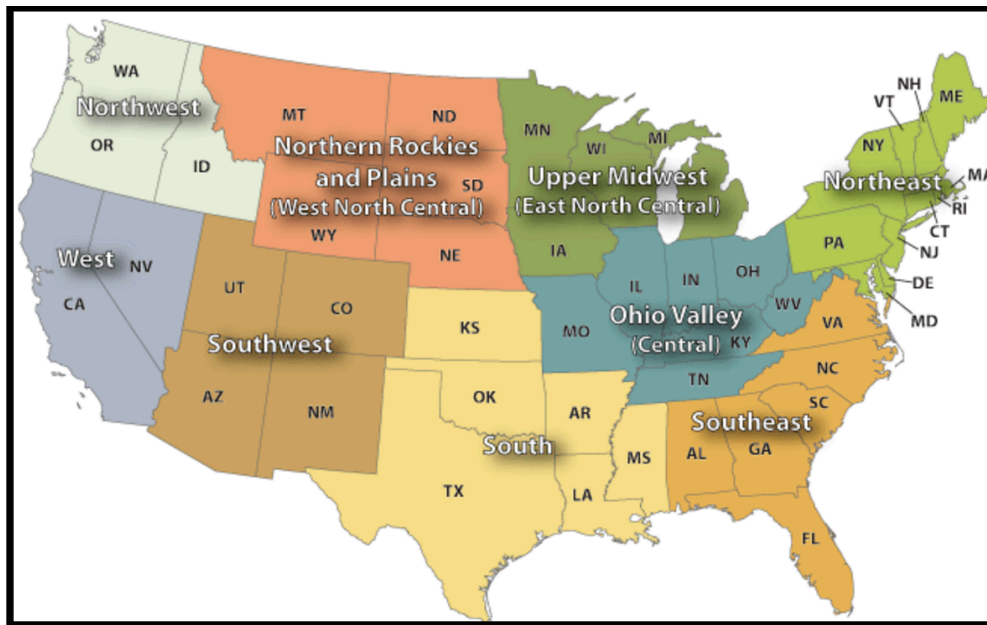


Figure 1: The nine climate regions of the United States (NCEI 2015)
(<http://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-regions.php>).

CHAPTER 2

Literature Review

2.1 Hydroclimatic Research at the National Scale

Several studies have aimed at improved understanding of precipitation patterns across the United States for the purpose of resolving if patterns have changed over time. Martino et al. (2013) examined precipitation variability by investigating data from 400 weather stations across the contiguous United States from 1917-2008. The variability of precipitation was analyzed using an entropy approach. For their study, a disorder index was calculated for each station and then analyzed for temporal variability on seasonal and monthly time scales. Martino et al. (2013) also investigated spatial precipitation variability by comparing the disorder indexes of stations in close proximity to one another. It was found that temporal inconsistency in precipitation variability is higher at seasonal time scales, and that precipitation variability was uniform spatially, except for within the Mediterranean climate in California where precipitation variability displayed high spatial variability in the fall and summer seasons (Martino et al. 2013).

The objectives of the study produced by Karl and Knight (1998) were to determine how precipitation had changed over time in the United States, and if changes were found, to determine how precipitation over time varied by season. This study used a variety of precipitation datasets including: the Historical Climatology Network (HCN) daily precipitation dataset, the climatological state divisional precipitation monthly dataset, and TD3200 daily precipitation dataset. Karl and Knight (1998) found that precipitation increased during the 1900s across the United States, with the most noticeable increases occurring in the spring and fall. Increases in precipitation during the winter and summer were also found, but were less

pronounced when compared to the other two seasons (Karl and Knight 1998). However, according to Karl and Knight (1998) the scale of the precipitation changes differs, up to 4% per century, depending on the dataset used.

Kunkel et al. (2003) took advantage of a newly expanded precipitation dataset. This new dataset was a result of digitizing the National Weather Service's Cooperative Observer Network (COOP) pre-1948 data. The expansion of precipitation data allowed Kunkel et al. (2003) to find that there were high precipitation frequencies in the late 1800s and early 1900s, in addition to the previously known increase in precipitation frequencies that has occurred since the 1960s. When comparing the periods of increased precipitation frequencies, the late 19th century and early 20th century increase was found to be higher than that which has occurred since the 1960s (Kunkel et al. 2003).

2.2 Regional Studies

Several studies have analyzed how precipitation is changing on a regional level. The temporal scope of these studies has varied, but a majority of the studies have taken place across the western half of the United States. Concern over water availability has been ubiquitous in the western states, while such concerns are less in the eastern states, even though the IPCC (2014) has very clearly stated that the only region in the United States where concern about water availability is unwarranted is the Pacific Northwest.

2.2a Western United States

Precipitation analyses conducted by geographers and climatologists have been heavily skewed toward the west coast region of the United States. Miller and Goodrich (2007) used

climate division precipitation data to examine trends and the regionalization of winter (October-March) precipitation across the northwestern United States. They used rotated Principal Component Analysis (PCA) to create four sub-regions across the northwestern United States. ENSO and PDO data were then analyzed with the precipitation data for trends. After examining trends in precipitation for the four sub-regions, Miller and Goodrich (2007) determined that there were differences in the trends of winter precipitation for the four sub-regions, suggesting that the northwestern United States precipitation patterns may not be as spatially coherent as past research has indicated. Ellis and Barton (2012) examined a possible relationship between the north Pacific jet stream and winter (December, January, and February) precipitation variability across the western United States. The mean seasonal position and speed of the north Pacific jet stream were calculated from re-analysis data obtained from the National Center for Environmental Prediction (NCEP) and the climate division precipitation data were gathered from the National Oceanic and Atmospheric Administration (NOAA) (Ellis and Barton 2012). Ellis and Barton (2012) found that the position of the north Pacific jet stream had a significant relationship with winter precipitation for 32 out of 64 climate divisions across the western United States. As for how these particular studies relate to the proposed work, the work of Miller and Goodrich (2007) will likely provide useful information regarding the regionalization of precipitation patterns. Depending on the initial results of the proposed research, the results found by Ellis and Barton (2012) may be useful to help explain precipitation variability at a regional level, or provide methods for examining the hydroclimatic impact of atmospheric jet streams for additional regions across the United States.

The only precipitation reversal analysis found in the literature was completed for the southwestern United States, and it appears that no study has examined precipitation reversals at

the national scale, as with the study proposed here. Goodrich and Ellis (2008) identified what they coined “extreme seasonal precipitation reversal (ESPR)” events across Arizona. The research presented in their paper sought to determine if extreme precipitation events had become more frequent in Arizona, and if so how the events might be tied to various climatic teleconnections. The methods portion of their study is important because of the similarities with the approach to the study that is presented in this thesis. Goodrich and Ellis used climate division data for the period 1895 through 2006. The data were aggregated to winter (DJF) precipitation totals and translated into percentiles. The absolute value of the percentile difference for consecutive years was used to characterize the magnitude of the year-to-year change. Going beyond the absolute value representation, Goodrich and Ellis also analyzed whether or not the change was from wet-to-dry, or from dry-to-wet. To provide context to how often different magnitudes of precipitation variability occurred historically, 1000 sets of 111 numbers (dictated by the 111 years in their study) were randomly generated. These numbers were then compared to the actual number of times extreme seasonal precipitation reversals (ESPR) occurred historically. The outcome was that the frequency of any ESPR within the historical record (independent of how extreme) was above the expected number for each of the seven climate divisions of Arizona. The number of high ESPR events (defined as occurrences of the absolute value of the difference in percentiles for consecutive years greater than 60) had also increased since 1960. Teleconnection data were also analyzed for relationships with the occurrence of ESPRs. ENSO neutral conditions coincided with roughly one-half of the ESPR events. However, Goodrich and Ellis (2008) were surprised to find that index values for the Atlantic Multidecadal Oscillation and Eastern Pacific Oscillation (EPO) were more strongly correlated to ESPRs than ENSO, regardless of the direction of the reversal (wet-to-dry or dry-to-wet). In conclusion, Goodrich

and Ellis (2008) found that the frequency of precipitation reversals had in fact increased across Arizona through the 20th century and that the frequency with which they occurred was related historically to large-scale climate teleconnections.

2.2b Central United States

One region that has not been rigorously studied is the central United States. Hu and Feng (2001) used gridded data to study interannual precipitation fluctuation across the central United States for the summer months of June, July, and August. It was found that the forcing variable for the fluctuation in precipitation actually changes every 30 to 40 years. It is important to note the temporal extent of this study was only 90 years, and this caused the authors to question their results due to the timescale of the forcing fluctuation. Another examination of precipitation variability using an entropy approach was completed for the state of Texas by Mishra et al. (2009). Their study, which was completed before the similar study by Martino et al. (2013) mentioned above, examined 43 stations across Texas from 1925-2005 on monthly, seasonal, and annual time steps. A disorder index was calculated to measure precipitation variability over time for each station, and those indexes were then compared temporally and spatially. The results revealed that the amount of variation in annual precipitation increases from east to west across Texas. Also, Mishra et al. (2009) found that the magnitude of variation through space of precipitation variability varied across Texas for different seasons, with winter precipitation exhibiting the most spatial variability and summer the least.

Woodhouse and Overpeck (1998) analyzed 2000 years of drought variability for the central United States. This study was completed using tree ring data, historical newspaper articles, and other accounts to map and temporally place the droughts of the past. Woodhouse

and Overpeck (1998) found that droughts have previously been more severe and had a much greater spatial extent than droughts in the past 150 years. Due to their findings of more serious droughts in the past, Woodhouse and Overpeck (1998) proposed that future studies consider the full range of natural interannual and interdecadal droughts, and not just the magnitudes of droughts in recent memory, when proposing possible impacts on today's population.

2.3 Conclusion

An area of hydroclimatology that has been understudied is the notion of precipitation volatility and relatively rapid reversals in precipitation anomalies. With the exception of Goodrich and Ellis (2008), who analyzed ESPR events for the seven climate divisions in Arizona, no studies have examined seasonal "extreme precipitation reversals". Goodrich and Ellis aimed to determine if extreme precipitation events had become more frequent in Arizona, and how the events might be tied to various climatic teleconnections. The results of their study illustrated that the frequency of ESPRs have in fact increased for much of Arizona (Goodrich and Ellis 2008). Based on their results, there is reason to hypothesize that other areas may have also experienced a change in extreme precipitation reversals. Other studies have looked at many different aspects of precipitation variability, including short-term and local variation, as well as the physical drivers of those changes. Studies have also examined how the frequencies and magnitude of precipitation amount might change under different global warming scenarios. Yet, extreme precipitation reversals surprisingly have not been studied on a broader spatial scale, and there could be great value for stakeholders in analyzing the frequency of reversals. Due to the lack of studies that have analyzed ESPR events and the importance of precipitation variability within the climate change arena as conveyed in IPCC's AR5 (2014), it appears that there is value

to performing an analysis of extreme precipitation reversals for the contiguous United States on varying temporal scales. While it is important to ultimately identify physical mechanisms that may help explain the cause of ESPRs and that could potentially be used to help forecast the magnitude and frequency of ESPRs, this thesis offers only a precursory analysis using one basic climate teleconnection index.

CHAPTER 3

A Climatology of Extreme Precipitation Reversals

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ABSTRACT

Precipitation reversals are a type of natural hazard that could stress dense populations as urban areas continue to expand and grow. The research presented here provides a climatology of precipitation reversals, singularly defined as an unusually wet (dry) period that is preceded by an unusually dry (wet) period. For this research, the magnitude of precipitation reversals is defined as the difference in percentiles from one increment of data to the next. This research expands upon previous work for the winter season within the Southwestern United States by extending the analysis to the entire continental United States and by including multiple temporal resolutions. A climatology of extreme precipitation events was created for nine climate regions at multiple temporal scales using climate division precipitation data. Analyzed were reversals for consecutive seasons (e.g., winter–spring, spring–summer), seasons from consecutive years (e.g., summer 2014–summer 2015), and consecutive “water years” (October 1 – September 30). The climatology illustrates regional expressions of the propensity for extreme precipitation reversals that may afford stakeholders guidance for proactive management. The west experienced significantly larger PR/EPR values for the second half of the study period for the winter-to-winter, spring-to-spring, and year-to-year analyses. For the fall-to-fall analysis there were shifts in PR/EPR values over time for several regions, including a significantly decreasing trend of PR/EPR values for the Ohio Valley. The winter-to-winter time series of precipitation reversals were also compared to fall season El Nino-Southern Oscillation index values. The time series of winter-to-winter precipitation reversals for the region of the Northern Plains and Rocky Mountains and the south-central region exhibited highly correlated relationships with fall season El Nino-Southern Oscillation variability.

3.1 Introduction

According to IPCC's AR5 (IPCC 2013), increased precipitation variability is expected to occur across the globe as Earth's atmosphere and surface continue to warm. As discussed in Chapter 1, precipitation volatility has the potential to impact several sectors of the United States, and several notable swings in precipitation have occurred in recent years.

Several past studies have focused on precipitation volatility. Martino et al. (2013) examined precipitation variability using station data, and pointed out that many previous precipitation variability studies used data that ended in the mid-1990s and focused on small spatial extents. Martino et al. (2013) also stated that the wide variety of climate types across the United States supports its use as a robust study area for precipitation variability studies. Goodrich and Ellis (2008) examined precipitation reversals, which they defined as dramatic changes in precipitation anomalies (wet-to-dry or dry-to-wet), for the southwestern United States. The magnitude of precipitation reversals within the work of Goodrich and Ellis (2008) were determined as the difference in the percentile expression of two consecutive events. The research presented here replicates the methods of Goodrich and Ellis (2008) for defining extreme precipitation reversals, and it aims to fill the gap in the literature mentioned by Martino et al. (2013) by examining precipitation data across the 120-year period 1895 through 2014 for the large spatial area of the contiguous United States.

A climatology of extreme precipitation reversal (EPR) events across the contiguous United States is presented in this chapter. It is anticipated that a deeper understanding of extreme precipitation reversals in the face of a changing climate will allow precipitation sensitive stakeholders to make more informed planning decisions related to shorter-term operational issues or to longer-term methodological or infrastructural changes.

3.2 Data

3.2a Precipitation Data

Time series of mean monthly precipitation data for all contiguous United States climate divisions (n=344) were downloaded from the National Centers for Environmental Information (NCEI) (<ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/>) for the time period from January 1895 through December 2014. These data were already quality controlled by NCEI and the records were complete, with no missing data. For this study, climate division data based on the recently developed version two divisional product were used. The new divisional dataset aims to provide more robust divisional averages by accounting for station elevation differences across a division by using interpolation techniques and by using an increased number of stations (Vose et al. 2014). For each climate variable (i.e., temperature, precipitation) “the value for each division, year, and month was computed as the area-weighted average of the composite gridpoint values whose centroids fell within the boundaries of that division” (Vose et al. 2014). The improved dataset has been quality assured and bias adjustments have been made to ensure that the data are of a high accuracy (Vose et al. 2014). As mentioned previously, the area of study for this research is the contiguous United States, but this large area of study will be examined at a finer resolution using “climate regions” defined by NCEI (Figure 1). Monthly precipitation values were computed for the nine climate regions by area weighting averages of monthly climate division precipitation data. The area-weighted averages were computed using the Albers equal-area conic projection to determine the area of each climate division. The area of each division was then divided by the total area of the climate region within which that division was located, and the areal weight was then multiplied by the monthly precipitation value for that specific climate division. Monthly time series of area weighted regional precipitation values for each of

the nine climate regions formed the basis for the precipitation reversal computations and their subsequent analysis within this research. For the remainder of this thesis, the climate regions will be abbreviated as outlined in Table 1.

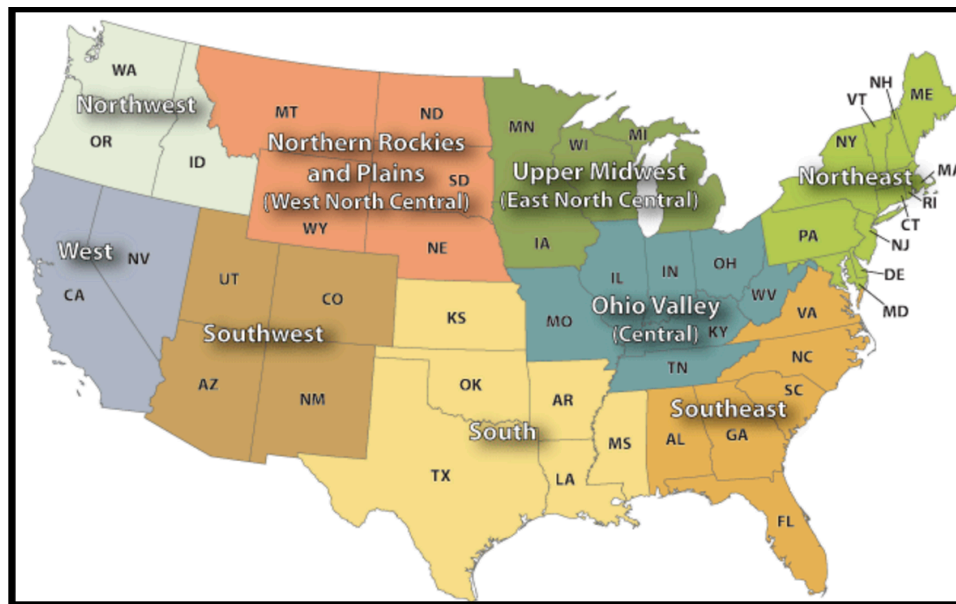


Figure 2: Same as Figure 1 – The nine climate regions of the United States as defined by the United States National Centers for Environmental Information (NCEI 2015). The figure is reproduced here in support of the accompanying text and table.

Table 1: Abbreviations for the nine climate regions that will be used for the remainder of this thesis.

CR1 – Northwest	CR2 – West
CR3 – Northern Rockies and Plains	CR4 – Upper Midwest
CR5 – Ohio Valley	CR6 – South
CR7 – Southwest	CR8 – Southeast
CR9 – Northeast	

In order to determine the relative importance of a particular time step for a CR, a monthly precipitation climatology was calculated (Figure 3). The climatology was calculated by determining the average percent of annual precipitation that occurs during each specific month,

for all CRs. The monthly precipitation climatology reveals that several CRs, including CR1 (Northwest) and CR2 (West), have pronounced dry seasons during the months of June, July, August, and September (Figure 3). CR1 (Northwest) and CR2 (West) also have pronounced wet seasons during the winter and spring months, while spring and summer are the wet periods for CRs 3 (Northern Rockies and Plains) and 4 (Upper Midwest). The annual precipitation is more evenly distributed through the year for the eastern and southern climate regions (Figure 3).

3.2b Niño 3.4 Data

A secondary objective of this thesis is to determine if a relationship exists between the El Niño-Southern Oscillation (ENSO) phenomenon and precipitation reversals. The Niño 3.4 index represents an average of sea surface temperatures (SST) across the area of the Pacific Ocean from 5°S to 5°N and from 120°W to 170°W, and it is viewed as a representation of the SST dimension of the ENSO phenomenon. The National Oceanic and Atmospheric Administration (NOAA) defines an El Niño event as when the SST anomalies across the Niño 3.4 region are greater than or equal to 0.5°C for three consecutive months. A La Niña event is defined by three consecutive months of SST anomalies less than or equal to -0.5°C. This study uses the NOAA definitions to define Niño/Niña events, with all else considered to be neither, or neutral. The monthly values of Niño 3.4 were downloaded from January 1896- December 2013 (<http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/.NINO34/>).

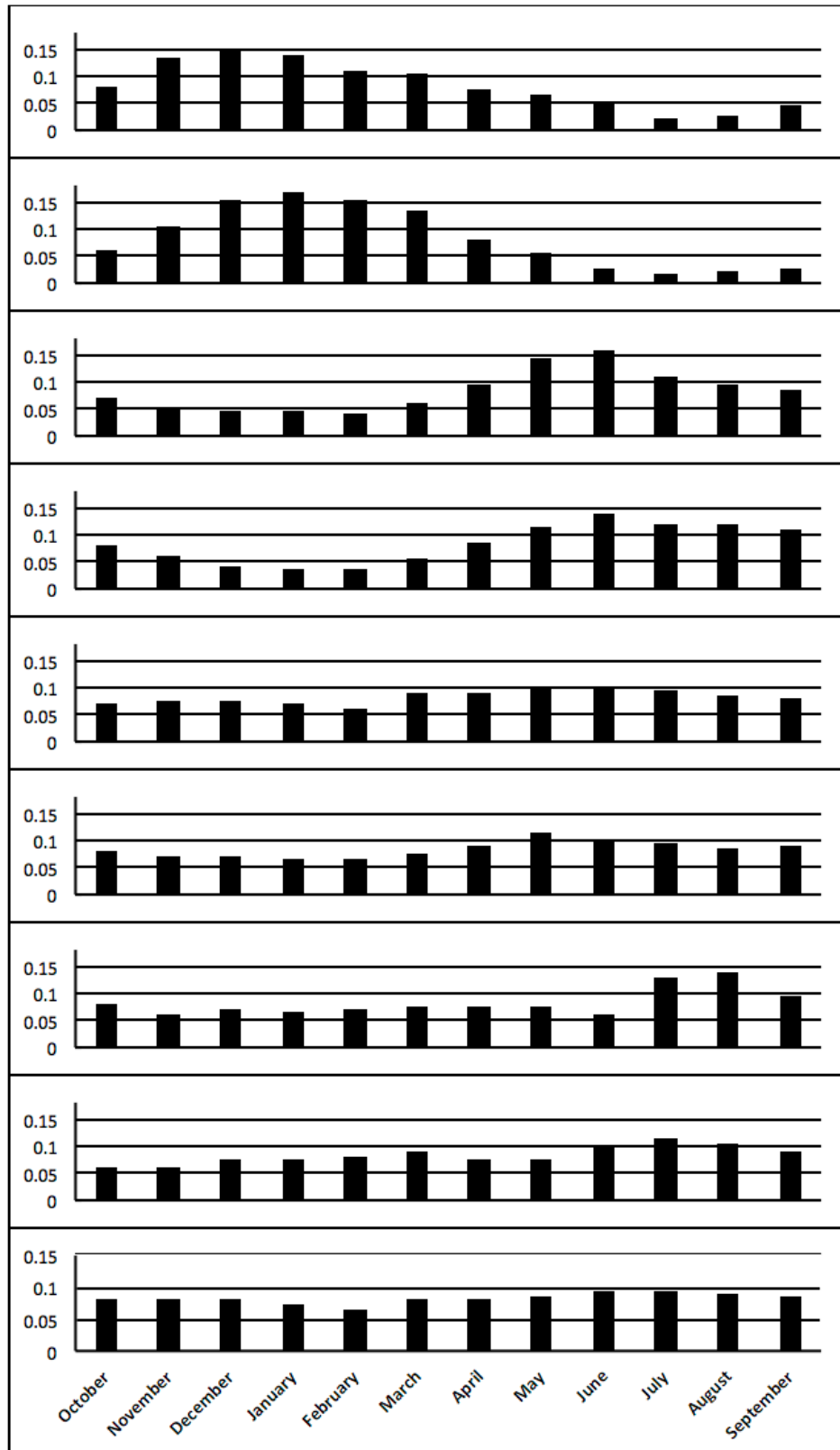


Figure 3: Average percent of precipitation for each month (y-axis), for all nine Climate Regions. The Climate regions are displayed in ascending order (1 to 9) from top to bottom.

3.3 Methods – Extreme Precipitation Reversal (EPR) Identification

In order to identify extreme precipitation reversal (EPR) events within the historical records of the nine climate regions, temporal increments were established and PR time series were calculated. According to Goodrich and Ellis (2008), PR values greater than 60 are large enough to likely be of importance to stakeholders. Following this standard, a PR value greater than or equal to 60 will be referred to as an extreme precipitation reversal (EPR), with the magnitude of the reversal listed after the EPR abbreviation (e.g., a reversal of 70 percentiles will be referred as an EPR70 event). For this study, the precipitation data were examined on seasonal and annual timescales. The seasonal analysis was based on four seasons: winter – December of the previous calendar year through February; spring – March through May; summer – June through August; fall – September through November. For example, the winter of 1896 included December 1895, January 1896, and February 1896. As the record for the winter season was therefore shortened by one year, and a consistent record length was desired, analysis of all seasons was confined to the 119-year period from the winter of 1896 through the fall of 2014. For the annual PR events, a year was defined as October 1 through September 30, which is the “water year” followed by water resource managers, with the benefit being that it does not interrupt the often hydroclimatically critical winter season (as a calendar year does). The annual PR analyses only included 119 years of data for this reason. October 1895 – September 1896 was the first year included for analysis in this research, and will be referred to as 1896 throughout this thesis. The years thereafter were also named in a similar manner, with October, November, and December being referred to as part of the following year.

At each of the respective time scales, the data were then ranked and a percentile was assigned for each increment of data. The PR value for each increment of data was then calculated

by subtracting the percentile for the previous record (i.e., season or year) from that for the current record to which the PR value was tagged. This replicated the method used by Goodrich and Ellis (2008). For example, a 2014 year-to-year PR value represents the 2013 annual percentile subtracted from the 2014 annual percentile. Initially, the sign of the reversal (e.g., wet-to-dry or dry-to-wet) was not of concern, so the absolute value of the differences was taken. These methods created 118 PR values for the seasonal and annual time scales. These PR lengths were the total lengths of the respective time series data minus one, stemming from the differencing method used.

For the EPR frequency results to be statistically valid, it must be revealed that the PR “values are random with minimal lag-1 autocorrelation”(Goodrich and Ellis 2008). This simply means that every temporal increment should have an equal chance of being wet or dry, independent of the precipitation anomaly for the previous increment or increments. For example, if last year was the wettest on record, this year should still have an equal chance of being dry as it does being wet. A serial correlation analysis was performed for each of the PR time series. For example, the serial correlation analysis for the winter-to-spring comparison examined the winter PR time series and the spring PR time series for correlation. The next step was to determine the expected return frequency and the frequency per century for each classification of EPR events and for each temporal increment. This was done by using a random number generator to create 1000 sets of 119 random numbers, as done by Goodrich and Ellis (2008). The PR methodology was performed on the 1000 sets of data to determine the expected frequency per century and the expected return interval for each EPR class (e.g., EPR90). These values created a baseline to which the actual EPR frequencies for each temporal increment were compared. In order to

determine if the overall pattern of precipitation variability has changed, PR time series for all regions and all temporal increments were subjected to a regression analysis.

The time series of PR values for each temporal period were then divided into halves. For both the seasonal and the annual analysis, the first half contained 59 years of PR values from 1897-1955 and the second half contained 59 years of PR values from 1956-2014. For each climate region the two halves of PR values were subjected to a two-sample t-test to determine if the average precipitation variability was statistically different between the two time periods. The frequencies of various magnitude EPR events within each of the two halves of the record were also compared for each CR. Finally, the largest 30 PR values for each half of the record were subjected to a two-sample t-test. The largest 30 values were selected to determine if there was a difference in the most extreme reversals for the two halves of data, at all temporal increments and for all CRs, while maintaining a sufficient sample size to subject the data to a two-sample t-test.

The PR time series of data, calculated without taking the absolute difference in percentiles, were examined for trends. For each CR, at all temporal increments, the time series of PR values were subjected to a regression analysis to determine if a type of reversal (i.e. wet-to-dry or dry-to-wet) has become prominent. The PR time series were then stratified into two groups according to the sign of the reversal (i.e., positive or negative). The two-subset PR time series were also subjected to a regression analysis to determine if the magnitude of reversals (dry-to-wet or wet-to-dry) became more or less severe over the study period.

Lastly, seasonal averages of the Niño 3.4 index were calculated by computing the average of the September, October, and November (SON) indexes for each year (1896 – 2013). The months of September, October, and November were chosen from the results presented by

(Harshburger et al. 2002), which indicated that winter precipitation across the western United States is most related to the average of anomalous SSTs for SON. The raw winter-to-winter PR time series was calculated using the winter percentile from directly before the fall season from which the Niño 3.4 value was calculated, and the winter directly following the fall season. For example, the winter-to-winter PR value calculated from the difference in percentiles between the 2013 winter (December 2012, January 2013, and February 2013) and the 2014 winter (December 2013, January 2014, and February 2014) was examined to the fall 2013 Niño 3.4 value. The fall season Niño 3.4 time series and the winter-to-winter PR time series were then subjected to Pearson correlation tests. Pearson correlation was chosen to determine if winter-to-winter precipitation reversals for any CRs were related to the time series of Niño 3.4 values. The number of various magnitude EPR events (e.g., EPR60, EPR70, and EPR80) that occurred during El Niño years, neutral ENSO years, and La Niña years were accumulated in order to determine if large reversal events for a particular CR were associated with a certain phase of Niño/Niña.

3.4 Results and Discussion

3.4a Year-to-Year PR and EPR Analyses

As mentioned previously, to compare the frequency of EPR events to the expected frequencies, lag-1 autocorrelation must be minimal. The year-to-year lag-1 autocorrelation results (Table 2) show statistically significant autocorrelation in the PR time series of CR1 (Northwest) and CR9 (Northeast). A trend analysis and a two-sample t-test were examined for the PR time series of CR1 and CR9, but the frequencies of PR/EPR events were not analyzed since the PR values for these regions were non-random.

Table 2: Autocorrelation results for the year-to-year analysis. Climate regions marked with an asterisk (*) exhibited statistically significant autocorrelation ($\rho < 0.05$).

	CR1*	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9*
Autocorrelation Coefficient	0.27	0.10	0.10	-0.05	-0.07	<0.01	0.15	-0.03	0.27
ρ	<0.01	0.29	0.29	0.62	0.45	0.99	0.12	0.73	<0.01

For climate regions without significant autocorrelation in the PR record, the expected frequencies per century for various PR and EPR classes were compared to the observed frequencies per century of the same PR and EPR classes (Table 3). Three climate regions, CR5 (Ohio Valley), CR6 (South), and CR7 (Southwest), experienced a higher than expected frequency of EPR60 events within the historical record. There were also three climate regions, CR3 (Northern Rockies and Plains), CR5 (Ohio Valley), and CR8 (Southeast), that had a higher EPR70 frequency per century than would be expected by random chance.

The complete time series of PR values were then tested for significant linear trends (Table 3). No climate regions exhibited statistically significant trends, although six regions are characterized by positive trends in PR values over the full length of the time series, while only three regions had negative trends in PR values.

Table 3: Frequency per century of various EPR and PR classes for the year-to-year analysis versus the expected frequency per century (“Random”) for each respective EPR and PR class. Blue values represent return frequencies below the expected 25th percentile, while red values represent return frequencies above the expected 75th percentile. The return interval (RI) is also listed for the various EPR and PR classes. The trend per decade of each PR time series and the significance (ρ) are also shown.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
EPR90	1	100	~~0.9~~	0.9	0.9	0.0	0.0	0.9	0.9	2.5	~~0.9~~
EPR80	4	25.0	~~5.1~~	4.2	4.2	0.9	1.7	4.2	2.5	4.2	~~3.4~~
EPR70	9	11.1	~~11.0~~	7.6	10.2	3.4	9.3	6.8	5.1	10.2	~~8.5~~
EPR60	16	6.3	~~20.3~~	13.6	13.6	11.9	17.8	17.0	17.8	15.3	~~15.3~~
Trend/Decade			0.47	1.04	0.43	0.42	-0.98	-0.34	0.18	-0.70	0.89
ρ			0.49	0.10	0.49	0.47	0.11	0.59	0.78	0.26	0.18

The year-to-year PR time series for all climate regions were then divided into halves. The first 59 years of PR values (1897-1955) were grouped into the first half, and the second 59 years (1956-2014) into the second half. For each CR, the two populations of PR values were subjected to a two-sample t-test. The number of EPR60 events, and the subsequent return interval for the two populations of data were also compared (Table 4). The two subsets of PR values for CR2 (West) were significantly different, with the mean of the PR values of recent history larger than that of the early portion of the historical record (Figure 4). The PR/EPR values plotted through time, shown in Figure 5, also reveals that a clustering of larger EPR values occurs during the second half of the study period that likely increased the mean of the more recent population. Table 4 also shows that CR2 (West) only had 3 EPR60 events during the first half of the study period, compared to 13 EPR60 events during the second half. Six out of the nine regions had a larger mean PR value for the second half of the period. It is also worth noting that four climate regions had at least 4 more EPR60 events in the second half than in the first half. Two climate regions had at least 4 fewer EPR60 events during the second half of the time series.

Table 4: Statistical comparison of each half of the year-to-year PR time series for each of the 9 climate regions. Variables with ‘.1’ indicate statistics for the 1st half (1897-1955), variables with ‘.2’ indicate statistics for the 2nd half (1956-2014). Blue values represent return intervals located in the lower 25th percent of expected return intervals, while red values represent return intervals in the upper 75th percent of expected return intervals. Climate regions with an asterisk (*) are those for which the average between the two periods is statistically different ($p < 0.05$).

	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
CR1	33.5	38.1	24.7	25.6	12	12	4.9	4.9
CR2*	28.0	38.9	19.1	26.1	3	13	19.7	4.5
CR3	31.3	33.7	21.2	25.0	6	10	9.8	5.9
CR4	30.5	33.2	20.3	22.4	5	9	11.8	6.6
CR5	35.1	27.6	23.8	21.6	15	6	3.9	9.8
CR6	34.4	33.1	23.3	23.0	11	9	5.4	6.6
CR7	30.9	32.6	22.3	24.4	10	11	5.9	5.4
CR8	37.8	33.1	24.7	20.8	11	7	5.4	8.4
CR9	26.2	31.7	22.1	27.0	6	12	9.8	4.9

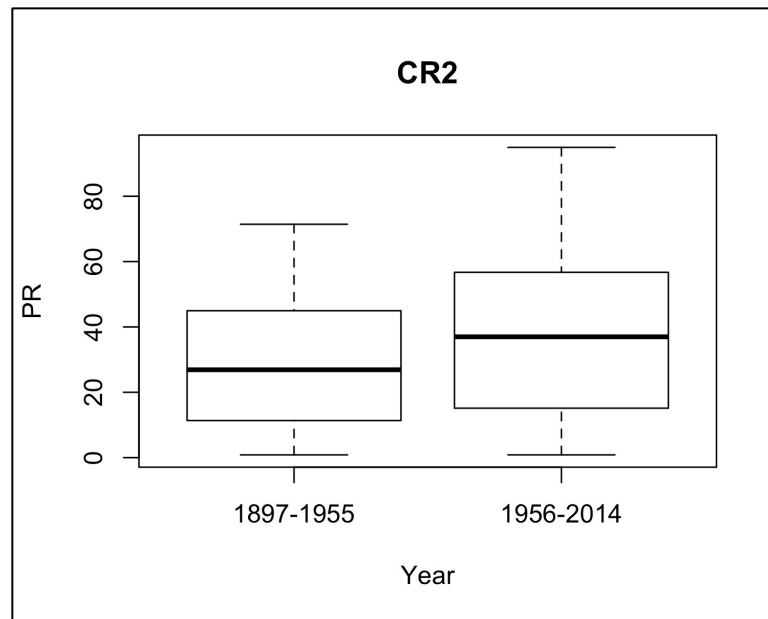


Figure 4: Boxplots of the PR distribution for both halves of the historical record for CR2 (West). The average PR value for the second half of the record was statistically different (larger) than the average PR value for the first half.

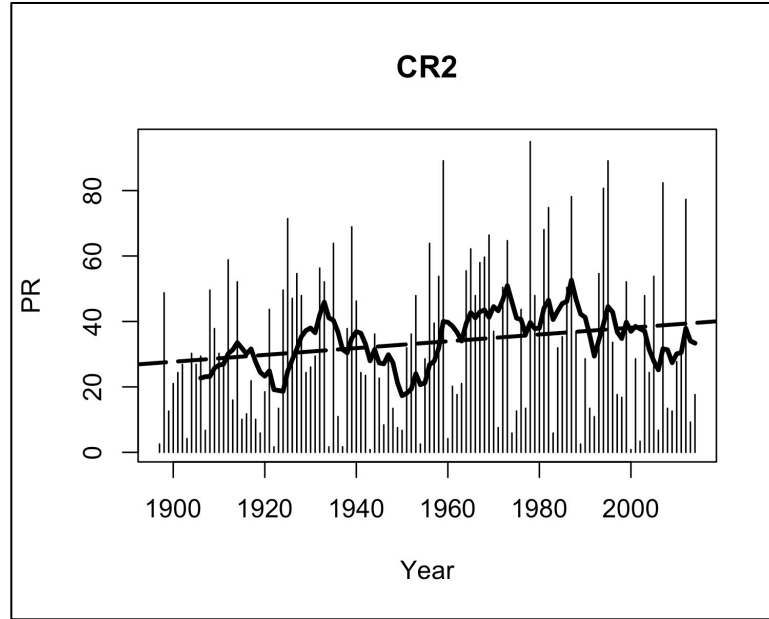


Figure 5: PR values of CR2 (West) plotted through time. The dashed black line represents the linear trend and the solid black line represents the 10-year moving average.

The largest thirty values from each half of the historical record were subjected to a two-sample t-test for each CR for the purpose of identifying a significant difference in the two populations (Table 5). CR2 (West) once again exhibited a significantly smaller average PR value for the earlier half of the historical record than for the latter half. Lastly, the PR/EPR time series, calculated without taking the absolute value, were examined for trends (Table 6). The overall trends of the year-to-year PR/EPR time series for all CRs were not significant. The positive and negative values of the PR/EPR time series were stratified, and tested for trends. The trends for all CRs, for both positive and negative time series were not significant (Table 6).

Table 5: Average of the largest 30 PR values for each half of the historical record for the nine climate regions. Climate regions with an asterisk (*) are those for which the two subsets are significantly different ($\rho < 0.05$)

	CR1	CR2*	CR3	CR4	CR5	CR6	CR7	CR8	CR9
1897-1955	53.9	43.3	48.6	47.3	54.7	53.1	48.9	57.9	43.7
1956-2014	58.3	60.6	52.8	52.6	44.6	51.4	52.2	49.5	53.1

Table 6: Linear trends in raw PR values (absolute value). None of the trends are statistically significant.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Overall Trend/Decade	-0.09	-0.10	0.30	0.23	0.11	-0.21	-0.07	-0.11	0.06
Positive Values Trend/Decade	0.76	0.76	0.07	0.03	-0.98	-0.22	-0.51	-1.09	0.97
Negative Values Trend/Decade	-0.14	-1.32	-1.04	-1.01	0.98	0.47	-0.81	0.35	-0.82

3.4b Interannual Analyses

i. Winter-to-Winter

It is important to note that on average only 14% of annual precipitation occurs during the winter months (DJF) for CR3 (Northern Rockies and Plains), and only 12% of annual precipitation occurs during the winter months for CR4 (Upper Midwest)(Figure 3). The results for these regions will still be discussed, but clearly winter precipitation may not be as critical in these regions as it is for the others. Lag-1 autocorrelation results (Table 7) reveal that the PR values for CR1 (Northwest) and CR9 (Northeast) were non-random, as they were for the year-to-year analysis.

Table 7: Same as for Table 2, but for the winter-to-winter PR time series.

	CR1*	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9*
Autocorrelation Coefficient	0.34	0.08	0.10	0.15	0.04	0.09	0.12	-0.03	0.30
ρ	<0.01	0.40	0.27	0.11	0.65	0.35	0.20	0.73	<0.01

Excluding CR1 and CR9, the frequency per century of various classes of PR and EPR values were compared to expected frequencies (Table 8). Three climate regions, CR3 (Northern Rockies and Plains), CR5 (Ohio Valley), and CR8 (Southeast) experienced a higher than expected frequency of EPR60 events. Two climate regions, CR2 (West), and CR4 (Upper Midwest) experienced a lower EPR60 frequency per century than would be expected by random chance.

The complete time series of PR values for each CR were then tested for significant trends per decade (Table 8). No climate regions exhibited statistically significant trends over the full time series. Four CRs had positive trends in PR values and five CRs had negative trends in PR values for the 118-year period of record.

Table 8: Same as for Table 3, but for the winter-to-winter PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
EPR90	1	100	~~0.0~~	0.9	1.7	0.0	2.5	1.7	2.5	2.5	~~1.7~~
EPR80	4	25.0	~~2.5~~	0.9	2.5	1.7	5.1	5.1	3.4	9.3	~~5.9~~
EPR70	9	11.1	~~7.6~~	5.9	9.3	5.1	11.9	10.2	7.6	12.7	~~10.2~~
EPR60	16	6.3	~~14.4~~	12.7	18.6	11.0	17.0	16.1	16.1	22.0	~~12.7~~
Trend/Decade			-0.35	0.62	0.06	-0.19	-0.46	0.38	0.18	-0.59	-0.89
ρ			0.55	0.30	0.92	0.75	0.49	0.56	0.78	0.42	0.17

The PR values for the halves of the historical record for CR2 (West) were significantly different (Table 9), as the population of PR values for the more recent record is greater than that

for the early portion of the record (Figure 6). CR2 (West) had five EPR60 events during the first half of the study period, compared to 10 during the second half. Although the means for CR6 (South) were not statistically different, there were 5 EPR60 events during the first half and 14 EPR60 events during the second half. CR7 (Southwest) had 7 EPR60 events during the first half, and 12 EPR60 events during the second half.

Table 9: Same as for Table 4, but for the winter-to-winter PR time series.

	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
CR1	36.8	33.7	21.3	22.7	10	7	5.9	8.4
CR2*	26.9	35.8	20.5	23.3	5	10	11.8	5.9
CR3	32.6	37.3	24.5	23.8	10	12	5.9	4.9
CR4	30.6	31.5	20.4	22.0	6	7	9.8	8.4
CR5	35.3	32.6	26.9	22.7	12	8	4.9	7.4
CR6	33.2	36.3	23.5	24.7	5	14	11.8	4.2
CR7	32.1	36.8	21.6	24.8	7	12	8.4	4.9
CR8	35.1	29.3	28.0	26.0	15	11	3.9	5.4
CR9	31.9	31.3	23.4	25.1	6	9	9.8	6.6

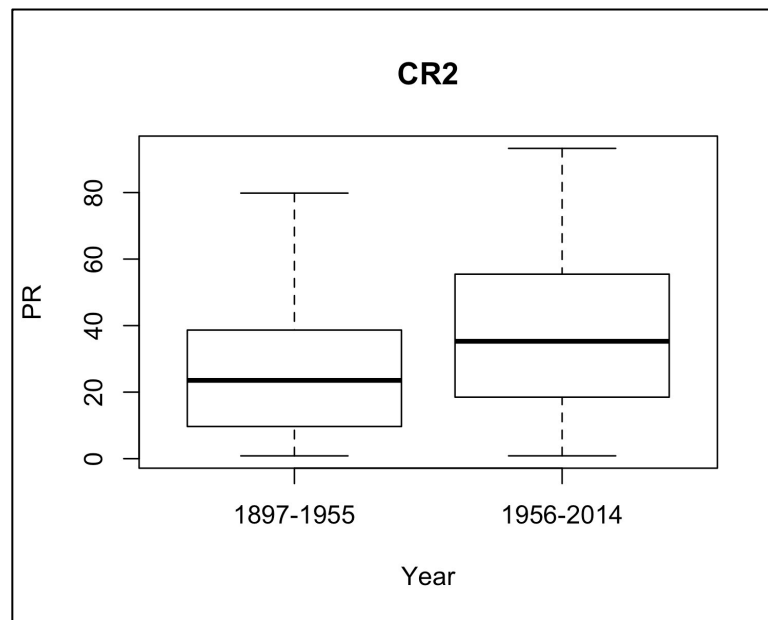


Figure 6: Same as for Figure 4, but for the winter-to-winter PR time series of CR2 (West).

The largest 30 PR/EPR values for CR2 (West) from the second half of the record are significantly larger than those from the first half of the record. The two-sample t-test on the largest 30 PR/EPR values from each half of the record are not shown because they were quite similar to the two-sample t-test results for all PR/EPR data (Table 9). Lastly, the PR/EPR time series, calculated without taking the absolute value, were examined for linear trends. The trends of the winter-to-winter PR time series of both positive and negative reversals, for all CRs, were insignificant. The positive and negative values of the PR/EPR time series were stratified and tested for trends. The trends for all CRs, for both positive and negative time series, were not statistically significant.

ii. Spring-to-Spring

For the spring-to-spring analysis, only the PR time series for CR1 (Northwest) exhibited statistically significant lag-1 autocorrelation (Table 10).

Table 10: Same as for Table 2, but for the spring-to-spring PR time series.

	CR1*	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Autocorrelation Coefficient	0.26	<-0.01	0.16	0.02	0.14	0.07	0.15	-0.05	-0.03
p	0.01	0.98	0.09	0.81	0.14	0.49	0.10	0.56	0.72

The observed frequency of EPR60 events per century for CR2 (West), CR3 (Northern Rockies and Plains), CR4 (Upper Midwest), and CR7 (Southwest), were higher than the expected frequency per century (Table 11). The observed frequency per century of EPR60 events for CR3 (Northern Plains and Rockies) was the highest observed of any CRs at 24.6. Furthermore, CR3 (Northern Plains and Rockies) recorded 3.4 EPR90 events per century, which is well above the expected value of 1 EPR90 event per century. CR5 (Ohio Valley), CR6

(South), and CR9 (Northeast) all experienced a lower than expected frequency per century for the spring-to-spring analysis. No PR/EPR time series exhibited statistically significant trends for the spring-to-spring time series (Table 11). Six of the nine regions had a positive trend in PR/EPR values for the full study period, while 3 regions were characterized by a negative trend in PR/EPR values.

Table 11: Same as for Table 3, but for the spring-to-spring PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
EPR90	1	100	~~2.5~~	0.9	3.4	0.0	2.5	0.9	1.7	0.9	1.7
EPR80	4	25.0	~~3.4~~	5.1	5.9	4.2	5.1	2.5	3.4	4.2	5.1
EPR70	9	11.1	~~10.2~~	9.3	13.6	8.5	9.3	7.6	10.2	6.8	6.8
EPR60	16	6.3	~~17.0~~	17.8	24.6	17.0	15.3	13.6	17.8	16.1	15.3
Trend/Decade			1.08	1.07	0.15	0.61	-0.22	-0.64	-0.74	0.54	0.18
ρ			0.10	0.11	0.83	0.33	0.73	0.30	0.27	0.41	0.78

PR values for the first half of the historical record for CR2 (West) are statistically significantly different than those for the second half of the historical record. Specifically, values from early in the record are smaller than for later in the record (Figure 7). CR2 (West) experienced 6 EPR60 events in the first half of the record compared to 15 EPR60 events over the latter half of the historical record (Table 12). Examining the largest 30 PR values from each half of the historical record did not yield results different from those when considering all PR values.

It is interesting to note that the dry-to-wet reversals for CR7 (Southwest) are decreasing in magnitude at 2.56 percentiles per decade (Figure 8). None of the other CRs exhibited statistically significant trends for the PR time series calculated without taking the absolute difference in percentiles from one increment to the next (Table 13).

Table 12: Same as for Table 4, but for the spring-to-spring PR time series.

	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
CR1	33.9	35.7	21.3	27.2	7	13	8.4	4.5
CR2*	30.1	37.8	19.5	27.3	6	15	9.8	3.9
CR3	38.7	37.7	26.7	23.3	18	11	3.3	5.4
CR4	33.9	34.8	21.3	24.7	8	12	7.4	4.9
CR5	34.3	31.7	26.0	21.1	10	8	5.9	7.4
CR6	34.6	32.0	21.8	23.4	8	8	7.4	7.4
CR7	35.2	31.0	24.6	24.4	13	8	4.5	7.4
CR8	29.6	34.4	23.5	24.3	10	9	5.9	6.6
CR9	35.3	35.8	22.9	24.3	9	9	6.6	6.6

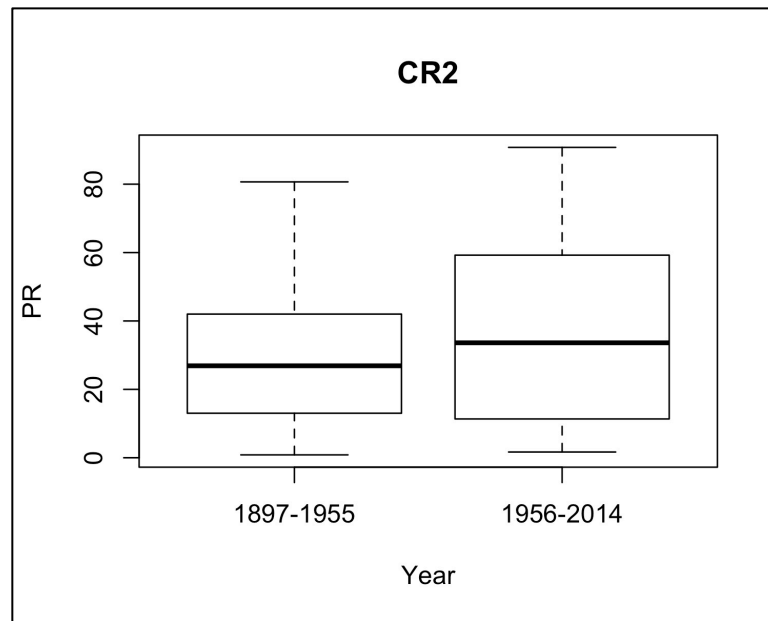


Figure 7: Same as for Figure 4, but for the spring-to-spring PR time series of CR2 (West).

Table 13: Same as for Table 6, but for the spring-to-spring PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Overall Trend/Decade	0.37	0.15	0.16	0.31	-0.08	-0.25	-0.26	-0.02	0.01
Positive Values Trend/Decade	0.40	0.59	0.46	0.90	0.48	-1.04	-2.56*	0.76	-0.02
Negative Values Trend/Decade	-1.76	-1.51	0.09	-0.34	1.01	0.32	-1.20	-0.20	-0.30

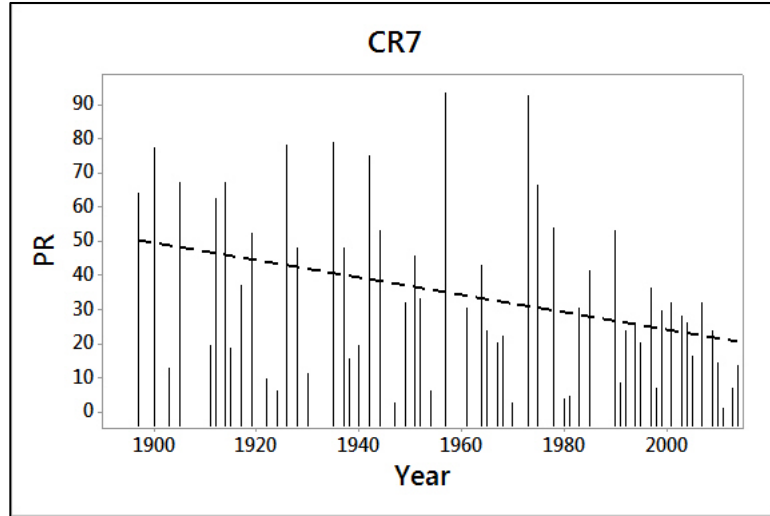


Figure 8: Positive (dry-to-wet) reversals for the spring-to-spring time step plotted through time for CR7 (Southwest). Dashed line represents the trend of PR values.

iii. Summer-to-Summer

It is important to note that on average, summer precipitation accounts for 10% of the total annual precipitation for CR1 (Northwest), and 7% of the total annual precipitation for CR2 (West)(Figure 3). For the summer-to-summer analysis, lag-1 autocorrelation was tested and three regions, CR1 (Northwest), CR2 (West), and CR7 (Southwest), have statistically significant lag-1 autocorrelation (Table 14). The PR and EPR frequencies were not compared to the expected frequencies for these CRs.

Table 14: Same as for Table 2, but for the summer-to-summer PR time series.

	CR1*	CR2*	CR3	CR4	CR5	CR6	CR7*	CR8	CR9
Autocorrelation Coefficient	0.20	0.23	-0.04	0.10	-0.02	0.09	0.37	0.11	0.13
ρ	0.03	0.01	0.67	0.27	0.87	0.32	<0.01	0.24	0.16

CR3 (Northern Rockies and Plains), CR4 (Upper Midwest), CR6 (South), CR8 (Southeast), and CR9 (Northeast) experienced a lower than expected frequency per century of

EPR60 events. Conversely, CR5 (Ohio Valley) experienced a higher than expected frequency per century of EPR60 events (Table 15). None of the climate regions had a statistically significant linear trend in PR values (Table 15). Further, none of the CRs are characterized by a statistically significant difference in PR values for the early and late halves of the historical record. CR8 (Southeast) had 3 EPR70 events in the first half, and 7 EPR70 events in the second half (Table 16). CR8 (Southeast) only had one EPR80 event in the first half, but three EPR80 events during the second half (Table 16). The largest 30 PR values for each half of the historical record exhibited no statistically significant differences. The PR time series, calculated without taking the absolute value of the difference in percentiles from one increment to the next, exhibited no statistically significant trends.

Table 15: Same as for Table 3, but for the summer-to-summer PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
EPR90	1	100	0.9	1.7	1.7	1.7	0.0	0.0	0.9	0.9	0.9
EPR80	4	25.0	8.5	5.9	2.5	3.4	3.4	0.9	2.5	3.4	1.7
EPR70	9	11.1	11.9	17.0	6.8	8.5	8.5	7.6	8.5	8.5	5.1
EPR60	16	6.3	14.4	21.2	12.7	14.4	17.8	12.7	17.8	15.3	13.6
Trend/Decade			0.37	-0.98	0.50	-0.19	-0.73	0.27	-0.70	0.42	0.69
p			0.58	0.17	0.41	0.76	0.24	0.64	0.26	0.51	0.25

Table 16: Same as for Table 4, but for the summer-to-summer PR time series.

	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
CR1	33.1	33.1	24.4	25.0	9	8	6.6	7.4
CR2	38.6	33.1	26.0	26.8	11	14	5.4	4.2
CR3	30.8	30.7	20.9	23.8	6	9	9.8	6.6
CR4	32.5	30.9	23.3	24.3	7	10	8.4	5.9
CR5	36.6	32.4	22.1	23.5	12	9	4.9	6.6
CR6	32.3	31.0	19.9	22.5	6	9	9.8	6.6
CR7	36.1	35.5	22.9	22.8	10	11	5.9	5.4
CR8	29.9	34.1	21.6	25.3	7	11	8.4	5.4
CR9	33.3	35.6	20.7	23.4	7	9	8.4	6.6

iv. Fall-to-Fall

The time series for CR6 (South), CR7 (Southwest), and CR8 (Southeast) exhibited statistically significant autocorrelation (Table 17). Excluding those CRs, the expected frequencies per century were compared to the observed frequencies per century. The observed EPR60 frequency per century for CR2 (West) and CR8 (Southeast) were higher than the expected frequency per century (Table 18). Conversely, the observed EPR60 frequency per century for CR3 (Northern Rockies and Plains), CR4 (Upper Midwest), and CR9 (Northeast), were lower than the expected frequency per century (Table 18). The PR/EPR time series for CR5 (Ohio Valley) exhibited a statistically significant negative linear trend of 1.65 percentiles per decade (Figure 9). Four CRs were characterized by a negative trend in PR/EPR values, and five CRs exhibited positive trends in PR/EPR values through the period of record (Table 18).

Table 17: Same as for Table 2, but for the fall-to-fall PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6*	CR7*	CR8*	CR9
Autocorrelation Coefficient	-0.08	0.13	0.11	0.08	0.17	0.20	0.26	0.28	0.06
ρ	0.42	0.16	0.26	0.42	0.07	0.03	0.01	<0.01	0.55

Table 18: Same as for Table 3, but for the fall-to-fall PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5*	CR6	CR7	CR8	CR9
EPR90	1	100	0.0	1.7	1.7	0.0	0.9	1.7	0.9	1.7	1.7
EPR80	4	25.0	0.9	3.4	3.4	1.7	1.7	8.5	4.2	5.9	4.2
EPR70	9	11.1	8.5	7.6	6.8	5.9	10.2	10.2	10.2	8.5	11.0
EPR60	16	6.3	16.1	17.0	13.6	15.3	17.0	15.3	19.5	19.5	15.3
Trend/Decade			-0.43	0.26	0.54	-0.95	-1.65	-0.12	0.61	0.13	0.89
ρ			0.49	0.71	0.37	0.13	0.01	0.86	0.35	0.84	0.17

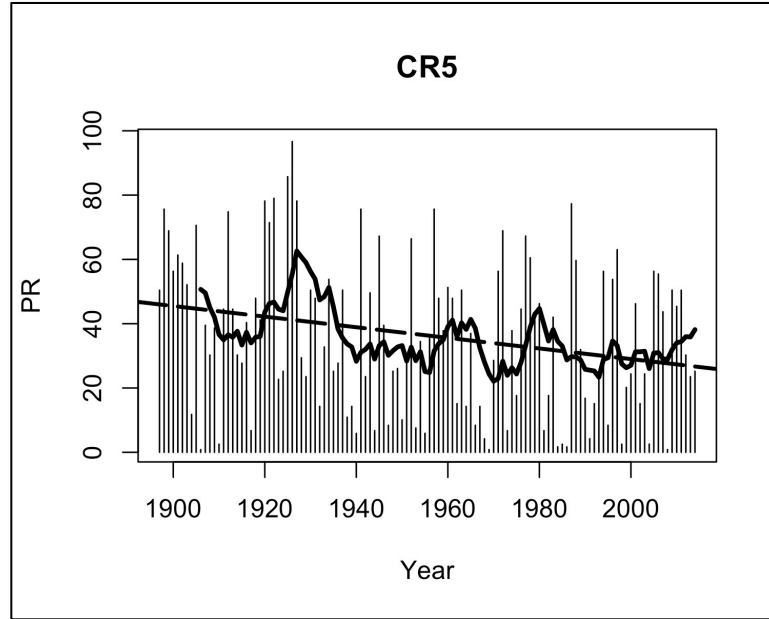


Figure 9: Same as for Figure 5, but for the fall-to-fall PR values of CR5 (Ohio Valley).

PR values from the halves of the historical record were compared for each of the CRs, and none were found to exhibit a statistically significant difference (Table 19). The number of EPR60 events for CR1 (Northwest) decreased from 12 during the first half of the historical record, to 7 during the second half of the record (Table 19). The number of EPR60 events for CR2 (West) increased from 7 to 13 (Table 19). The number of EPR60 events for CR5 (Ohio Valley) decreased from 14 to 6, and the number of EPR60 events for CR7 (Southwest) increased from 8 to 15 (Table 19).

Table 19: Same as for Table 4, but for the fall-to-fall PR time series.

	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
CR1	34.0	29.1	26.3	19.3	12	7	4.9	8.4
CR2	30.5	33.8	23.9	26.6	7	13	8.4	4.5
CR3	30.4	37.6	19.5	24.3	6	10	9.8	5.9
CR4	35.7	32.5	22.3	24.0	8	10	7.4	5.9
CR5	40.2	32.5	24.8	21.9	14	6	4.2	9.8
CR6	32.1	33.1	25.0	25.0	9	9	6.6	6.6
CR7	33.2	34.8	21.1	26.6	8	15	7.4	3.9
CR8	34.2	37.7	23.8	23.7	13	10	4.5	5.9
CR9	31.0	37.3	24.2	23.9	8	10	7.4	5.9

Focusing on just the largest 30 PR values from each half of the historical record (Table 20), CRs 1 (Northwest) and 5 (Ohio Valley) had significantly smaller PR values for second half of the study period relative to the first half (Figures 10 and 12, respectively). The opposite was the case for CR3 (Northern Rockies and Plains) (Figure 11). The trend of PR values, calculated without taking the absolute value of the difference in percentiles from one increment to the next, were examined for trends (Table 21). The trend of dry-to-wet reversals (i.e., a positive PR) for CR9 exhibited a statistically significant positive trend of 2.01 percentiles per decade (Figure 13). None of the other trends were statistically significant (Table 21).

Table 20: Same as for Table 5, but for the fall-to-fall PR time series.

	CR1*	CR2	CR3*	CR4	CR5*	CR6	CR7	CR8	CR9
1897-1955	55.8	50.8	46.1	53.9	60.6	52.2	48.7	53.1	51.3
1956-2014	44.8	54.6	57.1	52.4	51.3	51.8	56.9	56.0	55.0

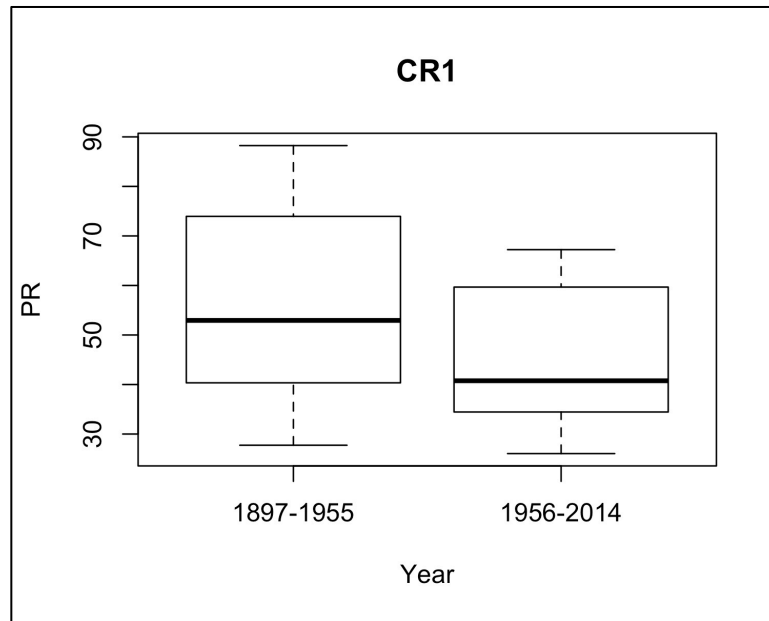


Figure 10: Boxplots that compare the largest 30 PR values for both halves of data. The average PR value of the largest 30 values for the second half of data for CR1 (Northwest) was statistically different (larger) than the average PR value for the first half.

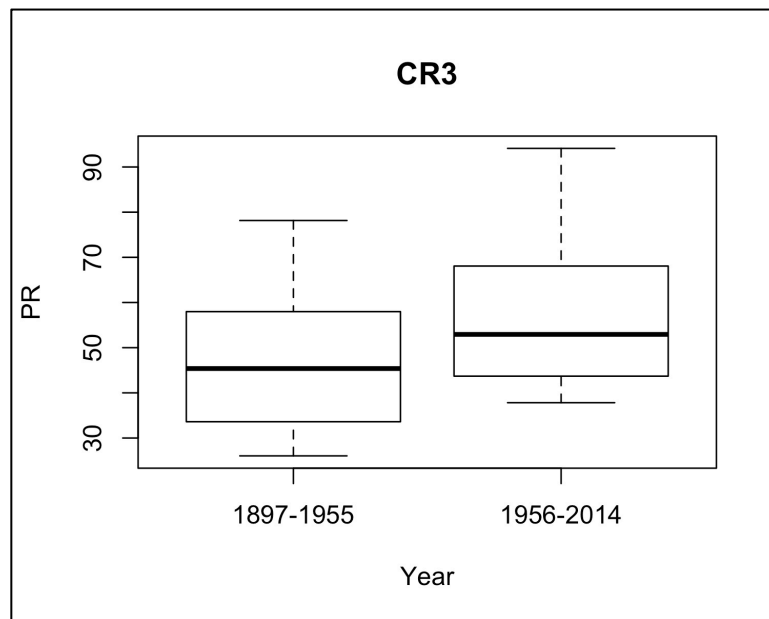


Figure 11: Same as for Figure 10, but for the largest 30 values of both halves for CR3 (Northern Plains and Rockies).

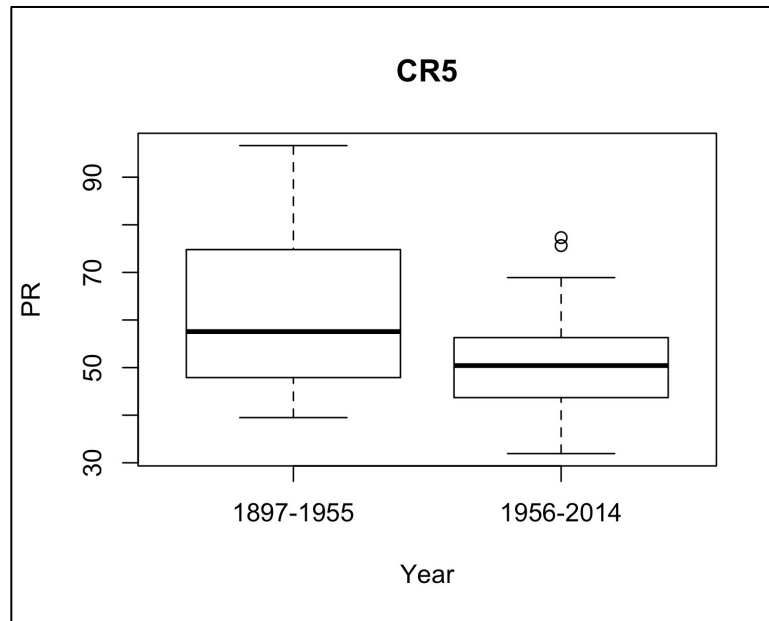


Figure 12: Same as for Figure 10, but for the largest 30 values of both halves for CR5 (Ohio Valley).

Table 21: Same as for Table 6, but for the fall-to-fall PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Overall Trend/Decade	0.25	0.11	0.16	0.19	0.10	0.07	0.25	0.08	<0.01
Positive Values Trend/Decade	-0.55	0.14	-0.07	-1.45	-1.76	-0.19	0.66	0.07	2.01*
Negative Values Trend/Decade	0.31	-0.33	-1.06	0.23	1.54	0.02	-0.55	-0.18	0.19

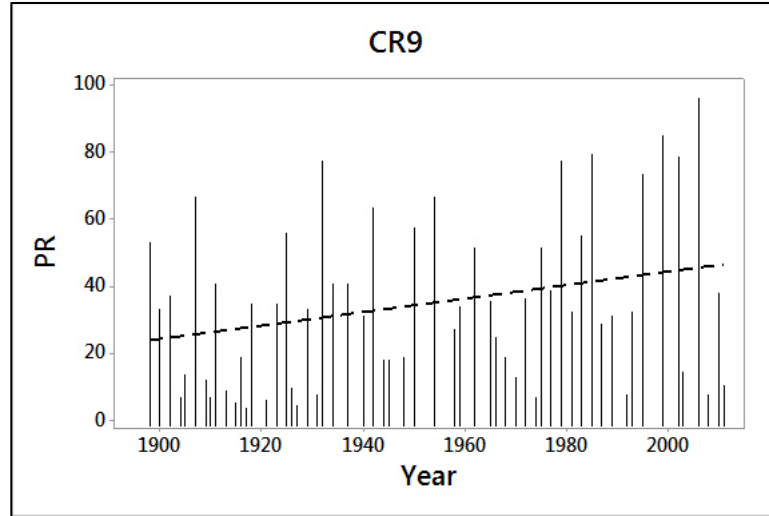


Figure 13: Same as for Figure 8, but for the fall-to-fall time step for CR9 (Northeast).

3.4c Intra-annual Analyses

i. Winter-to-Spring

The results from examining one season to the subsequent season (e.g. winter-to-spring) will be presented in the section. For the winter-to-spring analysis, none of the CRs exhibited lag-1 autocorrelation (Table 22). The expected number of various PR and EPR results was compared to the observed number of events for various PR/EPR classes (Table 23). Only CR1 (Northwest) had a higher EPR60 frequency per century than what was expected. Except for CR4 (Upper Midwest), which had an observed frequency of EPR60 events approximately equal to that of the expected value, the remaining CRs all had lower frequency per century values of EPR60 events than was expected by random chance (Table 23).

No regions exhibited a significant trend in PR values over the time period, although the PR value for CR9 decreased at a rate of 1.19 percentiles per decade ($p=0.06$) (Table 23). The time series of six CRs exhibited a negative trend in PR values. Conversely, the PR time series of three CRs exhibited a positive trend (Table 23).

Table 22: Same as for Table 2, but for the winter-to-spring PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Autocorrelation Coefficient	-0.06	-0.17	0.08	-0.09	0.05	-0.09	-0.06	-0.04	-0.09
ρ	0.51	0.08	0.40	0.36	0.57	0.36	0.52	0.67	0.32

Table 23: Same as for Table 3, but for the winter-to-spring PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
EPR90	1	100	0.0	0.9	1.7	0.9	0.0	0.0	0.9	0.0	1.7
EPR80	4	25.0	2.5	3.4	6.8	2.5	0.9	0.9	5.1	0.9	5.1
EPR70	9	11.1	8.5	9.3	10.2	9.3	8.5	1.7	6.8	2.5	8.5
EPR60	16	6.3	17.8	12.7	14.4	16.1	13.6	5.1	11.0	7.6	14.4
Trend/Decade			0.75	-0.34	-0.87	0.16	-0.30	0.37	-0.73	-0.09	-1.19
ρ			0.23	0.60	0.19	0.80	0.62	0.49	0.22	0.87	0.06

PR values from the halves of the historical record were compared for each of the CRs, and none were found to exhibit a statistically significant difference (Table 24). The largest 30 values of each half were also subjected to a two-sample t-test, but none of those results varied from the full two-sample t-test, and thus were omitted. The trends of PR values, calculated without taking the absolute value of the difference in percentiles from one increment to the next, were examined (Table 25). The dry-to-wet reversals for CR1 exhibited a statistically significant positive trend of 2.43 percentiles per decade (Figure 14). None of the other trends were statistically significant (Table 25).

Table 24: Same as for Table 4, but for the winter-to-spring PR time series.

	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60. 1	EPR60. 2	EPR60_RI. 1	EPR60_RI. 2
CR1	32.6	35.8	21.4	24.6	8	13	7.4	4.5
CR2	27.3	29.0	23.2	24.3	7	8	8.4	7.4
CR3	38.9	31.9	22.5	25.9	8	9	7.4	6.6
CR4	32.5	33.5	22.6	24.2	8	11	7.4	5.4
CR5	33.4	31.3	22.6	22.2	10	6	5.9	9.8
CR6	27.1	30.9	17.9	20.9	1	5	59.0	11.8
CR7	31.4	28.7	21.6	22.4	7	6	8.4	9.8
CR8	30.2	27.9	19.9	18.9	5	4	11.8	14.8
CR9	35.0	29.5	24.4	22.7	11	6	5.4	9.8

Table 25: Same as for Table 6, but for the winter-to-spring PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Overall Trend/Decade	1.82	-0.08	1.72	0.94	0.19	-0.93	-0.02	0.53	0.52
Positive Values Trend/Decade	2.43*	-0.33	-0.89	0.41	-0.05	-0.53	-0.62	0.88	-1.78
Negative Values Trend/Decade	1.05	0.36	0.81	0.07	0.54	-1.45	0.85	1.10	0.94

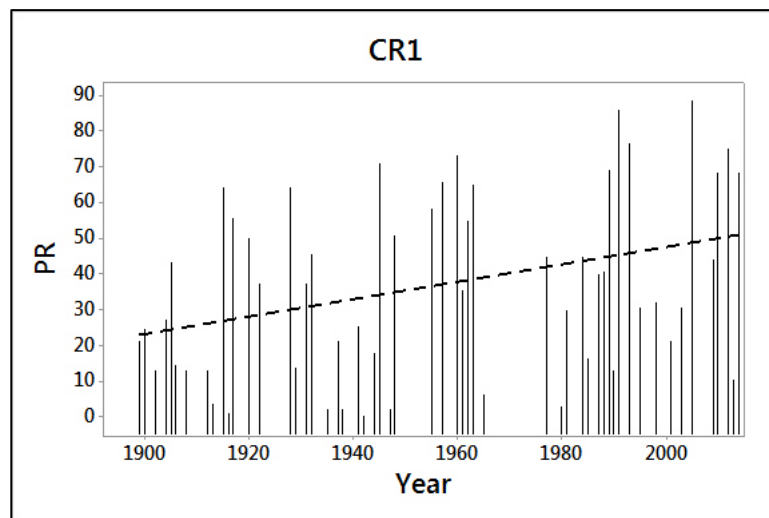


Figure 14: Same as for Figure 8, but for the winter-to-spring time step for CR9 (Northeast).

ii. Spring-to-Summer

None of the CRs exhibited statistically significant lag-1 autocorrelation (Table 26). CR3 (Northern Rockies and Plains), CR4 (Upper Midwest), CR5 (Ohio Valley), CR6 (South), CR8 (Southeast), and CR9 (Northeast), all experienced fewer EPR60 and EPR70 events than would be expected by random chance (Table 27). This large portion of the United States with fewer extreme events than expected suggests that the spring-to-summer transition is naturally less variable than random chance indicates. None of the spring-to-summer PR/EPR time series exhibited statistically significant trends although the PR/EPR time series for six CRs exhibited positive trends, while three exhibited negative trends over the study period (Table 27).

Table 26: Same as for Table 2, but for the spring-to-summer PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Autocorrelation Coefficient	-0.06	0.05	-0.01	-0.03	0.06	0.15	0.09	0.05	-0.06
ρ	0.51	0.59	0.89	0.77	0.51	0.10	0.35	0.62	0.54

Table 27: Same as for Table 3, but for the spring-to-summer PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
EPR90	1	100	0.0	0.0	0.9	0.0	0.9	0.0	0.0	0.0	1.7
EPR80	4	25.0	2.5	3.4	1.7	3.4	4.2	1.7	4.2	2.5	4.2
EPR70	9	11.1	9.3	9.3	5.9	7.6	8.5	6.8	10.2	7.6	7.6
EPR60	16	6.3	16.1	17.8	13.6	13.6	13.6	10.2	19.5	14.4	13.6
Trend/Decade			0.05	0.58	0.72	0.49	-0.80	0.44	-0.75	0.63	-1.03
ρ			0.94	0.37	0.24	0.44	0.20	0.46	0.26	0.33	0.11

The population of PR/EPR values for the first half of the historical record for CR9 (Northeast) was statistically larger than for the population of the second half of the record (Figure 15). For 6 of the CRs, the PR/EPR values from the first half of the historical record were larger than those from the second half of the record. CR2 (West), CR4 (Upper Midwest), and

CR6 (South), all experienced at least four more EPR60 events in the second half than in the first half of the record (Table 28). CR5 (Ohio Valley) and CR9 (Northeast) had at least four fewer EPR60 events during the first half of the time period (Table 28) when compared to the second half of the historical record. The 30 largest PR values from each half of the historical record for each region were examined for differences (Table 29). Both CR5 (Ohio Valley) and CR9 (Northeast) had significant decreases in the largest 30 PR/EPR values for the second half of the study period (Figures 16 and 17, respectively).

Table 28: Same as for Table 4, but for the spring-to-summer PR time series.

	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
CR1	30.5	32.7	22.1	24.4	9	10	6.6	5.9
CR2	28.3	33.4	21.8	25.9	8	13	7.4	4.5
CR3	31.0	32.6	22.9	23.0	8	8	7.4	7.4
CR4	30.1	33.3	23.3	23.1	5	11	11.8	5.4
CR5	36.4	30.1	24.8	21.1	10	6	5.9	9.8
CR6	29.4	31.9	20.6	22.8	4	8	14.8	7.4
CR7	35.9	32.8	24.8	24.0	12	11	4.9	5.4
CR8	29.4	31.2	22.7	24.7	7	10	8.4	5.9
CR9*	35.3	26.1	26.5	19.9	12	4	4.9	14.8

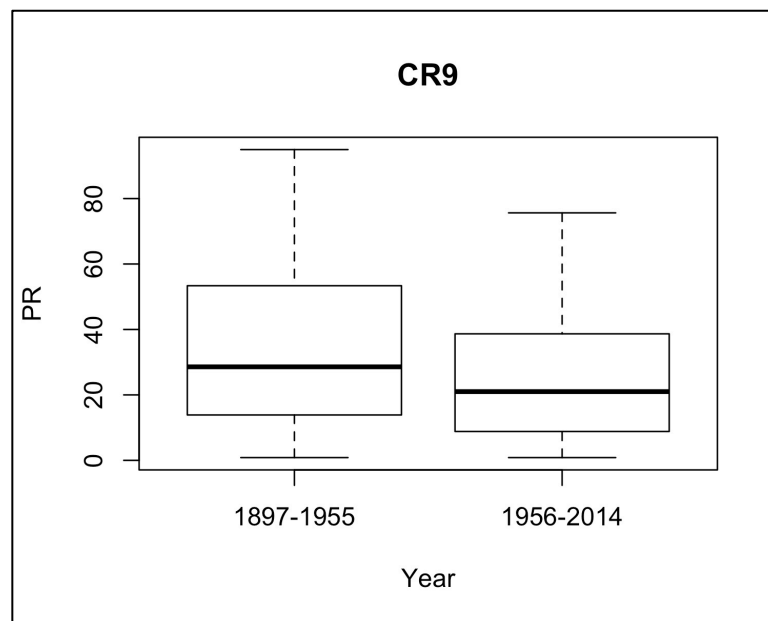


Figure 15: Same as for Figure 4, but for the spring-to-summer PR time series of CR9 (Northeast).

Table 29: Same as for Table 5, but for the spring-to-summer analysis.

	CR1	CR2	CR3	CR4	CR5*	CR6	CR7	CR8	CR9*
1897-1955	48.3	46.0	49.4	49.2	57.2	46.0	56.3	46.2	56.7
1956-2014	51.0	53.9	51.8	51.5	46.0	49.9	52.6	50.6	42.2

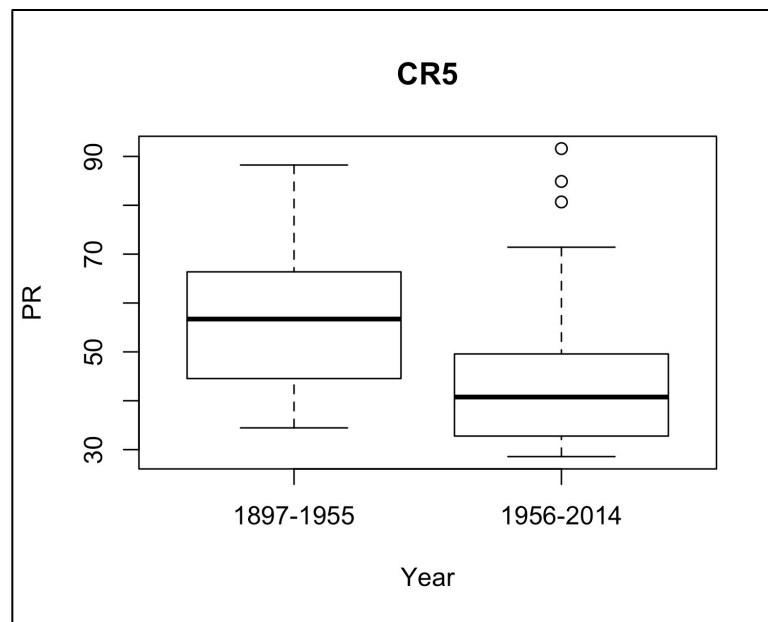


Figure 16 (left): Same as for Figure 10, but for the spring-to-summer analysis of CR5 (Ohio Valley).

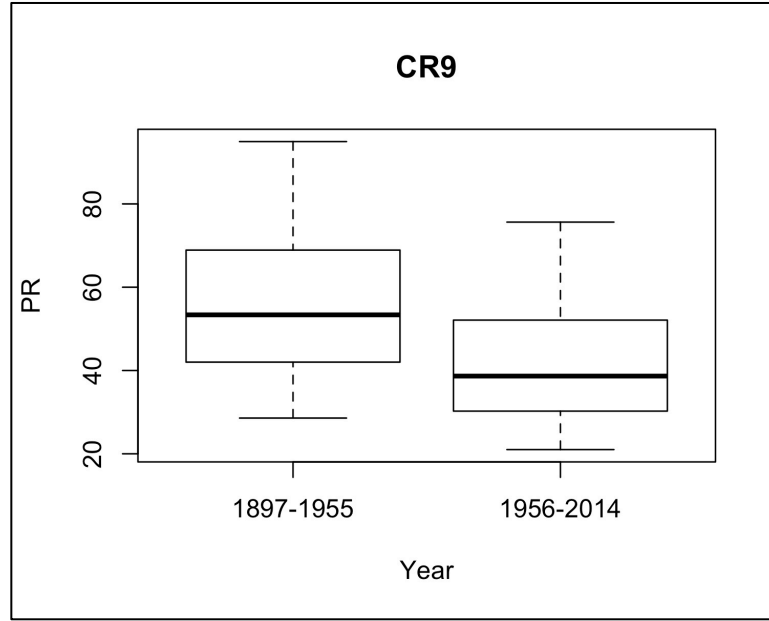


Figure 17 (right): Same as for Figure 10, but for the spring-to-summer analysis of CR9 (Northeast).

The trends of spring-to-summer PR values, calculated without taking the absolute value of the difference from one increment to the next, were then examined (Table 30). The trend of dry-to-wet reversals (positive PR values) significantly decreased by 1.84 percentiles per decade for CR5 (Ohio Valley) from 1897-2014 (Figure 18). The wet-to-dry PR values (negative PR values) significantly increased at 2.06 percentiles per decade for CR7 (Southwest) (Figure 19). The trend of wet-to-dry PR values (negative PR values) significantly decreased at 1.73 percentiles per decade for CR8 (Southeast) (Figure 20).

Table 30: Same as for Table 6, but for the spring-to-summer PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Overall Trend/Decade	-0.67	1.15	-0.96	-0.60	0.35	-0.25	0.88	-1.76	-0.23
Positive Values Trend/Decade	-0.76	0.63	0.57	-0.37	-1.84*	0.15	0.29	-0.34	-1.20
Negative Values Trend/Decade	-1.03	-0.42	-0.97	-1.43	-0.36	-0.78	2.06*	-1.73*	0.86

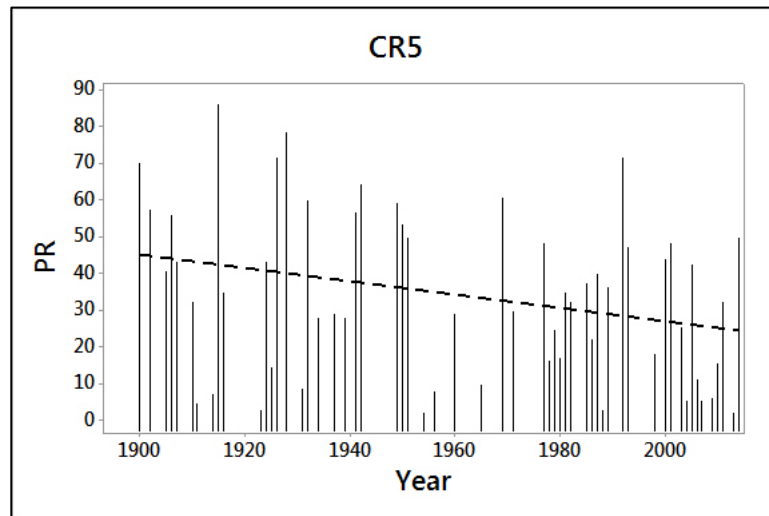


Figure 18: Same as for Figure 8, but for the spring-to-summer time step for CR5 (Ohio Valley).

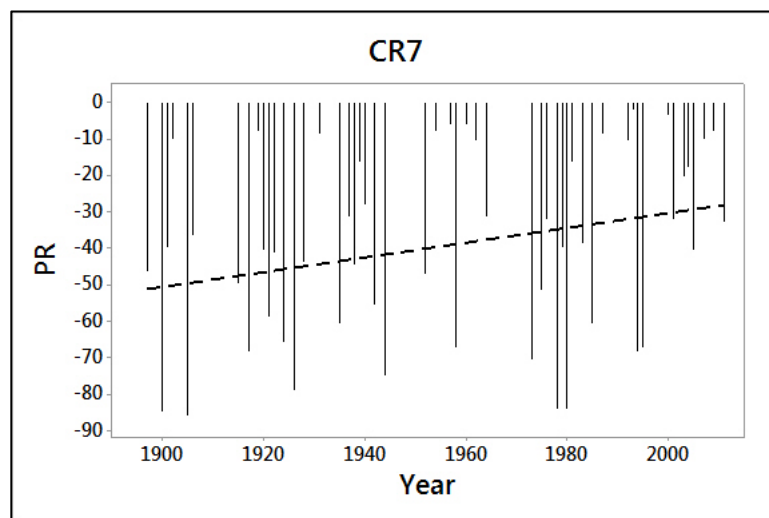


Figure 19: Negative (wet-to-dry) reversals for the spring-to-summer time step plotted through time for CR7 (Southwest). Dashed line represents the trend of PR values.

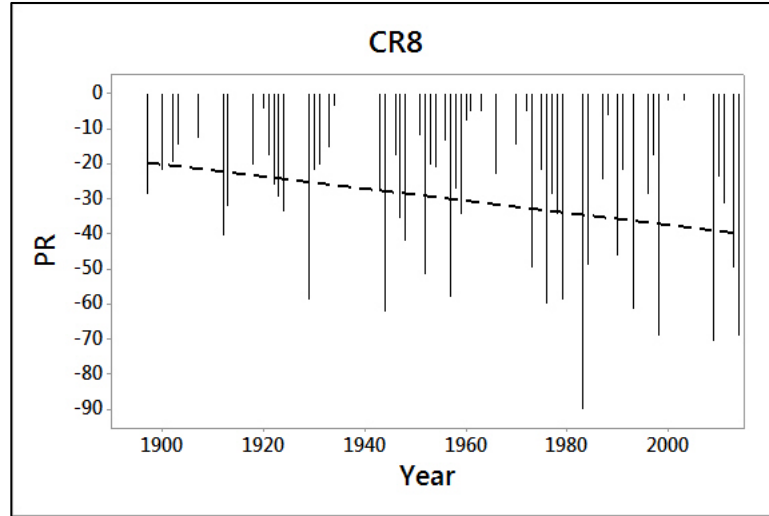


Figure 20: Same as for Figure 19, but for the PR values of CR8 (Southeast).

iii. Summer-to-Fall

The summer-to-fall PR time series of CR5 (Ohio Valley) and CR9 (Northeast) exhibited statistically significant lag-1 autocorrelation (Table 31). Excluding these two CRs, the observed frequencies per century were compared to the expected. The observed frequency per century for EPR60 events for CR1 (Northwest), CR3 (Northern Plains and Rockies), CR6 (South), and CR8 (Southeast), were higher than expected from random chance (Table 32). None of the CRs exhibited statistically significant trends in the summer-to-fall PR/EPR values (Table 32).

Table 31: Same as for Table 2, but for the summer-to-fall PR time series.

	CR1	CR2	CR3	CR4	CR5*	CR6	CR7	CR8	CR9*
Autocorrelation Coefficient	-0.06	0.04	-0.02	-0.03	0.19	-0.06	-0.02	0.14	0.20
ρ	0.52	0.65	0.82	0.78	0.05	0.51	0.87	0.14	0.03

Table 32: Same as for Table 3, but for the summer-to-fall PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
EPR90	1	100	1.7	1.7	0.0	0.9	~~0.0~~	0.9	0.9	0.9	~~2.5~~
EPR80	4	25.0	5.1	2.5	3.4	4.2	~~1.7~~	2.5	2.5	4.2	~~5.9~~
EPR70	9	11.1	8.5	8.5	8.5	10.2	~~6.8~~	8.5	10.2	10.2	~~7.6~~
EPR60	16	6.3	17.8	15.3	17.0	15.3	~~11.9~~	17.0	14.4	18.6	~~17.0~~
Trend/Decade			-0.69	-0.09	0.85	0.10	-0.13	-0.03	0.20	0.12	-0.04
p			0.29	0.90	0.17	0.87	0.83	0.97	0.75	0.86	0.95

PR/EPR halves were then compared for each of the CRs, and none were found to exhibit statistically significant differences (Table 33). The largest 30 values of each half were then examined (Table 34). The largest 30 values of CR3 (Northern Rockies and Plains) for the second half of the historical record were significantly larger than those of the first half of the record (Figure 20). The PR values, calculated without taking the absolute values of the difference from one increment to the following, were then examined (Table 35). The overall trend, including positive and negative PR values, significantly increased at 3.98 percentiles per decade for CR8 (Figure 22). The positive trend of PR values, in this instance, indicates that a shift from wet-to-dry reversals toward dry-to-wet reversals occurred during the historical record. The wet-to-dry (negative PR values) PR values for CR1 increased at 2.18 percentiles per decade for CR1 (Figure 22), indicating that the wet-to-dry reversals became smaller in magnitude towards the latter portion of the historical record.

Table 33: Same as for Table 4, but for the summer-to-fall PR time series.

CR	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
1	36.05	30.61	24.11	23.96	12	9	4.9	6.6
2	32.62	33.66	22.24	26.08	10	8	5.9	7.4
3	30.28	37.52	21.07	23.76	7	13	8.4	4.5
4	33.57	33.89	24.94	21.90	9	9	6.6	6.6
5	30.59	29.67	21.91	22.34	7	7	8.4	8.4
6	34.30	32.76	23.85	22.97	11	9	5.4	6.6
7	28.99	30.59	22.07	24.73	7	10	8.4	5.9
8	37.18	38.46	24.63	23.01	10	12	5.9	4.9
9	32.82	32.79	24.47	23.80	11	9	5.4	6.6

Table 34: Same as for Table 5, but for the summer-to-fall PR analysis.

	CR1	CR2	CR3*	CR4	CR5	CR6	CR7	CR8	CR9
1897-1955	55.7	50.4	46.8	52.9	48.1	53.8	45.2	56.8	52.0
1956-2014	48.8	55.6	57.0	51.2	46.3	50.6	50.3	57.9	51.0

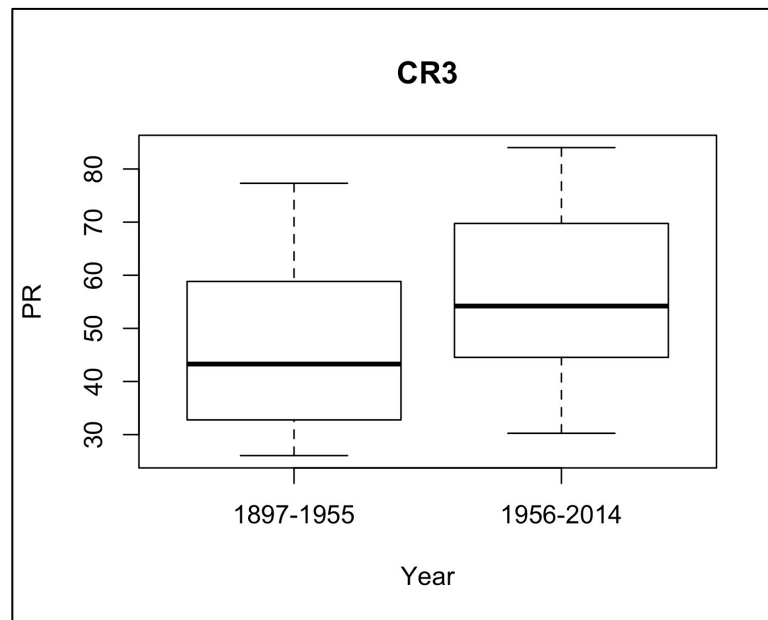


Figure 21 (left): Same as for Figure 4, but for the summer-to-fall PR time series of CR3 (Northern Rockies and Plains).

Table 35: Same as for Table 6, but for the summer-to-fall PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Overall Trend/Decade	-1.12	-0.84	1.28	0.04	1.15	2.15	0.83	3.98*	1.79
Positive Values Trend/Decade	0.56	0.60	1.38	-0.05	-0.31	0.53	0.66	1.19	1.06
Negative Values Trend/Decade	2.18*	0.77	-0.24	-0.28	0.17	0.69	0.24	0.84	1.04

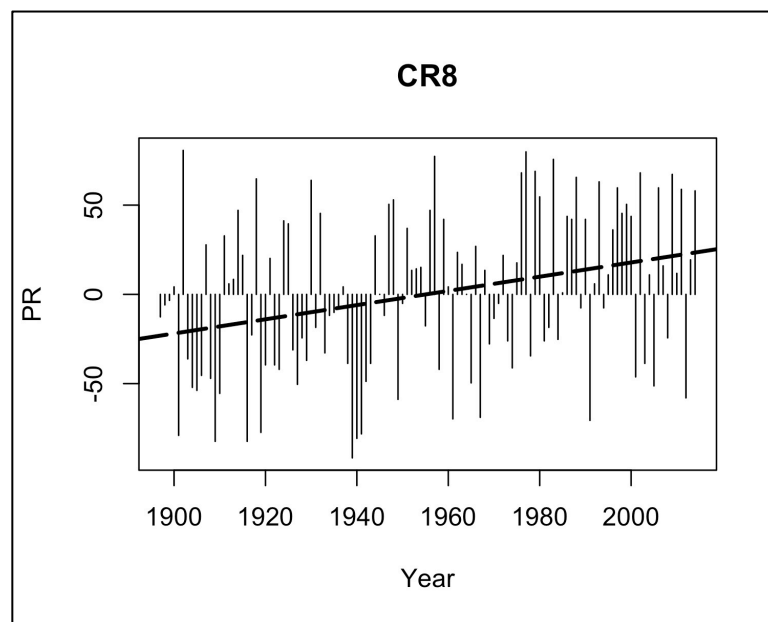


Figure 22: PR time series for CR8 (Southeast) of both positive (dry-to-wet) and negative (wet-to-dry) reversals for the summer-to-fall time step. The dashed line represents the linear trend.

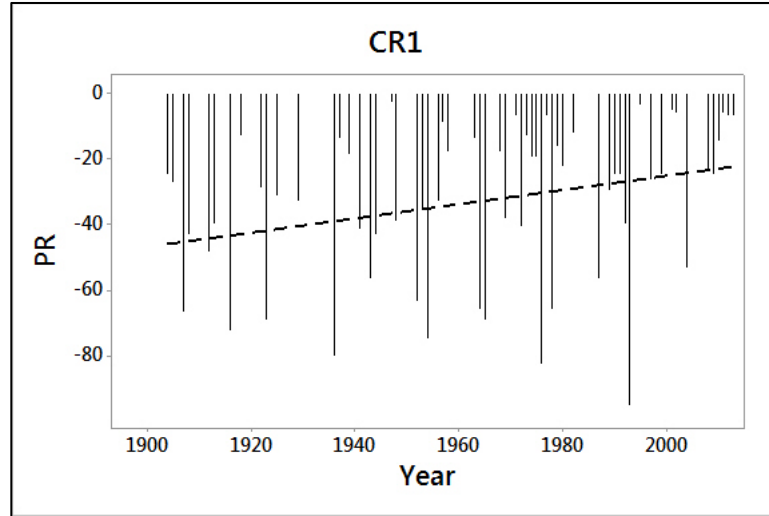


Figure 23: Same as for Figure 19, but for the summer-to-fall time step for CR1 (Northwest).

iv. Fall-to-Winter

None of the fall-to-winter PR/EPR time series exhibited statistically significant autocorrelation (Table 36). All of the CRs had a lower frequency per century of EPR60 events than was expected from random chance (Table 37), indicating that the transition from fall-to-winter may be naturally less volatile than random chance would suggest. In contrast to the EPR60 results, CR1 (Northwest) experienced 3.4 EPR90 events per century, but only 1 event per century was expected from random chance (Table 37). CR8 (Southeast) exhibited a statistically significant positive trend of PR/EPR values at a rate of 1.32 percentiles per decade (Figure 24).

Table 36: Same as for Table 2, but for the fall-to-winter PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Autocorrelation Coefficient	0.02	-0.13	0.02	-0.05	0.06	0.01	-0.07	0.05	0.06
p	0.85	0.18	0.82	0.62	0.55	0.92	0.45	0.63	0.52

Table 37: Same as for Table 3, but for the fall-to-winter PR time series.

	Random	RI (yr)	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8*	CR9
EPR90	1	100	3.4	0.9	0.9	0.9	0.0	0.9	0.0	0.9	0.0
EPR80	4	25.0	5.1	5.9	3.4	3.4	5.1	0.9	2.5	3.4	4.2
EPR70	9	11.1	8.5	7.6	6.8	9.3	8.5	4.2	6.8	10.2	6.8
EPR60	16	6.3	14.4	15.3	12.7	11.9	15.3	13.6	15.3	14.4	11.9
Trend/Decade			-0.43	-0.39	-0.18	-0.28	-0.84	-0.39	0.08	1.32	-1.12
ρ			0.52	0.54	0.77	0.66	0.18	0.51	0.90	0.04	0.09

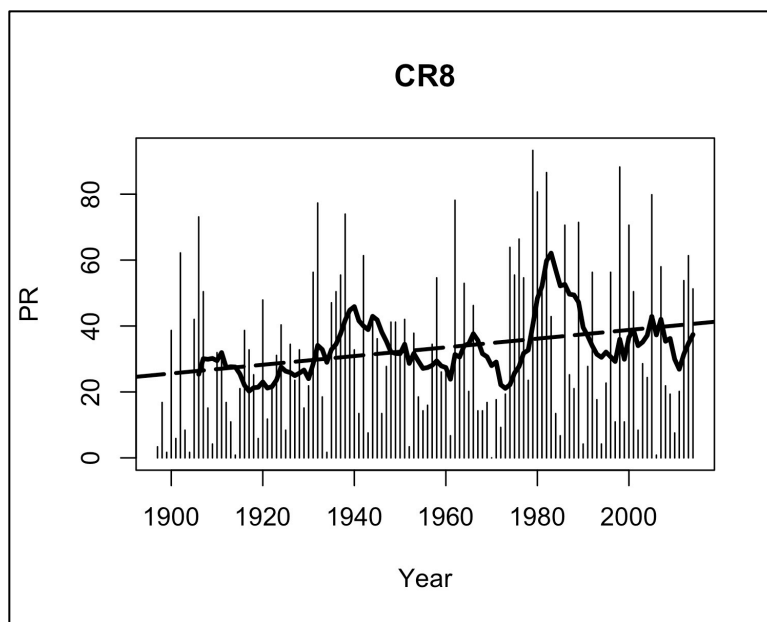


Figure 24: Same as for Figure 5, but for the fall-to-winter PR values of CR8 (Southeast).

PR values from the earlier and latter halves of the historical record were compared for each of the CRs, and none were found to exhibit a statistically significant difference (Table 38). The largest 30 PR/EPR values for the two halves were then tested for differences (Table 39). CR8 (Southeast) had significantly larger values within the population of the largest 30 second half values, while CR9 (Northeast) had significantly smaller values within the population of the largest 30 values in the second half (Figures 25 and 26, respectively). Finally, the PR values calculated without taking the absolute difference from one increment to the next were examined

for trends (Table 40). The trend of all PR values, positive and negative, decreased at a statistically significant rate of -2.66 and -2.08 percentiles per decade for CR8 (Southeast) and CR9 (Northeast), respectively (Figures 27 and 28, respectively).

Table 38: Same as for Table 4, but for the fall-to-winter PR time series.

CR	Avg.1	Avg.2	Std Dev.1	Std Dev.2	EPR60.1	EPR60.2	EPR60_RI.1	EPR60_RI.2
1	31.11	27.67	26.61	23.03	11	6	5.4	9.8
2	34.40	33.71	21.93	24.97	9	9	6.6	6.6
3	30.68	29.30	22.97	23.29	8	7	7.4	8.4
4	30.79	26.15	22.96	24.18	9	5	6.6	11.8
5	34.74	31.49	23.51	22.11	11	7	5.4	8.4
6	33.43	30.11	22.15	21.60	10	6	5.9	9.8
7	30.28	34.28	23.01	24.14	6	12	9.8	4.9
8	29.10	36.76	19.87	26.01	5	12	11.8	4.9
9	33.43	27.92	26.09	22.16	10	4	5.9	14.8

Table 39: Same as for Table 5, but for the fall-to-winter PR analysis.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8*	CR9*
1897-1955	52.4	51.4	48.5	48.8	53.1	51.7	49.7	45.3	54.9
1956-2014	44.2	54.4	47.0	43.9	48.5	47.8	54.0	58.2	46.4

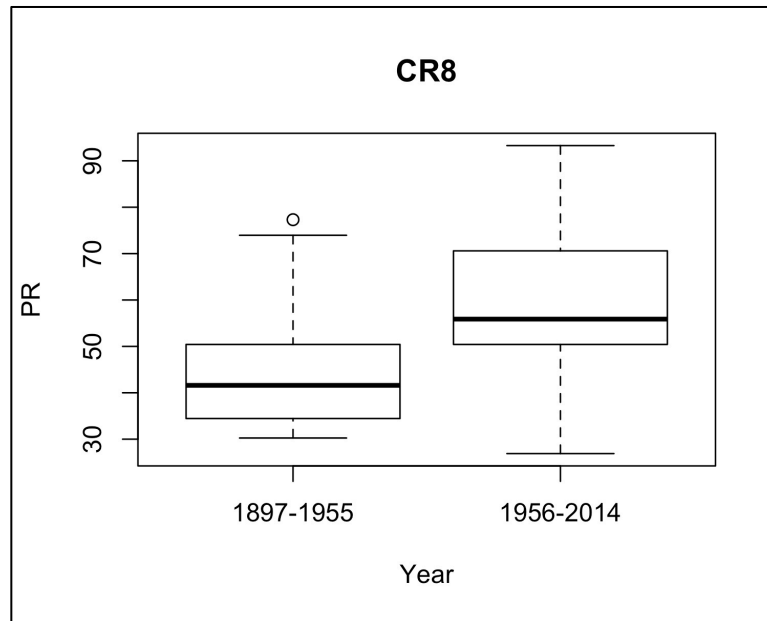


Figure 25 (left): Same as for Figure 10, but for the fall-to-winter analysis of CR8 (Southeast).

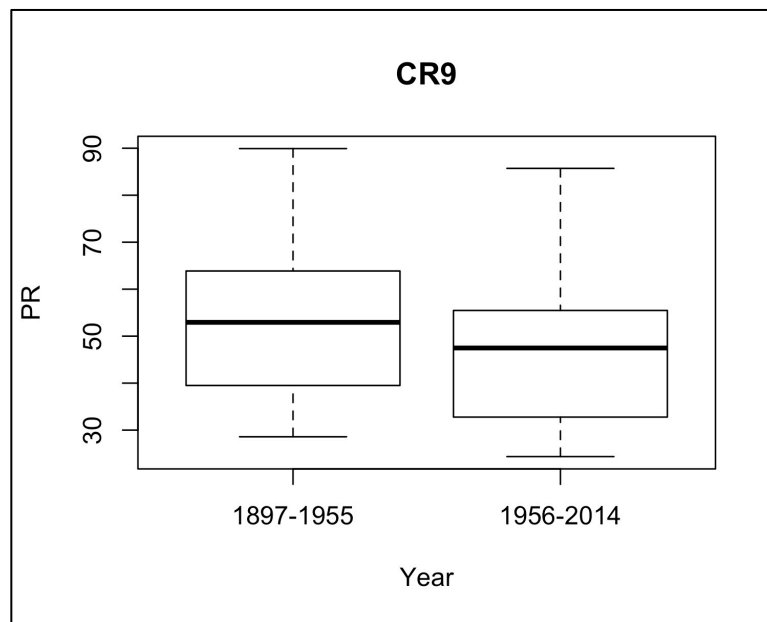


Figure 26 (right): Same as for Figure 10, but for the fall-to-winter analysis of CR9 (Northeast).

Table 40: Same as for Table 6, but for the fall-to-winter PR time series.

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Overall Trend/Decade	0.23	-0.13	-1.89	-0.20	-1.60	-0.91	-1.44	-2.66*	-2.08*
Positive Values Trend/Decade	-0.28	-1.58	-0.65	-0.40	-0.88	-0.48	-0.39	1.44	-1.94
Negative Values Trend/Decade	0.57	-0.46	-0.23	0.14	0.88	0.30	-0.45	-1.18	0.11

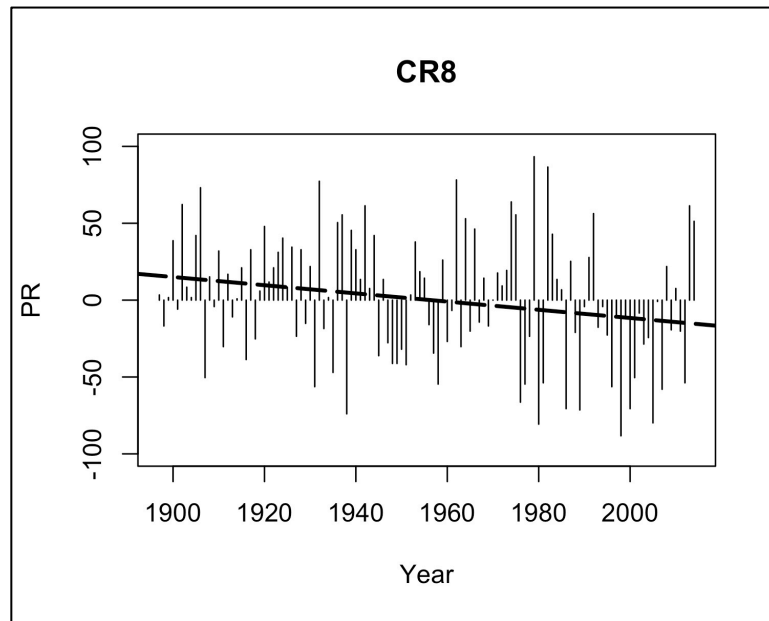


Figure 27: Same as for Figure 22, but for the fall-to-winter PR time series for CR8 (Southeast).

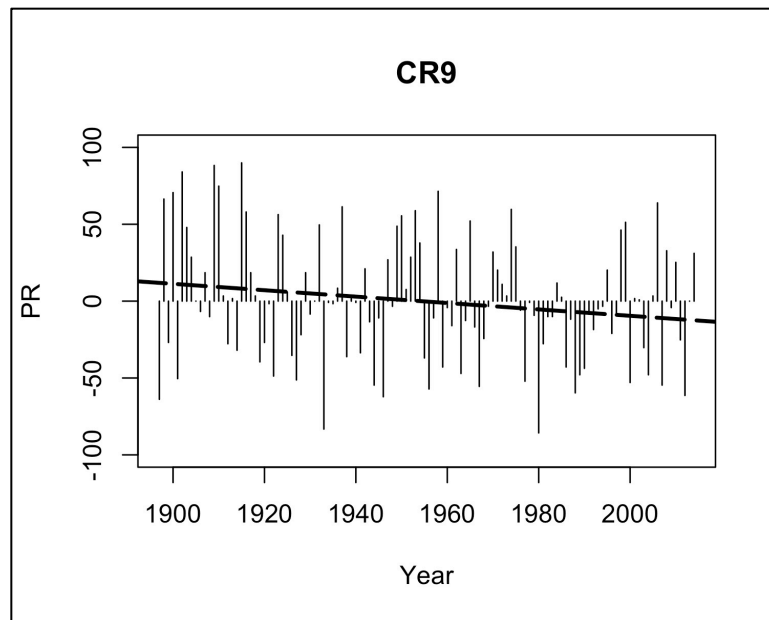


Figure 28: Same as for Figure 22, but for the fall-to-winter PR time series for CR9 (Northeast).

3.5 Winter-to-Winter PR/EPR relationships with Niño 3.4

To determine if relationships exist between the Niño 3.4 index and precipitation reversals, the historical time series of the mean of the Niño 3.4 values for the months of September, October, and November (SON) (Figure 29) and the time series of the winter-to-winter PR time series, calculated without taking the absolute difference between years, were subjected to a Pearson correlation test. The winter-to-winter PR time series of CR3 (Northern Rockies and Plains) exhibited a statistically significant inverse relationship with the SON Niño 3.4 time series (Table 41). The inverse nature of the relationship indicates that PR values are typically positive (dry-to-wet) during La Niña years and negative (wet-to-dry) during El Niño years. Conversely, the PR time series of CR6 (South) exhibited a statistically significant direct relationship with the SON Niño 3.4 time series (Table 41). This indicates that PR values are usually positive (dry-to-wet) during El Niño years and negative (wet-to-dry) during La Niña years. While the relationships between the Niño 3.4 time series and the winter-to-winter PR time series of CR7 (Southwest) and CR8 (Southeast) were not statistically significant ($p > 0.05$), both CRs exhibited strong direct relationships with the SON averaged time series of Niño 3.4 indexes. Lastly, the time series of SON Niño 3.4 values were stratified into three categories (i.e., El Niño, neutral, and La Niña) depending on the sign and magnitude of each SON value. The year of each EPR60 event, the magnitude of that event, and the phases of ENSO for two years prior, and the year prior to the event were listed to determine if patterns existed. It is interesting to note that for CR2 (West), 5 out of 7 EPR70 events occurred following El Niño years (Table 42).

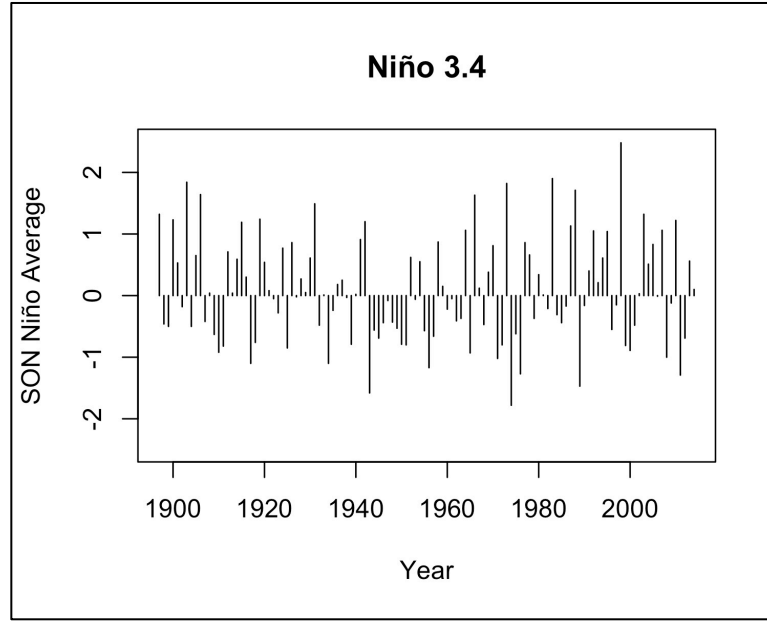


Figure 29: Averaged September, October, and November (SON) Niño 3.4 index time series (1896 – 2013).

Table 41: Pearson correlation coefficients and statistical significance (ρ) for the winter-to-winter PR/EPR calculated without absolute value and the time series and the time series of Niño 3.4 (SON).

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Correlation	-0.14	0.13	-0.28	0.08	-0.06	0.23	0.16	0.17	-0.01
ρ	0.13	0.15	<0.01	0.41	0.53	0.01	0.09	0.06	0.95

For the winter-to-winter PR analysis of CR2 (West), 13/15 EPR60 events were associated with a La Niña/El Niño event (Table 42). Only four of the EPR60 reversals for the winter-to-winter analysis of CR2 followed conventional wisdom with respect to relationships between precipitation and ENSO in the western United States. For the spring-to-spring PR analysis of CR2, 18/21 EPR60 events were associated with either a La Niña or El Niño event (Table 42). For the spring-to-spring EPR60 events for CR2, only six followed conventional wisdom with regard to ENSO relationships with precipitation in the western region of the United States.

Table 42: The occurrences of all EPR60 events for the winter-to-winter and spring-to-spring analysis for CR2 (West). The phases of ENSO for the SON period for two years prior to the reversal as well as the phase directly before the reversal occurred are listed (LN: La Niña, N: ENSO Neutral, EN: El Niño).

winter-to-winter			spring-to-spring		
EPR60 Year	EPR value	ENSO phase	EPR60 Year	EPR value	ENSO phase
1912	-75.63	LN - EN	1908	-80.67	N - N
1939	-64.7	N - LN	1936	-69.74	N - N
1957	-73.11	LN - LN	1939	-61.35	N - LN
1981	-65.55	N - N	1959	-89.92	EN - N
1994	-76.47	N - EN	1968	-69.74	N - N
2012	-63.87	LN - LN	1972	-63.87	LN - LN
			1976	-72.27	LN - LN
1914	79.83	N - EN	1984	-80.67	EN - N
1932	64.71	EN - N	1997	-68.91	LN - N
1940	70.59	LN - N	2004	-73.95	EN - EN
1956	68.07	LN - LN	2007	-88.24	N - EN
1965	63.03	EN - LN	2013	-61.35	LN - EN
1970	78.99	N - EN			
1978	93.28	EN - EN	1911	63.03	LN - LN
1986	68.07	N - N	1925	66.39	EN - LN
1995	62.18	EN - EN	1935	78.15	LN - N
			1967	84.87	EN - N
			1978	66.39	EN - EN
			1996	72.27	EN - LN
			1998	90.76	N - EN
			2003	66.38	N - EN
			2005	79.83	EN - EN

3.6 Conclusions

To determine if regions across the United States have experienced extreme reversals in precipitation, a precipitation reversal (PR) index was calculated by taking the absolute difference in percentiles of precipitation for successive time periods. By comparing the observed frequency per century of certain PR and extreme PR (EPR) magnitudes to expected values, several climate regions (CR) were noted for experiencing notably more variability than what is expected from

random chance. These regions included CR8 (Southeast) for the winter-to-winter analysis and CR3 (Northern Plains and Rockies) for the spring-to-spring analysis, which both experienced higher EPR60 ($EPR > 60$ percentiles) frequencies per century (20+ events per century) than expected (16 events per century). The observed frequencies of precipitation reversals were also compared to the expected frequencies to reveal CRs that have historically experienced fewer EPRs than expected. The winter-to-spring PR/EPR time series of CR6 (South) and CR8 (Southeast) experienced notably fewer EPR60 frequencies per century (5.1 and 7.6, respectively) than what was expected (16).

The trends of PR/EPR events were examined for each CR at all temporal increments to determine if the magnitude of variability changed across the historical record (1897-2014). The -1.65 percentiles per decade trend in fall-to-fall PR/EPR values for CR5 (Ohio Valley) indicated that smaller magnitude PR/EPR events have become more frequent during the latter portion of the study period. Likewise, the 1.32 percentiles per decade trend in fall-to-winter PR/EPR values for CR8 (Southeast) indicates that larger magnitude reversals have become more frequent during the latter portion of the historical record. An overall trend of positive or negative percentiles indicates that the precipitation patterns of these CRs have changed throughout the historical record and likely warrants further research.

The complete halves of PR/EPR values for the historical record for CR2 (West) were statistically different for the year-to-year, winter-to-winter, and spring-to-spring temporal increments. For the three time steps for CR2 (West), the PR values exhibited during the second half of the historical records were larger, meaning that larger magnitude reversals in precipitation occurred during the second half of the historical record. Significant differences exist in EPR60 values over the two halves of the historical record for CR2 (West) during the year-to-year,

winter-to-winter, and spring-to-spring analyses. There were 3, 5, and 6 EPR60 events during the first halves of the record for the three time steps, compared to the 13, 10, and 15 EPR60 events during the second halves of the historical record. These results indicate that the precipitation reversals have become larger in magnitude for CR2 from winter-to-winter, spring-to-spring, and year-to-year time steps. Winter and spring precipitation in the West is critically important, and mitigation efforts are likely needed to protect against the increasing magnitude of precipitation reversals.

The largest 30 PR/EPR values for each half of the historical record were examined to determine if a subset of the most extreme reversals were different between the two halves of the record. The results from the largest 30 values were similar to the statistical results of the two-sample t-test from the complete halves of the historical record for the year-to-year, winter-to-winter, spring-to-spring, and winter-to-spring analyses. Even though there were several stark contrasts between the number of EPR60 events that occurred from one half of the study period to the next throughout the analyses, the presence of smaller PR values among the large EPR values likely prevented statistical significance.

Lastly, relationships between the SON averaged time series of Niño 3.4 indexes and the winter-to-winter PR time series were examined. The winter-to-winter PR values of CR3 (Northern Plains and Rockies) were inversely related to Niño 3.4 values, meaning that negative (wet-to-dry) PR values were associated with El Niño events and positive (dry-to-wet) PR values were associated with La Niña events. Conversely, the winter-to-winter PR values of CR6 (South) were directly related to Niño 3.4 values, meaning that positive (dry-to-wet) PR values were associated with El Niño events and negative (wet-to-dry) PR values were associated with La Niña events.

CHAPTER 4

Conclusions

As mentioned previously, the Intergovernmental Panel on Climate Change (IPCC) stated that “almost all areas of North America exhibit very likely increases of 5 to 20% in the 20-year return value of extreme precipitation by the mid-21st-century”(IPCC 2014, pg. 1456). The IPCC also stated that two of the sectors affected by climate variability, and especially precipitation variability, are water resources and agricultural (IPCC 2014). Within the United States, there have already been several instances of extreme year-to-year precipitation variability, as outlined in Chapter 1.

In order to determine whether other instances of extreme annual or seasonal precipitation variability have occurred across the United States, this thesis used the concept of a precipitation reversal (PR) index to assess the frequency of large changes in seasonal-to-annual precipitation throughout the historical record. The PR concept was developed by Goodrich and Ellis (2008) in a study that was completed for the state of Arizona and spanned 111 years. To create time series of PR values for this thesis following the methods of Goodrich and Ellis (2008), climate division precipitation data were downloaded from 1895-2014, and area-weighted monthly precipitation values were calculated for each of nine climate regions (CR) within the United States for all months in the study period (1895-2014). The monthly precipitation values were used to create seasonal and annual averages. For all seasons and the water year, precipitation data were averaged, ranked, and a percentile was assigned. For all time steps studied (i.e., year-to-year, winter-to-winter, spring-to-spring, summer-to-summer, fall-to-fall, winter-to-spring, spring-to-summer, summer-to-fall, and fall-to-winter) the difference in percentiles from one temporal

increment to the next was calculated and tagged as the PR value. The 118-year time series of PR values for the nine climate regions, for all time steps, were then examined statistically.

The results of this thesis indicate that regional expressions of precipitation variability have changed within some climate regions of the United States since the late 1800s. CR2 (West) notably experienced more precipitation volatility in recent decades, as indicated by significantly larger PR/EPR values and a greater number of EPR60 events, during the second half of the study period (1956-2014) for the winter-to-winter, spring-to-spring, and the year-to-year time steps. The increased variability during the latter half of CR2 for the winter-to-winter PR/EPR analysis may hold particular value as, on average, 47% of the annual precipitation falls during this season (DJF). The results from the fall-to-fall analysis of PR/EPR values were also noteworthy. CR5 (Ohio Valley) exhibited smaller PR/EPR values during more recent years, as indicated in the results of the regression analysis and the two-sample t-test on the largest 30 values for each half of the historical record. CR1 (Northwest) exhibited smaller PR/EPR values in a subset of the largest 30 PR/EPR values during the second half of the historical record, indicating that the most extreme reversals were, on average, larger during the first half of the study period. Conversely, CR3 (Northern Rockies and Plains) exhibited larger PR/EPR values in the subset of the largest 30 PR/EPR values from the second half of the historical record, indicating that the larger reversals were more extreme during this time period when compared to the first half of the study period.

A secondary objective of this thesis was to examine relationships between the well-known El Niño-Southern Oscillation climate teleconnection and PR/EPR values. The winter-to-winter PR time series, calculated without taking the absolute difference between consecutive years, and the September through November (SON) averaged Niño 3.4 time series were examined for

relationships. The winter-to-winter PR time series of CR3 (Northern Rockies and Plains) and CR6 (South) are highly correlated ($\rho \leq 0.01$) with the SON averaged Niño 3.4 time series. The winter-to-winter PR/EPR values for CR3 (Northern Rockies and Plains) exhibited an inverse relationship with Niño 3.4 values, meaning that wet-to-dry (dry-to-wet) reversals are associated with El Niño (La Niña) events. Conversely, the winter-to-winter PR values for CR6 (South) exhibited a direct relationship with Niño 3.4 values, indicating that wet-to-dry (dry-to-wet) reversals are associated with La Niña (El Niño) events.

During the peak precipitation seasons (i.e. winter and spring) for CR2 (West), precipitation volatility became more extreme during the latter half of the historical record compared to the first half. This may further indicate that proactive measurements should be taken to prevent management difficulties within the agricultural and water resources sectors due to an overall shift in the magnitude of precipitation reversals. There may be need for further mitigation efforts, such as bigger dams, in order to prevent a water crisis during dry years. The transition to larger magnitude precipitation reversals occurring for other CRs (e.g., CR3 for the fall-to-fall analysis) may also deserve mitigation efforts, but the importance of winter and spring precipitation across the West certainly suggests that more extreme precipitation reversals could translate to significant impacts.

Future research could benefit from examining other possible relationships between precipitation reversals and synoptic scale climate patterns, as well as from examining autocorrelation in the PR/EPR time series. Establishing relationships between these PR time series and associated atmospheric phenomena could provide meaningful information as to why PR reversals are non-random, as well as help to predict when a large precipitation reversal may occur. Further investigation into relationships between ENSO and precipitation reversals is also

warranted, as many of the larger magnitude precipitation reversals are not associated with ENSO phases that conventional wisdom would suggest. Autocorrelation in the PR time series indicates that precipitation reversal values are clustered (non-random), and deeper study of these time series may be particularly interesting as there may be a driver of the clustering of PR values, which may ultimately lead to providing better forecasts of these dramatic reversals in precipitation anomalies.

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