A CLIMATOLOGY OF SINGLE-DAY RAPID DROUGHT CESSATION EVENTS IN THE SOUTHWESTERN UNITED STATES

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ABSTRACT

A CLIMATOLOGY OF SINGLE-DAY RAPID DROUGHT CESSATION EVENTS IN THE SOUTHWESTERN UNITED STATES

Emily Pearl Harris

Drought is a common and important component of the hydroclimatology of the southwestern USA. However, less attention has been paid to drought termination in the region, especially Rapid Drought Cessation Events (RDCEs). Here, the "Southwest" was defined by drought region using Principal Components Analysis (PCA) of the annual average Palmer Drought Severity Index (PDSI) for all NOAA state climate divisions in the U.S.A. For the Southwest, 765 droughts occurred between 1895 to 2017; 575 (6.2%) of these droughts ended abruptly (for one month's time). Furthermore, 54 (0.6%) of those RDCEs occurred in a single-day. The majority of RDCEs, and single-day RDCEs, occurred in the cool season. Droughts of short (<1 months) and long (>76months) duration were ended by single-day RDCEs. Similarly, RDCEs ended droughts of varying severity, the extreme being a -5.68 (PDSI; November 1951). While there is no significant trend when SD-RDCEs occur, the results showed that most occur in the winter season and most occurring in Arizona. Analyses are in progress to identify the storm type responsible for every occurrence of RDCE and describe the spatiotemporal properties of RDCE and associated storm type.

INTRODUCTION

A drought refers to a precipitation deficit over some time. Drought is a standard part of the hydroclimate of the southwestern U.S. (SWUS; Weiss et al. 2012). Drought trends and spatiotemporal patterns in the SWUS have received substantial attention, but little is known about the specific meteorological mechanisms that end droughts (Ortegren et al. 2011). With the western and southwestern United States (U.S.) continuing to grow and have the highest population levels in the country (U.S. Census Bureau 2018), there is increasing need to study the complex hydroclimatic variability and associated feedbacks that can impact the growing population. In addition to droughts impacting the growing population, droughts threaten water and food security, human health, and natural ecosystems (Acuna-Soto et al. 2002). The region's population and ecosystems face continuing periods of extreme aridity and episodic flooding and associated changes in water availability (Balling Jr. and Goodrich 2007). Rapid drought cessation events (RDCEs), or single-storm precipitation events that ameliorate droughts, have been studied in other parts of the U.S. (Faiers et al. 1994; Maxwell et al. 2017). The SWUS's dry climate naturally strains water resources. Therefore, it is essential for SWUS water managers and stakeholders to understand the frequency and intensity of droughts and RDCEs thereby implementing adaptive management strategies. This study aims to quantify and characterize drought and RDCE trends. The results could provide insight into the atmospheric forcing mechanisms and teleconnective features that enhance our ability to forecast future extreme weather events.

Literature Review

The southwestern U.S. climate. Typically, the SWUS is defined as Arizona, California, Colorado, Nevada, New Mexico, and Utah (Garfin et al. 2014). Sometimes, the region includes Texas and Oklahoma or omits California (Seager et al. 2007). Regardless of the specific spatial definition, the Southwest is topographically diverse. The juxtaposition of the Southwest's many landscapes--mountains, valleys, plateaus, canyons, and plains--affect both the region's climate and seasonality. The Mojave and Sonoran Deserts of southern California, Nevada, and Arizona are the driest regions of the U.S. (Garfin et al. 2014). The Southwest has several mountain ranges such as the Sierra Nevada, Coastal Mountains, the Colorado Plateau, and the Southern Rocky Mountains, all of which tend to get more precipitation in comparison to the lower elevations (Garfin et al. 2014).

It is difficult to define the Southwest's seasonal average precipitation totals due to spatial variability. Depending on the elevation and terrain, the regional annual precipitation averages from less than 100 mm to over 3000 mm (PRISM Climate Group 2015). Lower elevations, such as the Mojave and Sonoran Deserts, southwestern Arizona, and southeastern California average lower precipitation totals (PRISM Climate Group 2015). Across coastal California, northeast Utah, and the San Luis Valley of Colorado and New Mexico, precipitations averages are higher (PRISM Climate Group 2015). Due to topography, the Coastal Mountains, southern Cascade Mountains, and the Sierra Nevada exhibit significant variations in annual precipitation (Daly et al. 1994). Across the mountains of Utah, Colorado, and the Sierra Nevada, 60% of the average annual precipitation is snow (Sheppard et al. 2002). Spring and summer runoff from the mountain snow supply most of the Southwest's surface water (Sheppard et al. 2002). From April to July, 50% to 90% of the snowmelt runoff drains into river basins thus supplying a portion of the region's available surface water sources (Serreze et al. 1999; Stewart et al. 2004).

Despite the intra-regional variability in average annual precipitation, the dominant seasonal precipitation systems are reasonably well understood. May through October define the warm season. The North American Monsoon (NAM) system supplies most of the region's warm-season precipitation and the occasional land-falling tropical cyclone or remnant. Mid-latitude cyclones and atmospheric rivers deliver the majority of the cool-season (November through April) precipitation (Etheredge et al. 2004; Rivera et al. 2014). Winter storms often produce high amounts of rain across the lower valleys and basins and high amounts of snow across the various mountain ranges (Weiss et al. 2009). Cool-season precipitation and warm-season snowmelt recharge groundwater and surface reservoirs (Weiss et al. 2009; Kahn, 2012). The microclimate and diverse weather throughout the region cause the Southwest to be considered one of the most "climate-challenged regions of North America" (Garfin et al. 2013).

Southwest droughts. According to paleoclimate research, droughts are typical and recur in the Southwest (Weiss et al. 2009). Long-lasting droughts are also standard and can last months or years, including multi-decadal periods (Weiss et al. 2009). Large and prominent droughts occurred in the early 1900s, 1950s, and early 2000s in Arizona and New Mexico (Swetnam and Betancourt 1998; Weiss et al. 2009). A megadrought (multi-decadal droughts) occurred in Arizona during the 1100s and in the Upper Colorado River Basin from 1579 to 1598 (Meko et al. 1995). More so, paleoclimate research also linked the 1950's SWUS drought to a positive AMO and negative PDO (McCabe et al. 2004). Given the prior known drought events and associated drivers in the SWUS, we could explore possible future drought scenarios and response strategies. Summer temperatures are expected to increase and during La Niña phases could experience drier conditions. With increasing temperatures and less fluvial events, drought intensity and frequency could increase in the future (Coe et al. 2012).

Drought cessation events. Like droughts, drought cessation and its impacts are reasonably well documented (Parry et al. 2016). Drought cessation (the end of a drought) has both positive and negative effects. An example of the positive effect of a drought cessation occurred 2010 and 2011 with the Australian drought termed "The Big Dry" (Leblanc et al. 2009). Large precipitation totals related to a persistent La Niña event in the eastern tropical Pacific Ocean produced enough precipitation to end the Australian drought. The "back-to-average" precipitation totals relieved water-stressed industries, such as reinstating rice farming. An example of an adverse effect from a drought cessation and that occurred closer to the SWUS occurred in September 2013 and the Central-Midwestern U.S. The drought ended due to an increase of humid southerly airflow and successive frontal systems over seven days (Parry et al. 2016). The record-breaking 36-hour precipitation total over parts of the Colorado Rockies caused many dams to fail which triggered floods and landslides which damaged over 16,000 homes and caused fatalities (Lavers and Villarini 2013). The consequences of droughts and drought cessations are far-reaching and have varying influences.

The Central Midwest drought cessation event in 2013 is an example of a drought cessation's adverse effect but also demonstrates the uniqueness of a brief weather event and associated consequences. The short, "rapid" timeframe that the area went from drought to normal conditions is significant due to potential consequences. Rapid drought cessation events (RDCEs) are short-term periods (within 30 days) in which a moderate to extreme drought end and conditions return to near-normal or wetter. For this to occur enough precipitation accumulates, in a location, to categorically end a moderate drought (or greater) and by the end of the 30 days is within normal to above-normal conditions, no matter the drought metric. RDCEs have received some attention as a component of precipitation anomalies in the west coast and southeastern U.S., but at this time no similar studies have been conducted for the SWUS (Faiers et al. 1994; Dettinger 2013; Maxwell et al. 2017).

Objectives

The purpose of this study is to identify the spatiotemporal characteristics of single-day rapid drought cessation events (SD-RDCEs) across the Southwestern U.S., 1895 to 2017. Specifically, I plan to

a. Quantitatively identify a homogenous drought region(s) in the SWUS;
b. Document variability in drought and SD-RDCEs;
c. Describe the spatiotemporal characteristics of SD-RDCEs;
d. Identify potential trends in the characteristics of SD- RDCEs, including RDC rainfall as portions of total rainfall, intensity, and frequency of RDCEs, and potential seasonal trends in RDCE.

DATA AND METHODS

Data

Drought data. I used the Palmer Drought Severity Index (PDSI; Palmer 1965) to classify drought. The PDSI measures the severity of meteorological drought (dry periods lasting several months) by considering the moisture climate of the current and preceding months. Therefore, the PDSI responds to changing moisture conditions and not short-term soil moisture variations (Ortegren et al. 2011). Meteorological droughts are based on a region's specific atmospheric condition's that cause precipitation deficits (National Drought Mitigation Center 2019). The PDSI is more responsive to short-term changes in the moisture balance compared to the Palmer hydrological drought index (PHDI), which measures the long-term hydrological droughts (Heim Jr. 2002). While the PDSI has it is limitations (Alley 1984), the PDSI will continue to be used until a better index is developed. The PDSI is widely used to determine drought frequency, spatiotemporal characteristics of droughts, and to evaluate water supply systems. Additionally, the U.S.' PDSI values are easily accessible and computable. I used the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (National Oceanic and Atmospheric Administration 2019) to obtain the Palmer Drought Severity Index (PDSI; Table 1).

Table 1. PDSI values and classification (Palmer 1965).

Palmer Index	Class
4.0 or more	Extremely wet
3.0 to 3.99	Very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.5 to -0.99	Incipient dry spell
-1.0 to -1.99	Mild drought
-2.0 to -2.99	Moderate drought
-3.0 to -3.99	Severe drought
-4.0 or less	Extreme drought

Precipitation data. I used the NOAA National Centers for Environmental Information (National Oceanic and Atmoshperic Administration 2019) to obtain historical daily precipitation totals. The data source archives the daily precipitation measurements for the contiguous U.S.' 344 climate divisions. The daily precipitation is required to determine if a single storm produced 50% or more of the month's total precipitation. The month's daily precipitation values are needed to identify RDCEs as outlined in the methods section that defines RDCEs.

Methods

Drought regionalization. Due to the Southwest's complex climate, it is difficult to define the region's spatial boundaries. Therefore, I chose to run a Principal Component Analysis (PCA) of the annual PDSI. PCA is a reliable method often used for climate regionalization (Ortegren et al. 2011). I calculated the annual average PDSI for each climate division from 1895 to 2017. I used the yearly average, instead of monthly or seasonal values, to provide a homogenous spatial boundary that reflects broad-scale climate complexity while also retaining a manageable number of regions. I used a PCA to determine the leading (principal) modes of annual drought (PDSI) variability for the U.S.' contiguous 344 climate divisions. I compared the factor loadings from the PCA with Varimax rotation to determine the number of Principal Components (PCs) of PDSI variability. The PCs reflect contiguous and logical drought regions (Ortegren et al. 2011).

Defining drought events. A drought event begins when a (any) month in a (any) climate division has a PDSI of ≤ -2.0 and ends in the first subsequent month in which that climate division has a PDSI of near-normal (or greater) moisture (PDSI ≥ -0.5). For example, in Arizona climate divisions 5, a drought event occurred in September 1987 (Figure 1). The drought ended in October 1987 based on the PDSi value of 1.02. A second (separate) drought event occurred from September 1988 to February 1991 (Figure 1). The drought ended in March 1991 based on the PDSI value of 1.08. For the period 1895 to 2017, I tabulated for every SWUS climate division the total number of drought events (drought frequency), length of each drought (in months), and severity of each drought (average PDSI).

State - Climate Division	Year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
AZ 5	1987	-0.26	-0.57	-1.05	-1.62	-1.66	-1.53	-1.6	-1.98	-2.03	1.02	1.24	1.42
AZ 5	1988	1.5	-0.13	-0.81	0.65	0.22	0.04	0	1.66	-0.67	-1.02	-1.28	-1.67
AZ 5	1989	-0.94	-1.16	-1.83	-2.45	-2.53	-2.48	-1.88	-2.04	-2.56	-2.53	-2.79	-2.97
AZ 5	1990	-2.6	-2.51	-2.93	-3.04	-2.89	-2.61	-1.74	-1.61	-1.06	-1.26	-1.55	-1.8
AZ 5	1991	-1.65	-1.9	1.08	1.18	-0.3	-0.44	-0.98	-1.55	-1.35	-1.35	-1.4	-1.4

Figure 1. Examples of distinct drought events by my drought definition. The two drought event examples occurred in Arizona climate division 5. The 1987 drought lasted one month (September) and ended as a RDCE (October 1987). The drought beginning in April 1989 lasted 23 months and ended in March 1991 but was not a RDCE because the prior month (February 1991) the PDSI was not a qualified drought (≤ -2.0). The darker yellow cells represent continuous drought months as defined as ≤ -2.0 PDSI criteria. The lighter yellow cells indicate the months with recorded drought conditions as defined by the Palmer Drought Index. Green cells represent near-normal or wetter conditions.

Defining rapid drought cessation events (RDCEs). A rapid drought cessation event (RDCE) occurs based on the following criteria. First, an RDCE occurs when the SWUS climate division's monthly PDSI is classified as near-normal or wetter conditions (PDSI ≥ -0.5) and the preceding month is classified as a moderate to extreme drought (PDSI ≤ -2.0; Maxwell et al., 2017; Figure 2). The moderate drought value was used since the region is arid. Using the moderate drought value to near-normal PDSI change indicates a single storm or series of storms from a single tropical or non-tropical system produced enough precipitation to spur a drastic change in drought values (Maxwell et al. 2017).

State - Climate Division	Year	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
AZ 5	1987	-0.26	-0.57	-1.05	-1.62	-1.66	-1.53	-1.6	-1.98	-2.03	1.02	1.24	1.42
AZ 5	1988	1.5	-0.13	-0.81	0.65	0.22	0.04	0	1.66	-0.67	-1.02	-1.28	-1.67
AZ 5	1989	-0.94	-1.16	-1.83	-2.45	-2.53	-2.48	-1.88	-2.04	-2.56	-2.53	-2.79	-2.97
AZ 5	1990	-2.6	-2.51	-2.93	-3.04	-2.89	-2.61	-1.74	-1.61	-1.06	-1.26	-1.55	-1.8
AZ 5	1991	-1.65	-1.9	1.08	1.18	-0.3	-0.44	-0.98	-1.55	-1.35	-1.35	-1.4	-1.4

Figure 2. Example of a rapid drought cessation event. Rapid drought cessation event occurred October 1987 (drought month is ≤ -2.0 and the subsequent month is ≥ -0.5). Example of a gradual drought cessation event and thereby does not qualify because the drought gradually ends from July 1990 through February 1991. Yellow cells represent drought. Green cells represent near-normal or wetter conditions.

Second, I analyzed the daily precipitation data for the climate divisions with a PDSI of near-normal or wetter conditions. I used the NOAA National Centers for Environmental Information (National Oceanic and Atmospheric Administration 2019) to obtain historical daily precipitation totals. The data source archives the daily precipitation measurements from individual rain gauges for the contiguous U.S.' 344 climate divisions. The purpose of evaluating the precipitation data is to determine if a storm event produced 50% or more of the monthly precipitation total in five or less consecutive days. The 50% value is a conservative approach that ensures that an RDCE produced the majority of monthly precipitation (Maxwell et al. 2017).

Third, if the storm produced 50% or more of the precipitation, the event was classified as an RDCE, if it occurred within five days or less. Past RDCE research (Faiers et al. 1994; Maxwell et al. 2017), defined an event solely on the distinct day or two of recorded precipitation that produced 50% or more of the month's total precipitation. However, in the SWUS, it is not uncommon for some climate divisions to have consecutive days of precipitation, sometimes for the entire month. Since there is not a distinct break and a conspicuous number of days in the recorded precipitation, I had to identify rapid and slow drought cessation. I calculated the 25^{th}, 50^{th}, and 75^{th} percentile based on the distribution of the number of consecutive days with recorded precipitation in each identified event.

Last, a single-day rapid drought cessation event (SD-RDCE) is defined as an RDCE so long as it meets the criteria listed above but 50% or more of the month's total precipitation was recorded on a single date (Figure 3). SD-RDCEs are less common, but indicate significant rainfall, with the potential for both positive (water resource recharge) and negative (flooding) impacts.

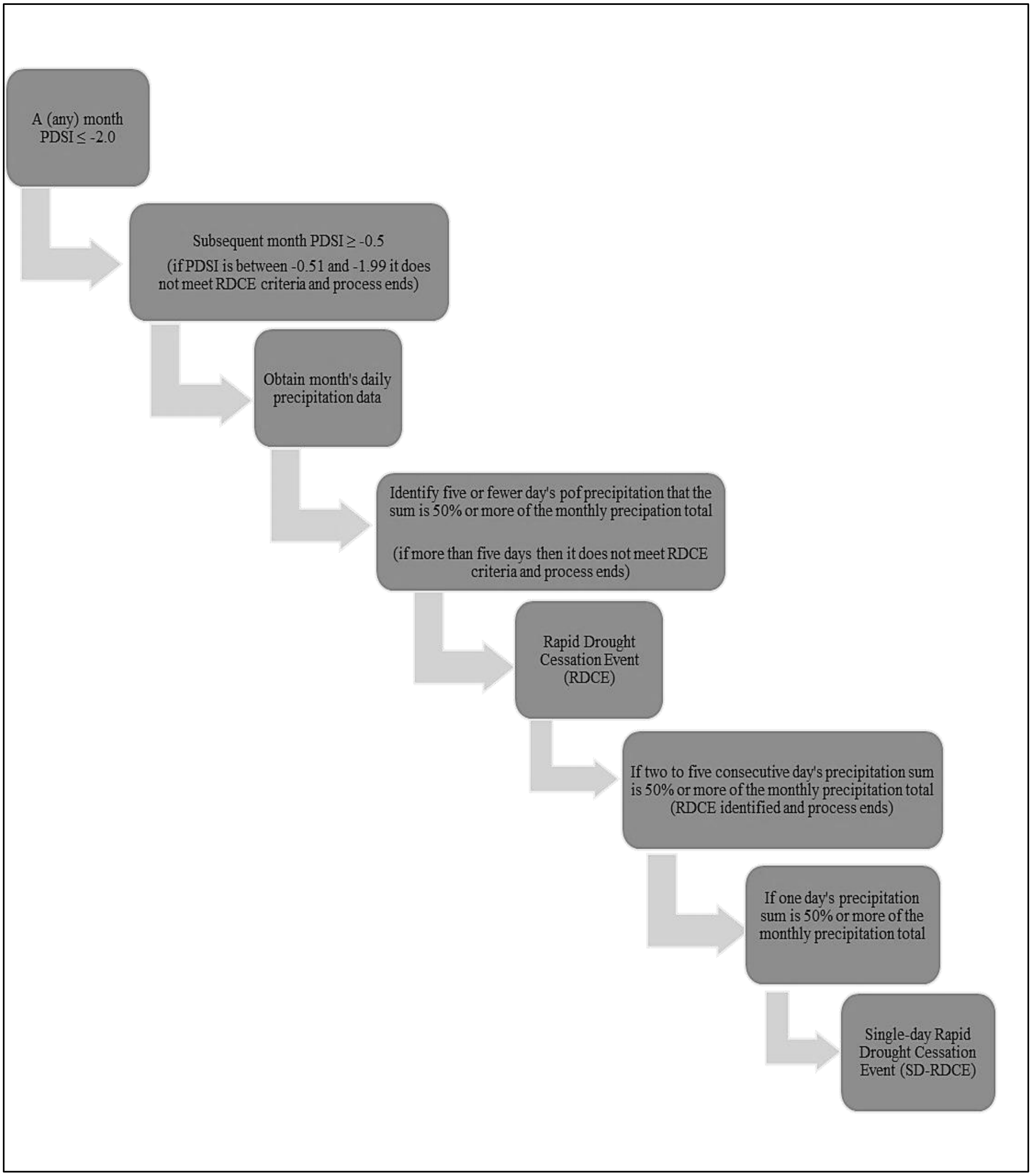

Figure 3. The process to identify an SD-RDCE. These processes must occur to qualify as an SD-RDCE.

RESULTS

Drought Regionalization

Based on the maximum factor loadings of the rotated PCA, I defined ten regions of homogeneity in annual average PDSI variability in the contiguous U.S. for the temporal period. The ten regions (principal components; PCs) explained 70.1% of the PDSI variance. The ten PCs effectively represent homogenous regions of similar drought variability. However, five (1.5%) of the climate divisions were not smoothly contiguous (i.e., splintered into other regions). In all cases except PC 10, the splintered divisions correlated with the surrounding PC (region) factor score. Splintered divisions may represent natural transition zones of drought variability (Ortegren et al. 2011). I reassigned splintered climate divisions to adjacent regions, to which the data were correlated. PC 10 consisted of two climate divisions in Mississippi. I reassigned Mississippi climate divisions 2 and 3 to an adjacent region. Thus, nine regions were obtained and assigned colloquial names (Figure 4). The Southwest consists of twenty-five climate divisions and is abbreviated by the state abbreviation and climate division number (Table 2; Figure 5).

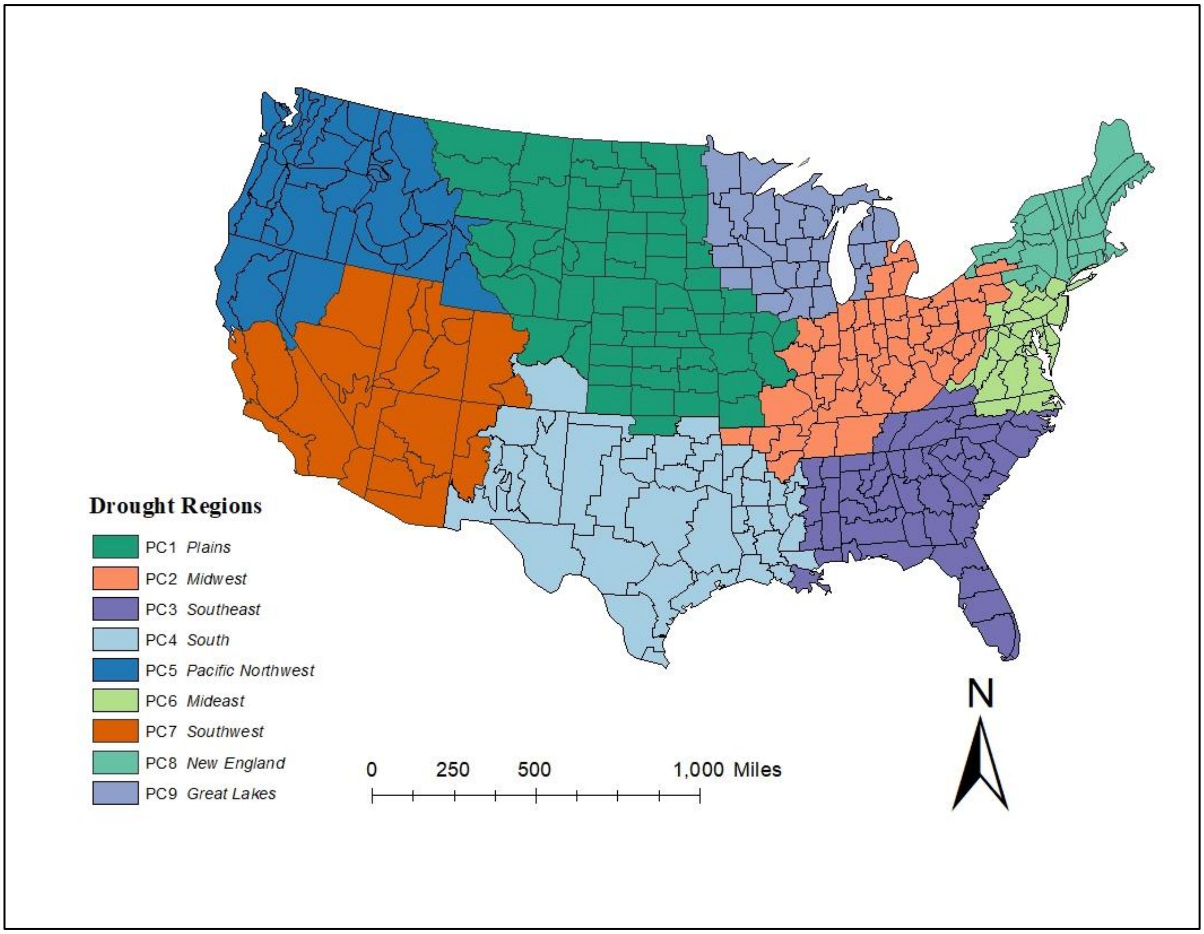

Figure 4. Drought regions. Drought regions based on maximum loading scores for the first nine rotated principal components of annual average PDSI variability in the contiguous United States from 1895 to 2017.

Table 2. Labels for the twenty-five climate divisions within the Southwest United States based on the PCA results.

State	State Climate Division	Southwest Climate Divisions (CDs)
AZ	1	AZ 1
AZ	2	AZ 2
AZ	3	AZ 3
AZ	4	AZ 4
AZ	5	AZ 5
AZ	6	AZ 6
AZ	7	AZ 7
CA	4	CA 4
CA	5	CA 5
CA	6	CA 6
CA	7	CA 7
CO	2	CO 2
CO	5	CO 5
NM	1	NM 1
NM	4	NM 4
NV	2	NV 2
NV	3	NV 3
NV	4	NV 4
UT	1	UT 1
UT	2	UT 2
UT	3	UT 3
UT	4	UT 4
UT	5	UT 5
UT	6	UT 6
UT	7	UT 7

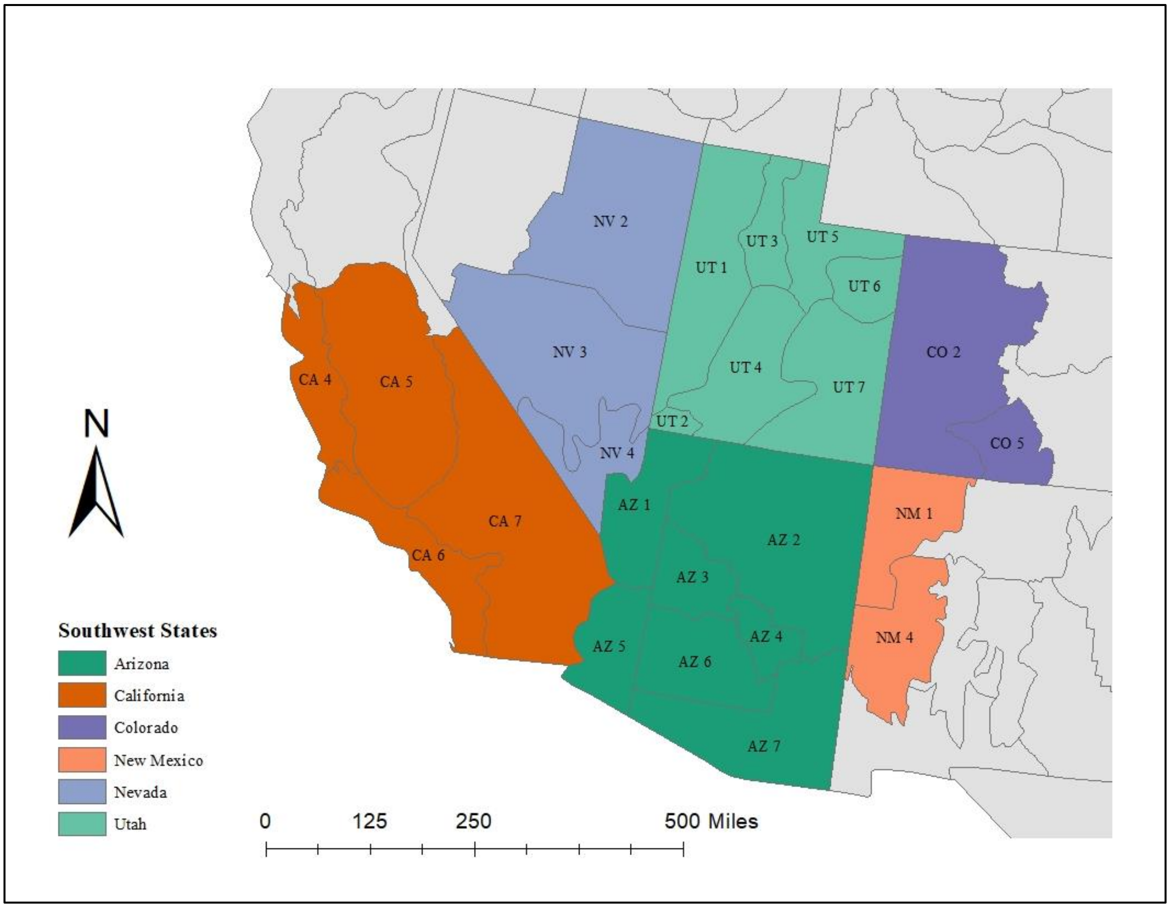

Figure 5. Southwest climate divisions. Twenty-five climate divisions in six states based on the PCA results.

Droughts

For the twenty-five SWUS climate divisions, I identified 765 droughts for the record. On average the Southwest experienced 30.80 droughts for the record (Table 3). Each drought had at least one month of qualifying drought. SWUS drought frequencies ranged from 26 to 36 total occurrences. UT 2 had the least number of droughts, whereas CO 5 had the most (Figure 6). Consistently, Arizona had the highest frequency of qualified droughts. Qualified droughts have increased and are more prominent in the region's southern, western, and far eastern climate divisions. The central and northern climate divisions experienced fewer droughts in comparison to the rest of the region.

Table 3. Summary of drought in SWUS from 1895 to 2017. List of drought event frequencies, the average length of each drought event and PDSI value based on the climate division's data. Drought events are based on qualified droughts (PDSI -2.0 or less).

SWUS climate divisions	**Drought events**	**Drough event length in months**	**Drought event severity (PDSI)**
AZ 1	30	17.50	-2.95
AZ 2	30	16.40	-3.14
AZ 3	33	14.21	-3.11
AZ 4	33	14.13	-3.39
AZ 5	32	13.44	-2.72
AZ 6	33	16.64	-3.00
AZ 7	31	17.45	-3.05
CA 4	31	12.71	-2.93
CA 5	34	11.62	-2.80
CA 6	29	16.52	-2.88
CA 7	30	18.33	-2.74
CO 2	32	11.00	-2.99
CO 5	36	11.46	-3.04
NM 1	33	13.18	-3.25
NM 4	27	17.37	-3.54
NV 2	28	16.11	-3.50
NV 3	30	17.63	-2.90
NV 4	30	15.47	-2.71
UT 1	30	14.45	-2.90
UT 2	26	16.92	-2.93
UT 3	29	14.83	-3.17
UT 4	28	12.61	-3.15
UT 5	29	11.62	-3.02
UT 6	30	13.10	-3.07
UT 7	31	11.71	-3.05
SWUS climate divisions	**Drought events**	**Drough event length in months**	**Drought event severity (PDSI)**
Sum	765		
Average	30.60	14.66	-3.04

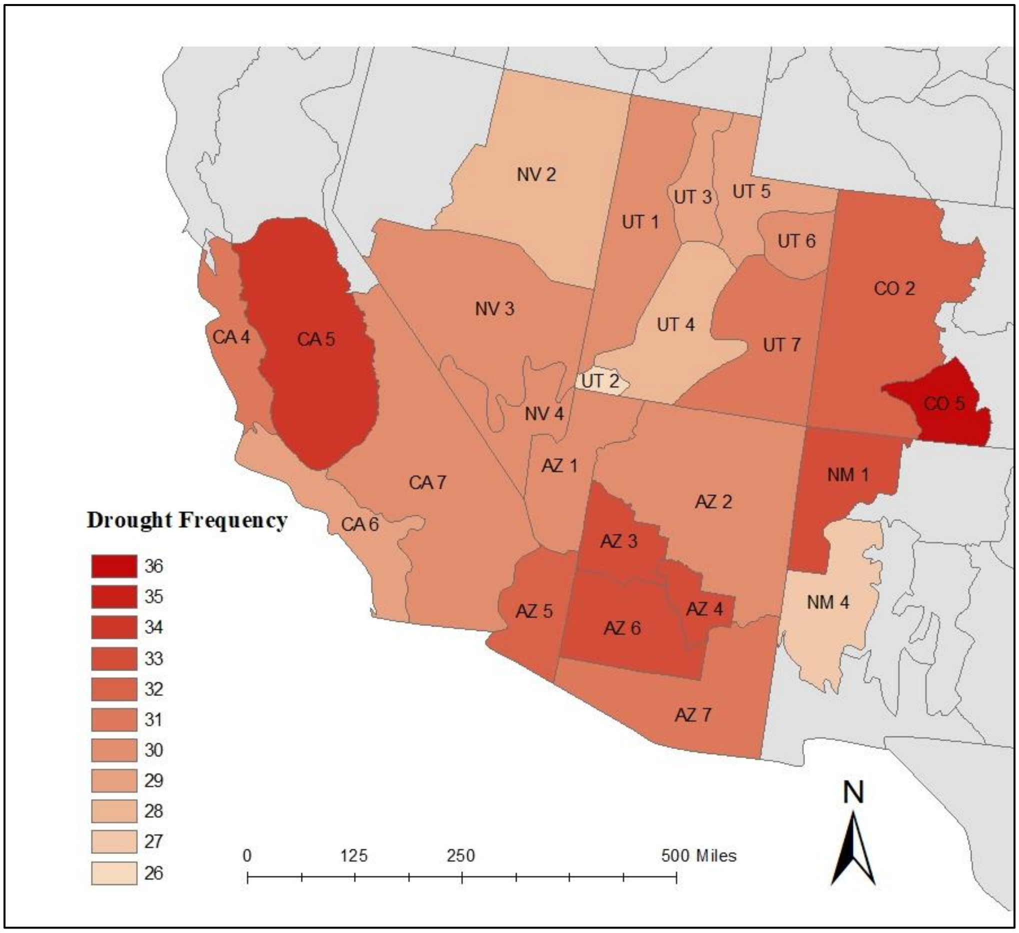

Figure 6. Total number of droughts, 1895 to 2017**.**

SWUS drought lengths averaged 14.66 months. Drought lengths ranged from 11.00 months (CO 2) to 18.33 months (CA 7). The longest drought on record lasted short of 9.5 years (September 2005 to May 2015) and occurred in AZ 2 (Table 4). The length of severe droughts is significant because if a region has severe long-term droughts coupled with intense RDCEs the risk for flooding and landslides increase due to high volumes of water flow across impervious and stably weak and dry soil structures.

Table 4. Longest qualified drought lengths recorded in each SWUS state.

Month/Year Drought Ended	Nov. 1947	Mar. 1965	Nov. 1992	Sept. 2004	Oct. 2004	May 2015
Drought Length (months)	64	69	70	57	68	113
Location (Climate Division)	NM 4	UT 2	NV 2	CO 2	CA 7	AZ 2

Not only does the SWUS risk having more long-term droughts, but severe droughts are also highly plausible. The average SWUS drought is classified as severe and valued at -3.04 (PDSI). SWUS droughts range from a -2.71 (PDSI; "moderate drought") to -3.54 (PDSI; "severe drought"). The PDSI has decreased over the record (Figure 7). With more severe drought in the region, RDCEs could pose as well needed relief from dry conditions, but the frequency and intensity of SD-RDCE precipitation totals can also induce flooding.

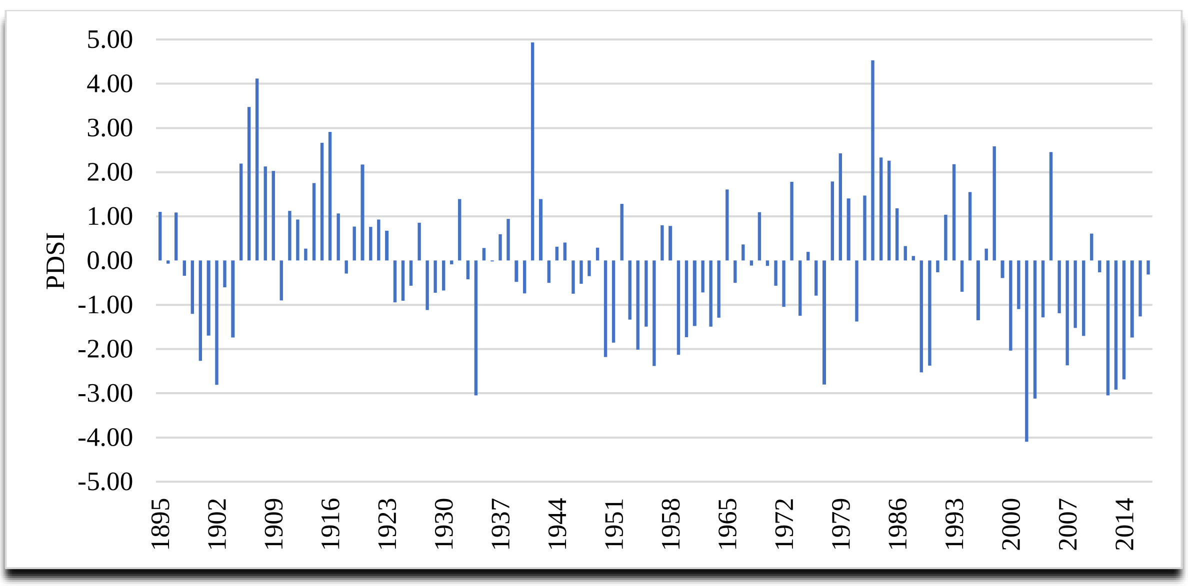

Figure 7. Southwest PDSI from 1895 to 2017.

Single-Day Rapid Drought Cessation Events

For the study period, I identified 765 drought events; 54 of those droughts ended by a single-day rapid drought cessation event (SD-RDCEs; Table 5). On average each SD-RDCE ended a drought length of 18.69 months. SD-RDCEs ended droughts of various lengths, from a minimum of one month to a maximum of 76 months. On average, SD-RDCEs ended droughts with a PDSI value of -3.02 ("severe drought"). The most extreme drought ended by an SD-RDCE (CO5; January 1941) was valued at -5.68 (PDSI; "extreme drought"). SD-RDCEs produced an average of 1,126.21 millimeters (mm) precipitation. The most precipitation produced by an SD-RDCE occurred on November 29, 1970, in CA 6, with a reported 10,869.1 mm. The year with the least amount of precipitation produced by an SD-RDCE was 1.8 mm on August 8, 1904, in NM 1 (table 3). There is a large discrepancy in the precipitation totals produced from SD-RDCEs which is likely due to the inconsistency in the number of rain gauge stations and that the precipitation totals are not aggregated across each climate division.

While there is no significant trend in SD-RDCE occurrences, there are some notable occurrences such as in 2009 when five SD-RDCEs occurred, which is the most in one year for the record. (Figure 8). Also, more SD-RDCEs occurred between 1943 and 1977 with a total of 22 events compared to the rest of the record. During that period, the most SD-RDCE in one decade, 1950-1959, occurred with nine events. During those 35 years, an SD-RDCEs occurred in the SWUS an average of 0.63 a year. In contrast, in the latter 35 years (1983 to 2017), 14 SD-RDCEs occurred at an average of 0.40 a year (Figures 8 and 9). Unsurprisingly, SD-RDCEs coincide with higher drought occurrences. During periods of fewer droughts and wetter conditions, fewer SD-RDCEs occurred.

Table 5. Summary of the Southwest's recorded SD-RDCEs.

Climate Division (CD)	Month	Year	Drought Length (months)	Drought Index (PDSI)	Precipitation Amount (mm)
AZ 1	Aug	1930	24	-2.55	103.6
AZ 1	Dec	2009	46	-4.05	241.1
AZ 2	Jan	1905	76	-4.87	273.5
AZ 3	Jun	1955	2	-2.39	883.4
AZ 3	Sept	2004	32	-4.15	490.0
AZ 3	Dec	2009	47	-3.88	677.1
AZ 4	Jul	1955	3	-3.08	707.8
AZ 5	Feb	1901	31	-3.47	66.8
AZ 5	Jan	1905	39	-2.62	22.1
AZ 5	Oct	1948	17	-2.43	134.6
AZ 5	Dec	1961	9	-2.07	269.7
AZ 5	Nov	1964	2	-2.26	108.7
AZ 5	Oct	1972	7	-3.02	567.4
AZ 5	Sept	1997	23	-3.64	415.5
AZ 5	Jan	2010	47	-2.88	477.1
AZ 5	Dec	2016	9	-3.16	211.5
AZ 6	Dec	2007	24	-3.6	1,012.0
AZ 7	Sept	1951	18	-3.05	569.1
CA 4	May	1930	14	-2.33	172.1
CA 4	Sept	1972	6	-3.77	533.6
CA 4	Nov	2002	1	-2.4	2,771.3
CA 4	Oct	2009	33	-2.84	7,535.5
CA 5	Jan	1963	1	-2.18	5,153.2
CA 5	Aug	1989	32	-2.44	93.3
CA 5	Oct	2009	33	-2.8	4,150.9
CA 6	Apr	1929	9	-2.01	1,748.6
CA 6	Oct	1934	6	-2.49	2,658.9
CA 6	Oct	1951	47	-3.11	2,974.6
CA 6	Nov	1966	6	-2.33	7,732.5
CA 6	Nov	1970	9	-2.86	10,869.1
CA 6	Oct	1996	9	-2.17	2,586.0
CA 7	Nov	1900	29	-2.7	24.2
CA 7	Oct	1934	7	-3.27	700.3
CA 7	Oct	1948	17	-3.32	913.6

CO 2	--	--	--	--	--
CO 5	May	1913	1	-2.14	13.0
CO 5	Dec	1943	16	-2.55	180.2
CO 5	Jan	1951	21	-5.68	69.5
NM 1	Feb	1903	49	-4	35.3
NM 1	Aug	1904	9	-5.49	1.8
NM 4	--	--	--	--	--
NV 2	--	--	--	--	--
NV 3	Nov	1954	20	-2.57	134.1
NV 3	Oct	1957	16	-2.54	290.0
NV 4	Jul	1896	4	-2.75	8.4
NV 4	Nov	1923	2	-2.56	91.2
NV 4	Jun	1925	13	-3.07	12.5
NV 4	Jul	1946	1	-2.41	83.1
NV 4	Aug	1957	19	-2.68	233.8
NV 4	Sept	1959	4	-2.33	26.4
NV 4	Dec	1977	8	-2.23	133.4
NV 4	Dec	2009	46	-3.61	222.0
UT 1	Sept	1996	1	-2.27	174.4
UT 2	Jul	1902	43	-2.9	46.2
UT 3	--	--	--	--	--
UT 4	Sept	1972	6	-3.19	1,013.0
UT 5	--	--	--	--	--
UT 6	Nov	1931	4	-2.95	42.1
UT 7	Nov	1943	11	-2.39	156.0

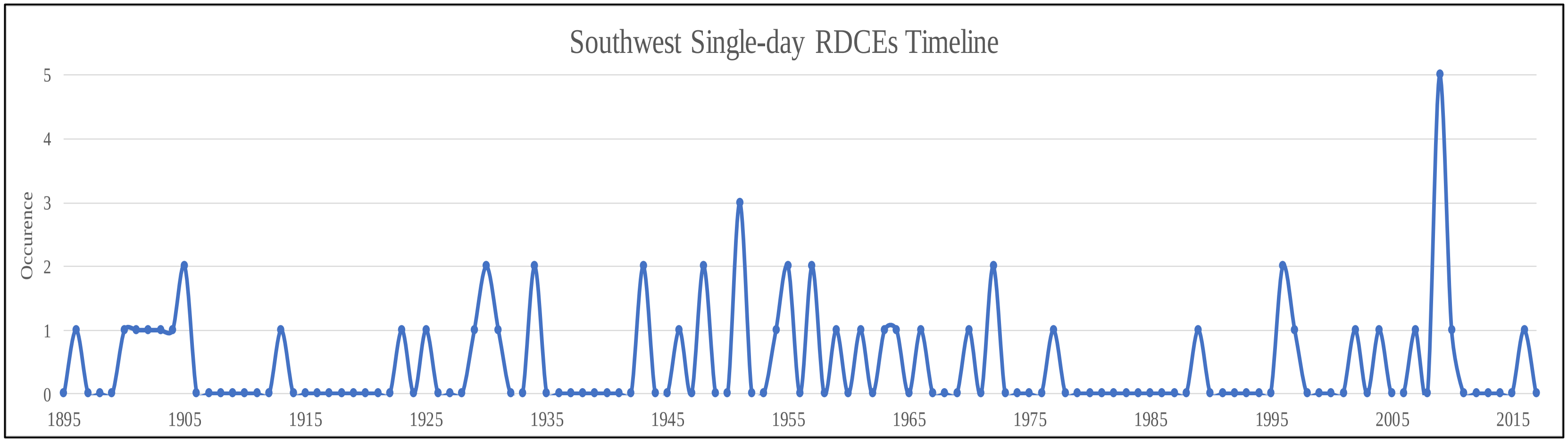

Figure 8. SWUS Single-day RDCEs from 1895 to 2017.

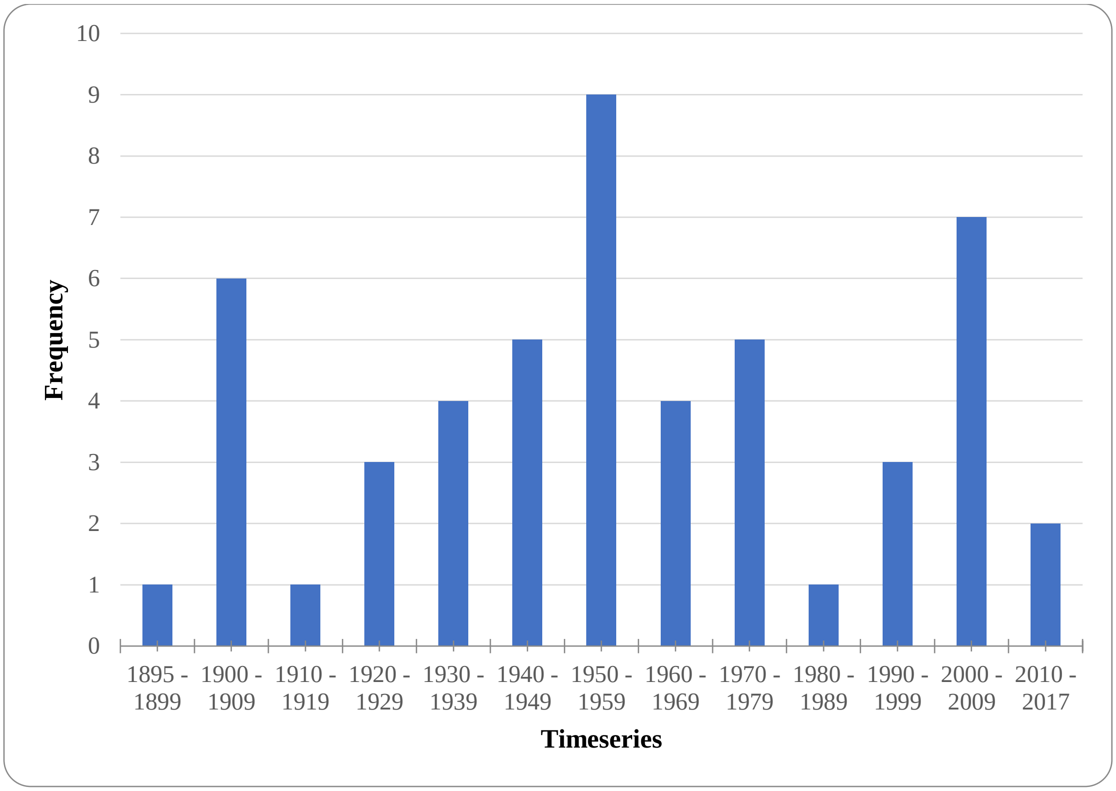

Figure 9: Number of single-day RDCEs by decade 1895 to 2017.

Most SD-RDCEs occurred in the southern and western portion of the region. SD-RDCEs occurred more frequently in AZ 5 and NV 4. The northern and eastern climate divisions recorded the fewest SD-RDCEs. Climate divisions NV 2, UT 3, UT 5, CO 2, and NM 4 did not have any SD-RDCEs (Figure 10).

SD-RDCEs occurred most often in October and most of those events occurred in California (Figure 11). A majority (55.6%) of SD-RDCEs occurred during the warm-season. Of the warm-season SD-RDCEs most occurred in California, Nevada, and Utah. However, those occurred in September and October which is the natural time of the year when the climate transitions into the cool- and wet-season. SD-RDCEs occurred more frequently in the cool-season across Arizona, Colorado, and New Mexico and coincides with seasonal precipitation.

Monsoon storms are likely attributed to the warm-season SD-RDCEs that occurred in Arizona, Colorado, and New Mexico.

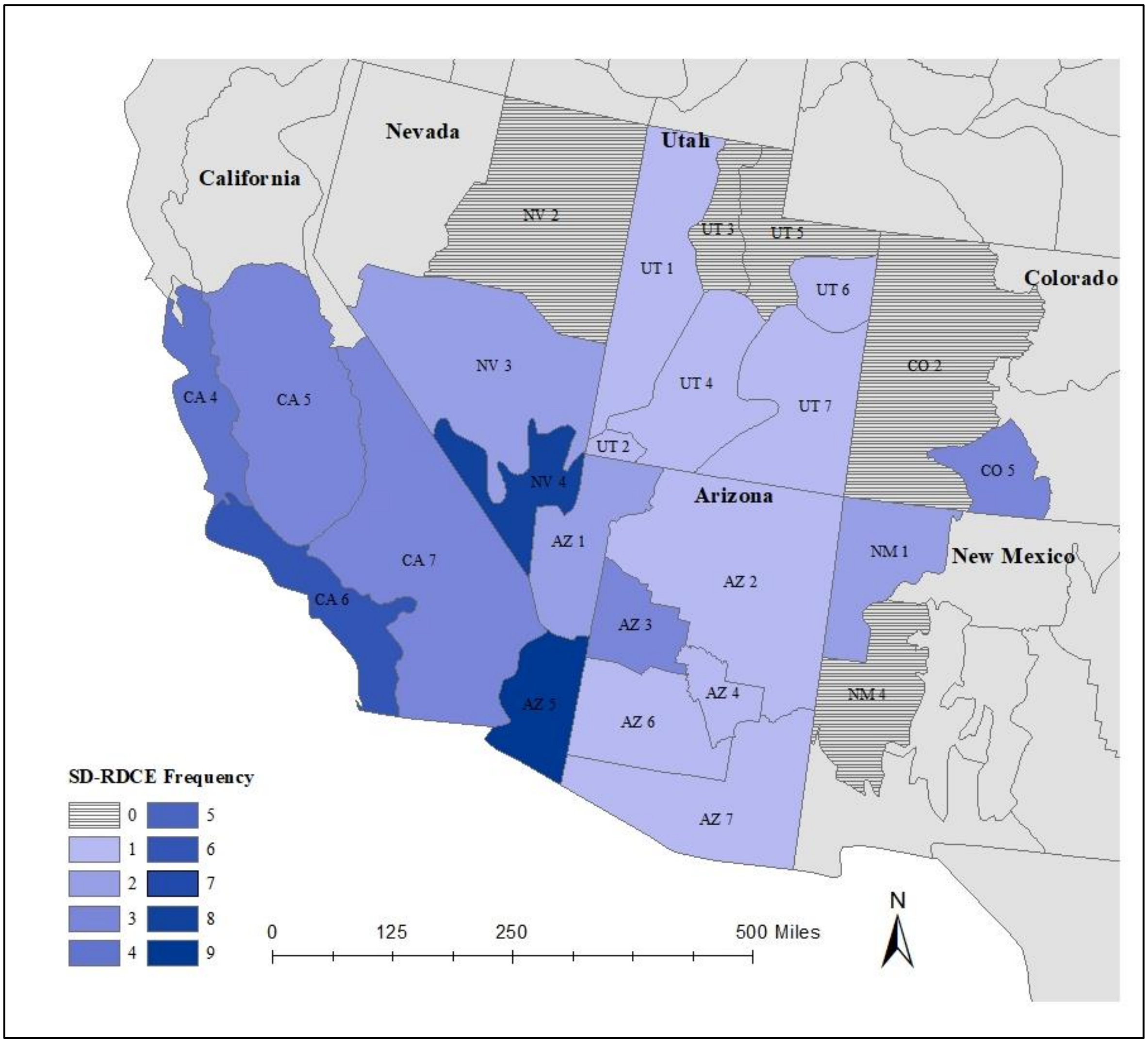

Figure 10. Total single-day RDCE frequency per climate division.

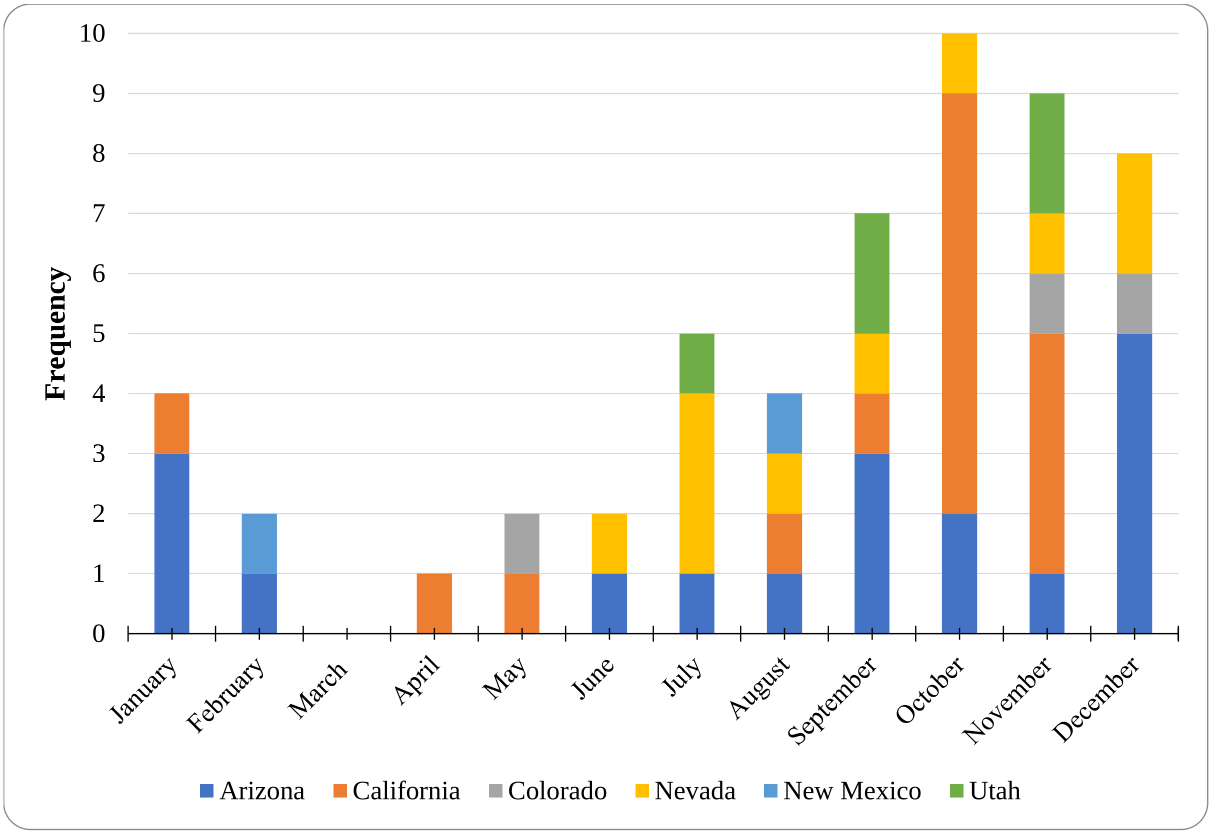

Figure 11. Total number of single-day RDCEs per month and divided by state.

DISCUSSION

Defining the Southwest and characterizing drought and drought effects has its challenges due to the region's diverse climate. The PCA results indicate that the Southwest climate divisions have similar annual drought conditions. Furthermore, the nine drought regions comparably align with past research used to define homogenous drought regions (Ortegren et al. 2011). This similarity indicates that PCA is a viable method used to reduce the Southwest's climate data variability and define reasonably interpretable spatial boundaries.

During the study period, both drought frequency and intensity increased in the SWUS. Since 1987, moderate and severe drought frequency increased across the Southwest, particularly in Arizona and California. Compared to the other SWUS states, droughts occurred most frequently in Arizona and agree with other studies related to the region's drought climatology (Garfin et al. 2013). This is valuable for regional and local water managers since increasing drought frequency and intensity can be disastrous for water-reliant industries and municipalities. The heavily water-reliant agriculture industry throughout California must respond to decreasing water availability. During droughts, farmers must adapt to decreased freshwater and increased salinity levels and must manage with less water and anticipated low yields as a result of drought and associated heat waves (Ciancarelli et al., 2013). With climate change and predicted more frequent and intense droughts, water-reliant industries and municipalities risk facing more dry conditions with decreasing water supplies.

RDCEs provide relief to the drought-prone Southwest. Due to high-volume precipitation in a short time, SD-RDCEs also can pose adverse effects. Flash floods often occur in the Southwest. High volumes of rainfall and water flow across the landscape and can cause destruction, severe erosion and mass wasting events due to the impervious soil. SD-RDCEs have the potential of flooding newly-planted farms and washing away germinating seedlings. Heavy rains and flash floods can force businesses and schools to close, force drivers to abandon vehicles in rising waters, and cause fatalities. Recent examples include flood events in Phoenix and Tucson, AZ, in September 2014 (Howitt et al., 2009), but at this time it is unknown if such event is classified as an RDCE.

Southwestern Arizona, specifically AZ 5, experienced the most SD-RDCEs. The Colorado River runs through this climate division. The findings from this study could play a role in how stakeholders manage the river's resources. Across AZ 5, SD-RDCEs happen most frequently in the cool-season which is also when the annual precipitation peaks.

Further research is needed to determine the significance and explanation of the SD-RDCEs total precipitation variability. For example, two RDCEs had significantly different precipitation totals: (1) across AZ 2 an 83-month long drought ended in January 1905 from 273.5 mm of precipitation compared to (2) an 8-month drought, in CA climate division 6, that ended in November 1970 with 10,869.1 mm of precipitation. One explanation could be the discrepancy in daily precipitation summaries. Historical records from further in the past have fewer rain-gauge recordings compared to recent years. Some climate divisions have dozens of reporting weather stations, whereas others have fewer. Since I averaged the climate division's rain gauge totals, the totals may not accurately reflect the daily precipitation since the number of gauges is not weighed evenly. A future study could revise the methods so that the daily precipitation totals accurately reflect the climate division's area.

The next phase of this research will further explore the climatology of the Southwest's multiday (two to five day) RDCEs. Additionally, further analysis will explore the spatiotemporal characteristics of regional RDCEs and potential associations with long-term teleconnections such as El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO). Those findings may help explain the spatiotemporal patterns of single- and multi-day RDCEs.

CONCLUSION

I identified nine distinct regions of annual drought variability in the coterminous U.S. from 1895 to 2017. The Southwest region is topographically diverse with multiple microclimates. Therefore, it is essential to understand the spatiotemporal characteristics and frequency of drought cessation. I identified 54 SD-RDCEs, and 765 droughts (PDSI ≤ -2.0; PDSI) that occurred across the Southwest. While RDC in an arid or semi-arid environment brings positive impacts in terms of soil moisture and surface reservoir recharge, SD-RDCEs likely pose adverse effects due to high-volumes of precipitation over saturating drought-stricken land. Drought frequency and intensity increased across the Southwest. Therefore, this region would benefit from an enhanced analysis of multi-day RDCEs and determine any ocean-atmospheric teleconnections that might increase the predictability of Southwest RDCEs.

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